Appendix 3-B

Hydrodynamic Effects on Offshore Wind Turbine Support Structures

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HYDRODYNAMIC EFFECTS ON OFFSHORE WIND TURBINE SUPPORT STRUCTURES

1.0 INTRODUCTION

When determining a viable location for the siting of a commercial-scale offshore wind farm, a number of physical and meteorological siting criteria must be evaluated. The most important of these criteria are wind speed and duration, and the overall quality of the wind resources necessary to produce sustainable wind-generated energy.

The quality of wind resources is known to be much higher over open water due to generally higher sustained wind speeds and lower turbulence (due to the lack of topographical friction and obstructions) when compared to winds over most land-based locations. As a result, offshore locations for commercial wind farms offer significant performance advantages over land-based installations.

However, the dynamic offshore environment presents several challenging design issues that must be determined to be acceptable to create a safe and structurally sound wind turbine generator (WTG) foundation and support system. WTGs are designed to be dynamically sensitive structures to account for turbine blade rotation and wind stress forces. When WTGs are sited in a similarly dynamic offshore environment, breaking waves, storm surge conditions, and other hydrodynamic forces must be considered in their structural design. Much of the knowledge of offshore hydrodynamic forces on pile-structures is based upon the experience of the existing offshore platform industry (oil rigs, etc.) that operate in extreme deep water locations, and is not readily applicable to the state-of-the-art technical limitations of the offshore wind energy industry.

This paper will address the foundation design criteria and examine the current practical limits of hydrodynamic loading that are presently considered on commercial WTG installations presently under design and development.

2.0 WIND TURBINE GENERATOR (WTG) COMPONENTS

In order to appreciate the design challenges presented by offshore hydrodynamic forces, it is necessary to first understand the components of a WTG structure. The WTG is broken down into five discrete components: the rotor assembly with blades; the nacelle which houses the gear generator and auxiliary systems; the tower; the transition piece; and the foundation.

Collectively, the rotor, nacelle and tower produce an aerodynamic loading which in turn creates a certain dynamic behavior of the structural components which affects the overall WTG design and influences the foundation system design. This aerodynamic behavior is common for either land or offshore locations being considered, and therefore is not discussed in technical detail within the scope of this paper.

The WTG components that relate specifically to offshore hydrodynamic loading by sea and wave conditions discussed herein include:

Tower
The purpose of the tower is to support the nacelle at its design elevation, allow personnel access for systems maintenance via internal ladders, and to transfer the various loads and aerodynamic forces from the rotor to the foundation system and ultimately the supporting seabed. The tower design is optimized as to strength, stability and resonant frequency and is based on standard steel construction design criteria. The tower design does not typically account for external impact forces from waves and therefore must be located at an elevation that is greater than the crest elevation of the highest wave in an extreme storm sea state. This design wave is referred to as the extreme storm wave (ESW) for that particular offshore location.

Transition Piece
Between the tower and the monopole foundation there is a transition piece which compensates for any possible inclination of the pile and/or deformation of the pile head which may have occurred during installation. The transition piece includes the access platform and is designed to transfer all loads from the tower to the foundation.

Monopile Foundation

The monopile foundation system design represents the most suitable and preferred foundation solution for offshore applications. This type of foundation design system is the predominant system type presently utilized for offshore WTGs. The monopile is simply a large diameter pile (14 to 16 feet) driven 50 to 90 feet into the seabed depending on the local load bearing characteristics of subsurface marine sediments. The monopile is open-ended, allowing sediment to be encased within the monopile to provide for additional structural support. The monopile will extend up to the transition piece, and its length is dictated by the ESW and maximum water elevation to allow an air gap between the wave crest and the platform. As with any foundation, monopiles must be carefully designed from a detailed analysis of the site-specific geotechnical and physical exposure conditions. One of the most significant challenges associated with the use of a monopile is the limited commercial availability of facilities that can fabricate large enough structures due to the significant weight and sizes required. As the water depths and loads increase the pile diameter and thickness must increase as well.

There are two other types of foundations that could be considered: the gravity design and a multi-pod (tripod or quad-pod) design. The gravity foundation has been utilized for several of the existing offshore European WTG installations that have bottom characteristics that preclude the use of monopiles (e.g. ledge, rocks or soil characteristics unsuitable for piles). Experience has shown that they are not suitable for the larger offshore wind farms and would require a shipyard and dry dock near the site to construct and allow the massive foundation structures to be floated out to the site and sunk. The gravity foundation design also presents a much greater environmental impact than a monopile due to the large diameter (approximately 60 feet) The Middelgrudden wind farm in Denmark represents the largest gravity foundation utilized which is on a 2 MW WTG.

The multi-pod (most likely to be a tripod) structure is being evaluated by the industry for future generations of deeper water WTG's. This conceptual design provides a very stiff foundation system, and is governed by the fatigue loading and the high stress concentrations inherent to welded tubular joints. Some of the design issues are beyond the current state of the art of the wind industry and are not commercially available at this time.

3.0 Offshore Environment

The offshore environment has extremely variable and unpredictable weather conditions, sea state conditions, water level fluctuations, high humidity, corrosive salt, and the potential for icing. These environmental factors must be accounted for when designing a WTG to be sited in offshore conditions. In addition, the WTG must be designed to withstand the effects of wind, waves, currents and marine growth, as well as possible ship impacts under dynamic loading conditions.

To provide a structurally sound and serviceable structure that will operate through its design life, the design must be suitable for the extreme conditions based on a 50-year storm return period including the coincident conditions of wind, wave, current and storm surge.[1] This has been adopted as standard design criteria in the offshore wind industry. Of the three primary offshore environmental factors (wind, wave and current), waves are normally the most critical factor when designing offshore structures. Waves contain large amounts of kinetic energy and pressure forces that produce large, repeated loads on structures, and contain a wide range of frequencies that have a significant influence on the dynamic behavior of the structure. The greatest concern in the design of the WTG structure is the ESW and the potential of waves breaking on the structure.

This paper will focus on wave induced hydrodynamic forces and their impact on design. For the purposes of this discussion, it is assumed that the aerodynamic forces are the same for any offshore location being considered. It should be noted, however, that fatigue loads on structures located farther offshore are likely to be higher due to higher wind speeds, greater water depths, and greater incident wave forces.

Hydrodynamic loads that are considered in the design of the WTG include wave passage, wave breaking, wave slam (a vertical face that slams against the structure and causes an extremely high intensity, short duration pressure on the structure), and slap (associated with the rate of added mass when engulfed by a steep wave). Local currents exert lesser loads on the WTG, but must be considered. A factor for marine growth is also considered in the design.

[1] M.B. Zaaijer. "Properties of Offshore Support Structures For Large Scale Wind Turbines."

The calculation and determination of design wave loads on offshore structures is a complex undertaking involving different wave models and load calculation methods. Both the extreme event and fatigue load cases need to be considered to develop a safe, durable, and cost effective structural foundation and support system.

4.0 WAVE CHARACTERISTICS

A great deal has been written about wave characteristics. Linear and non-linear water wave theories have been developed and various wave models have been created for wave characteristic determination. This discussion will focus on how waves apply to the design of structures using the normal characterization of wave period and the associated significant wave height.

Several different values are used to describe the wave height component of waves at an offshore site. The maximum observed wave height (maximum H_{mo}) is an actual observation, and it describes the maximum wave height observed during the 20 year period included in the USACE Wave Information System (WIS) hindcast data[2]. H_{mo} is determined from values of the water surface elevation given by the wave record. The significant wave height (H_s) is the average height of the one-third highest waves of a given wave group (in this case, the WIS data), and is determined by applying a Beta-Rayleigh distribution to H_{mo}, the peak spectral wave period, and the water depth. For waves in deep water that are not too steep, H_{mo} and H_s are approximately equal. For steep waves and waves in intermediate and shallow water, H_s becomes increasingly larger than H_{mo}. The extreme storm wave height is a statistical representation of an extreme sea state that is frequently used as a design parameter. Extreme storm wave height is often taken to be the average height of the highest 1% of all waves in a Beta-Rayleigh distribution (H_1 or $H_{1/100}$) when designing offshore structures. H_1 is typically estimated as 1.67 times the significant wave height.

Wave height with various other probabilities of exceedance can also be calculated by applying the Beta-Rayleigh distribution to H_{mo}, the peak spectral wave period, and the water depth. In addition, several other methods are available to estimate long-term wave probabilities that are based on hindcasting sea states during the most severe storms in the area of interest.

A combination of observed and statistically derived wave information is used to develop the design wave characteristics (i.e., wave height, wave period, propagation direction, and spatial distribution) for an offshore structure. This information is then used to determine the resulting hydrodynamic forces on the structure under various wind, current, and sea state conditions. These forces are in turn used to determine fatigue loads on the structures.

Wave loading from both non-breaking and breaking waves must be considered. These forces are a result of the water particle velocities and accelerations in the wave- or tide-induced flow. For structural design, it is important to determine the total maximum force and the total maximum moment about the seabed interface acting on the pile. Modeling of wave forces on a pile relies on the use of empirical coefficients to supplement theoretical formulations. Variables that must be considered include wave height, wave period, water depth, wave/seabed interaction (friction), pile diameter, and pile roughness.

Forces exerted on piles by non-breaking waves (e.g., swell) result in a fatigue type load since waves pass the WTG with varying periodicity. Specific design guidance for this loading condition is readily available through various sources such as the USACE *Coastal Engineering Manual*.[3,4]

Once design wave characteristics and forces resulting from non-breaking waves are determined, the loading effects of breaking waves on the WTG are then analyzed. As waves approach shallower waters they begin to feel the bottom and the wavelength decreases while the wave height increases. This results in increased wave steepness. When waves become so steep that they can no longer remain stable, they break. Since wave breaking is related to water depth, the height of a breaking wave can be estimated from the following equation:

[2] The USACE Wave Information System data can be accessed at http://bigfoot.wes.army.mil/u003.html
[3] R.M. Sorensen. "Basic Coastal Engineering." 2nd Edition, 1997.
[4] U.S. Army Corps of Engineers. 2002. *Coastal Engineering Manual*. Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington, D.C. (in 6 volumes). .

$H_b = 0.78*d_w$
Where H_b = breaking wave height
d_w = water depth

The shallow water breaking wave height is dependent on seabed slope and bed characteristics, and can be affected by strong winds or currents in the direction of wave travel.

Breaking waves are classified as spilling, plunging, or surging. In an offshore environment, spilling and plunging breakers are usually encountered. Spilling breakers break gradually, thus dissipating their energy over a larger area. Plunging breakers curl over at the crest, sending a mass of water over the crest. The energy from a plunging breaker is dissipated over a relatively smaller area, and results in very high impact loads and consequently “ringing” of an impacted structure. Therefore, plunging breakers are considered as the design extreme case when siting and designing WTGs in offshore conditions. Plunging breakers can lead to very high structural loads, particularly if the structure is located at a distance of approximately five times the wave height down wave from the point of breaking.[5]

The kinematics (velocity and acceleration) of breaking waves are not as well understood as the kinematics of nonbreaking waves. Since kinematics are the prime factors that control wave induced loads, the loads due to breaking waves are also not as well understood. The related issues of wave slam and wave slap also must be considered. Reasonable approximations of the forces from a breaking wave are on the order of two to four times that of a non-breaking wave.[6]

The dynamic forces from waves that affect a tubular structure with diameter D can be broken into three components (according to the widely used Morison equation):[7] and in accordance with API Recommended Practices.[8]

1) Drag forces that are caused by viscous effects, friction and vortices resulting from water passing the structure. Drag forces are proportional to DH^2 where H is the wave height.
2) Slap forces, which are proportional to DH^2.
3) Inertial forces which are related to the acceleration of water particles rather than their velocities. The inertia force is proportional to HD^2.

It can be seen from above that the actual wave height conditions at the site has the maximum impact on the force acting upon the WTG foundation system. It can also be seen that wave forces increase with wave height.

5.0 FATIGUE LOADING

The fatigue loading of an offshore WTG is a combination of wind and wave loading incorporating any relevant dampening effects and giving consideration to the soil characteristics. Complex time domain simulations of combined wind and wave loading have to be performed to cover the dynamics of the WTG. This analysis will determine the excitation frequencies of the structure and establish the fatigue loads.

Various models and methods exist that are utilized to compute the frequencies at which the system will oscillate, the corresponding displacement patterns, and the system forms. Most analyses utilize a finite element eigenfrequency analysis of the undamped vibrating system and then introduce an algorithm to adjust for damping effects. This type of analysis calculates eigenfrequency and compares it to the resonance range of the system.

The support structure (foundation, transition piece and tower) must be designed to meet the WTG manufacturer’s specified dynamic criteria to avoid resonance and to ensure satisfactory fatigue durability. When an excitation frequency comes close to a natural frequency of the system, resonance occurs. This situation must be avoided because it may lead to enormous fatigue damage or other large loads, which adversely affect the

[5] A.R. Henderson. “Breaking Wave Loads On Offshore Wind Turbines.”
[6] Wienke J., Sparboom U, Oumeraci H “Breaking Wave Impacts on a Slender Cylinder”
[7] Morison, J.R: O’Brian, M.P at al. 1950, “The Force Exerted by Surface Waves on Piles” Petroleum Transactions AIME. 189, 1950.
[8] American Petroleum Institute Recommended Practice 2A-WSD (RP 2A-WSD) twenty first edition December 2000

structural design. The conventional structural stiffness regimes that are considered in relationship to the fundamental frequency of the overall structural system (f_o), the rotor frequency (f_r) and the blade passing frequency (f_b) are defined as:[9]

soft-soft $f_o<f_r$
soft-stiff $f_r<f_o<f_b$
stiff-stiff $f_o>f_b$

Structures in the soft-soft or soft-stiff ranges are preferred because stiff-stiff structures will be much heavier and consequently more expensive to construct. In addition, installation may not even be feasible if some type of tripod arrangement is required. The monopile designs that have been utilized are primarily of the soft-soft designs while gravity foundations that have been utilized for smaller WTGs, and conceptual tri-pod variants are stiff-stiff designs.

To design a WTG to withstand large breaking wave forces associated with plunging breakers would require a stiff-stiff design structure to reduce the probability of fatigue failure due to these sustained breaking forces on the structure. The structure would most likely be a heavily reinforced tripod-type foundation system, which is currently not commercially available.

6.0 CASE HISTORIES

The most recent example of a large offshore wind farm is Horns Rev in Denmark, which has 80 WTGs located in water depths between 21 and 44 feet and ESW of 19.6 feet. The other existing offshore wind farms in Europe have water depths within this range and lower wave heights, with the exception of the two WTGs at Blyth in the United Kingdom. The Blyth installation has an average water depth of 26 feet and has an ESW of 28 feet. As a result, these WTGs are experiencing a significantly accelerated fatigue life from the breaking waves. This installation is being monitored to study breaking wave loads on a megawatt size WTG.

7.0 CONCLUSION

To design an offshore wind farm that is structurally sound and viable, an accurate understanding of the fatigue and wave loads is required. Particular attention must be paid to the ESW and the associated forces, and how they impact the monopile foundation design. It can be seen that as the pile length increases with increasing water depth and wave height the required stiffness increases due to the fatigue loads until a point is reached where a monopile foundation is no longer feasible or considered a structurally sound solution. This opinion has been reached with various engineers involved in the design and evaluation of WTG foundation systems. A complete and detailed engineering analysis of wave depth / wave height / structure stiffness is beyond the scope of this paper. According to the best available data and current industry experience, this critical design threshold is reached with a design wave (ESW) of approximately 20 feet in up to 50 feet of water. It is assumed that this envelope may be extended slightly when favorable geological conditions are present and if larger diameter piles with increased wall thickness and the associated heavier weights can be manufactured and installed.

It is further concluded that to design a WTG to withstand the large forces associated with plunging breakers (e.g., offshore shoals in deeper waters) is not practical since it will result in large stiff structures that are not commercially available at the present time. The proper application of monopile foundation systems for offshore WTGs is at sites where the possibility of large breaking waves is minimized such as in shallower and embayed offshore waters.

In addition, the economic reality for a privately financed wind farm is that the foundation design is one of the largest cost components of offshore WTG project development[10]. Therefore sound structural solutions must be optimized to enhance the wind farm's commercial viability.

[9] Kuhn, M. (1997) Soft or Stiff: A fundamental question for designers of offshore wind energy convertors. Proc. European Wind Energy Conference (EWEC 1997) Dublin.
[10] James F. Manwell Ph.D University of Massachusetts Renewable Energy Research Laboratory. http://wind.raabassociates.org/articles/offshore%2011_02x.ppt