Ocean Engineering 101 (2015) 1–11

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

An investigation into the effect of scour on the natural frequency of an offshore wind turbine

L.J. Prendergast*, K. Gavin, P. Doherty

School of Civil, Structural and Environmental Engineering, University College Dublin, Newstead, Belfield, Dublin 4, Ireland

ARTICLE INFO

Article history:
Received 29 August 2013
Accepted 6 April 2015
Available online 21 April 2015

Keywords:
Scour
Acceleration
Wind turbines
Frequency
Soil stiffness
Monopiles

ABSTRACT

Rapid expansion of the offshore wind industry has stimulated a renewed interest in the behaviour of offshore piles. There is widespread acceptance in practice that pile design methods developed for the offshore oil and gas industry may not be appropriate for designing wind turbine foundations. To date, the majority of offshore wind turbines are supported by large diameter monopiles. These foundations are sensitive to scour which can reduce their ultimate capacity and alter their dynamic response. In this paper, the use of a vibration-based method to monitor scour is investigated. The effect of scour on the natural frequency of a model monopile was measured in a scale model test. A spring–beam finite element numerical model was developed to examine the foundation response. The model, which used springs tuned to the small-strain stiffness of the sand, was shown to be capable of capturing the change in frequency observed in the scale test. This numerical procedure was extended to investigate the response of a full-scale wind turbine over a range of soil densities, which might be experienced at offshore development sites. Results suggest that wind turbines founded in loose sand would exhibit the largest relative reductions in natural frequency resulting from scour.

1. Introduction

The development of offshore wind energy converters is viewed as one of the most cost effective and politically acceptable short-term means of reducing society's reliance on fossil fuels. Since 1991, the majority (over 75%) of offshore wind turbines have been founded on large diameter steel tubular monopiles (EWEA, 2012). These piles with diameters (D_{pile}) in the range 4–6 m are typically driven to penetrations (L_{embed}) of between 20–30 m (Doherty and Gavin, 2012). The resulting piles are relatively stiff, with low slenderness (L_{embed}/D_{pile}) ratios. Monopile design is usually performed using spring–beam (p–y) models which are described in the American Petroleum Institute (API, 2007) and Det Norske Veritas (Det Norske Veritas, 2007) design codes. The design should consider all limit states including the ultimate limit state (ULS). However, because of strict rotational tolerance specifications, serviceability requirements tend to govern design.

Wind turbines are dynamically sensitive structures with the primary excitation forces arising from the rotor spinning at a given rotational velocity, termed the 1P frequency and the blade passing frequency, termed N_bP, where N_b is the number of blades on the turbine. LeBlanc et al. (2010) noted that typical ranges for the 1P frequency are 0.17–0.33 Hz, whilst for a standard three bladed turbine; 3P is in the range 0.5–1 Hz (see Fig. 1). Wind and wave frequencies are typically below the 1P frequency, although wave frequencies are highly variable and can span a relatively wide frequency spectrum, see Tempel and Molenaar (2002). During the design phase for the turbine support structure, it is important to minimise the potential dynamic amplification of the load and avoid resonance by ensuring that the natural system frequency of the turbine and its support system does not coincide with any of the excitation frequencies discussed above. This is achieved by tailoring the stiffness of the structural system at the foundation-superstructure interface through careful design of a sub-structure system. In terms of the foundation, a designer can choose a very stiff structure (termed stiff–stiff) such as a jacket, leading to a natural system frequency above the 3P range. Alternatively, a structure with a system frequency between the 1P and 3P values, termed a soft-stiff structure can be created by using a monopile foundation. It is possible to design a flexible structure, with a system frequency below 1P, termed a soft–soft structure. However, these soft–soft design options are susceptible to resonance from sea waves due to the alternating stresses induced on the structure by the period of passing waves.

It is widely recognised that offshore piles installed in non-cohesive deposits can be affected by local scour. Local scour occurs around piles when the near bed shear stresses exceed the critical

* Corresponding author. Tel.: +353 1 7163231/+353 1 7163222.
E-mail addresses: luke.prendergast@ucdconnect.ie (L.J. Prendergast), kenneth.gavin@ucd.ie (K. Gavin), paul.doherty@ucd.ie (P. Doherty).

http://dx.doi.org/10.1016/j.oceaneng.2015.04.017
0029-8018/

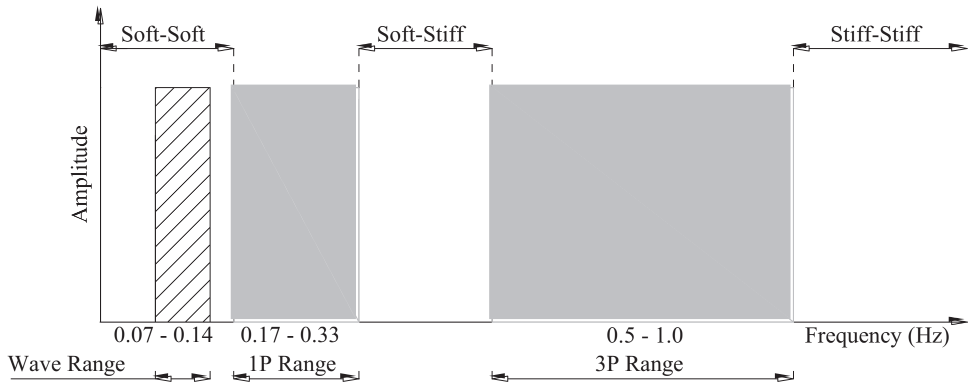

Fig. 1. Excitation frequency ranges for typical offshore wind turbines.

shear stress at which sediment starts to move and occurs as a result of the installed pile changing the local waterflow characteristics (Peder Hyldal Sørensen and Bo Ibsen, 2013). The DNV design codes recommend that a local scour hole depth of 1.3 pile diameters ($1.3D_{pile}$) should be considered for both the ultimate and serviceability limit state design cases in the case of a monopile subjected to current only-induced scour (Det Norske Veritas, 2007). In the marine environment however, it must be recognised that these structures can be jointly subjected to currents, tides and waves which makes the problem more complex than that of scour around structures in rivers (which are generally under steady current conditions) (Negro et al., 2014). It is also noteworthy that natural variation in seabed level over a large area can give rise to a further global scour effect, which could have an effect over an entire wind farm site leading to more severe scour depths. Under the action of waves, the expression for the equilibrium scour depth (S_{eq}) around a tubular monopile as recommended by the DNV is shown in Eq. (1) (Det Norske Veritas, 2011; Peder Hyldal Sørensen and Bo Ibsen, 2013). This expression was derived by Sumer et al. (1992) based on several small-scale tests:

$$S_{eq} = 1.3D_{pile}\{1-\exp[-0.03(KC-6)]\}, \quad KC \geq 6 \tag{1}$$

where KC is the Keulegan–Carpenter number, a dimensionless parameter that is a function of the maximum horizontal particle velocity at still water level (u_{max}), the intrinsic period of the waves (T_i) and the monopile diameter (D_{pile}). The equilibrium scour depth increases as KC values increase and tends toward the current-only equilibrium scour depth for large KC values. Sumer and Fredsøe (2001) proposed a modification to Eq. (1) for the case of a pile subjected to combined steady current and waves. Their modification introduces a dimensionless parameter that describes whether currents or waves are dominating. In general, the design scour depth will be large when currents are dominating and small when waves are dominating (Peder Hyldal Sørensen and Bo Ibsen, 2013).

Uncertainties in the magnitude and variability of the various parameters governing the scour process can lead to difficulties in the accurate estimation of a design scour depth for a given foundation design. Moreover, Matutano et al. (2013) have compiled a list of different formulae used in the prediction of maximum scour depths which have been derived assuming different flow conditions (current-only, wave-only or combined current and waves). They have highlighted that different standards and recommendations used in the offshore industry suggest different formulations for scour depth estimation, leading to natural variability in design scour depths. In a detailed study, they compared the maximum design scour depths obtained by the implementation of various design formulae with the actual measured scour depths for various wind farm sites around Europe. This analysis revealed that the maximum observed scour depth was less than the estimated value in all but two of the cases considered, which further highlights the uncertainties present in accurate scour depth estimation. Furthermore, Negro et al. (2014) acknowledges the requirement that for effective scour protection design, it is necessary to include sediment properties, geotechnical characteristics of the site, environmental parameters for wave loads and turbine foundation specifications in order to accurately predict the maximum scour that could occur in the absence of such protection. They also call into question the DNV's (Det Norske Veritas, 2013) recommendation for scour characterisation around offshore wind turbines under combined current and waves, deeming it to be inaccurate.

In the absence of adequate scour protection, scour has the effect in design of increasing the cantilever length (or effective water depth) by between the order of 5.2 and 7.8 m for the piles sizes currently used in practice, under the assumption of current-only induced scour. Scour has the effect of reducing the ultimate capacity of a foundation and reducing the system stiffness (Prendergast and Gavin, 2014). This could, in certain circumstances, lead to the occurrence of resonant vibrations in the structure if the structure's natural system frequency aligns with any of the excitation frequencies from the rotating blades or the passing sea waves. Peder Hyldal Sørensen and Bo Ibsen (2013) present a desk study investigation on the potential effects of scour on an existing offshore wind farm at Horns Rev 1. Using frequencies obtained from estimates of soil stiffness derived from p–y curves given in the API code, they found that the first natural frequency of a structure reduced by 5% when the scour depth reached $1.3D_{pile}$. To counteract the effects of scour, mitigation measures which typically comprise placing rock armour at the sea bed, have been undertaken at a number of sites. These can have the effect of stiffening the foundation response and hence, increasing the system's natural frequency. For a soft-stiff structure, such measures have the potential to cause dynamic load effects with excitation frequencies above the structure's natural frequency.

Recent efforts to measure the natural frequency of offshore structures have revealed that the stiffness of heavily overconsolidated soils may be underestimated when using design values recommended in current design codes (API, 2007; Det Norske Veritas, 2007). For heavy offshore oil and gas platforms, under-estimating the soil stiffness does not have major implications for safety. However when considering light, dynamically sensitive offshore wind turbines it is crucial to accurately predict the structure's system frequency. Even more importantly, it is crucial to demonstrate how changes arising during the lifetime of the structure due to soil stiffness degradation as a result of cyclic loading, or from scour may affect the dynamic response.

This paper presents scale model tests and simple finite element numerical modelling to examine the effects of scour on the natural frequency of a wind turbine supported by a monopile embedded in typical offshore sand deposits. In the first part of the paper, an experiment is performed on a scale model monopile where scour is artificially induced and the change in the natural frequency is