Soil Dynamics and Earthquake Engineering 115 (2018) 90–103

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Dynamic response of monopiles in sand using centrifuge modelling

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ARTICLE INFO

Keywords:
Centrifuge modelling
Wind turbine foundation
Monopile
Natural frequency

ABSTRACT

Monopiles are one of the most commonly used offshore foundation for wind turbines. Their static capacity, p-y curve and cyclic loading behaviour have been studied using 1 g tests and centrifuge tests, but there is little experimental data regarding their natural frequency, especially using centrifuge testing. The design of offshore wind turbine foundations is largely governed by natural frequency as resonance due to cyclic loading can cause damage and even failure. Understanding the dynamic response of the monopile under free vibration is thus critical to design. This paper presents the results of novel monopile (large diameter) and single pile (small diameter) tests in a centrifuge to for the first time directly determine the natural frequency (f_n) of the pile-soil system. An experimental methodology was used to define the natural frequency via measured acceleration and force time histories and their fast Fourier transforms (FFT) under a force applied at a controlled frequency. The effects of pile diameter, embedded length, free length of the tower and soil density on f_n were investigated in the centrifuge tests. The same models used in the centrifuge test at 50 g were also tested at 1 g in order to assess the relevance of earlier 1 g investigations into system behaviour. The measured natural frequency of wind turbine monopiles in centrifuge models during harmonic loading from a piezo-actuator, confirmed that soil structure interaction at an appropriate stress level must be taken into account to obtain the correct natural frequency. The experimental data was compared to theoretical solutions, giving important insights into the behaviour of these systems.

1. Introduction

Wind energy is becoming increasingly more attractive as a source of renewable energy and has widespread potential for application in different regions of the world. Wind turbine technology has been continuously improving, particularly with respect to mechanical and electrical innovations, leading to progressively larger and more powerful turbines And consequently tower heights have increased. This trend looks set to continue, with Wiser et al. [3] suggesting that the hub height will reach 160 m by 2030. In this scenario, the dynamic response of the tower and foundation will be of the utmost importance. The European Offshore Wind Energy Association [4] reported that 3018 MW of offshore wind energy was installed in European waters in 2015. By 2016, Europe had 81 wind farms with 3589 turbines and the cumulative installed capacity reached 12,631 MW. Although the majority of wind turbine capacity is being built in Europe, America and China have also established targets to develop 3305 MW and 10,000 MW of offshore wind energy by 2020 respectively [5]. Offshore wind turbines will hence play a significant role in the global electricity market in the future.

Currently monopiles account for 80% of offshore wind turbine foundations with gravity bases accounting for 9% [4]. The remaining foundations include jackets, tripods, tri-piles and floating foundations. The monopile is a short and rigid circular steel pipe pile, which has a slenderness ratio of approximately 5 [6]. It is a common foundation design for offshore wind turbines because it is economical at shallow water depths (10–25 m). The typical dimensions of a monopile are a 3–6 m outer diameter and 22–40 m length [7]. Although a monopile is a simple foundation design concept, understanding the dynamic soil-structure interaction (SSI) of a wind turbine on a monopile foundation is a complex task [6].

Offshore wind turbines (OWTs) experience high lateral loading and

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Abbreviations: FFT, fast Fourier transform; MEMS, micro-electrical-mechanical system; OWT, offshore wind turbine; SSI, soil-structure interaction

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https://doi.org/10.1016/j.soildyn.2018.08.007
Received 10 September 2017; Received in revised form 31 July 2018; Accepted 2 August 2018

Nomenclature

a and b	empirical parameters to calculate C_R and C_L, respectively
$A(\gamma)$ and $m(\gamma)$	strain-dependent parameters for G_{max} calculation
C_R and C_L	factors that account for the flexibility provided by the pile [1]
D	pile diameter
D_{10}	particle-size diameter for which 10% of the sand by mass was finer
D_{50}	particle-size diameter for which 50% of the sand by mass was finer
Dr	relative density
e	void ratio
E_o	elastic modulus at a depth of one pile diameter
E_{pe}	equivalent elastic modulus of pile
e_{max}	maximum void ratio
e_{min}	minimum void ratio
$f(\nu)$	Poisson's ratio effects as presented by Randolph [2]
F_h	horizontal force
f_n	natural frequency or measured natural frequency
$f_{n\text{-}str}$	natural frequency calculated as a fixed base or cantilever beam
$f_{n\text{-}TSSI}$	theoretical natural frequency considering SSI
G_{max}	small strain shear modulus
Gs	specific gravity of soil particles
L_P	embedded length of pile
I	moment of inertia
K	constant that depends on the soil's relative density
K_h	horizontal pile stiffness
K_{hr} or K_{rh}	coupling between horizontal and rotational pile stiffness
K_r	rotational pile stiffness
K_{str}	structural stiffness of the tower
L	free length.
L_T	free length of structure (single pile or monopile).
L_{Teq}	equivalent length
m	lumped mass on top of the tower
M	moment
n	gradient of elastic modulus referent, a linear variation with depth
N	scale factor of centrifuge modelling
p'	mean principal effective stress
PL	monopile
PS	single pile
t	wall thickness of monopile
u	horizontal displacement
η_L, η_{LR} and η_R	non-dimensional lateral, cross-coupling and rotational stiffness values, respectively.
β	parameter regarding SSI in the theoretical natural frequency
γ	shear strain
γ_d	dry soil unit weight
θ	rotation angle

a large moment at the seabed in comparison to the vertical loading. Byrne and Houlsby [8] stated that for a typical 3.5–5 MW turbine, the horizontal load from combined wind and wave loads is 4–6 MN, whereas the vertical loading is 6–10 MN. The wind and wave loads are cyclic in nature; thus a combination of extreme sea and wind states have to be taken into account. According to Byrne and Houlsby [8], on a hub that is 90 m above the sea floor, the maximum operational wind load would be approximately 1 MN and wave and current loads acting below the water surface level are approximately 1 ± 2 MN, thus producing a net lateral load of 2 ± 2 MN and a resulting moment of 200 ± 20 MNm. For design purposes, Arany et al. [9] developed a framework to calculate appropriate loading values based on a variety of turbine and environmental parameters. OWTs are dynamically sensitive structures because of their slender structural nature and the applied cyclic loads. The excitation frequency of offshore wind turbines should hence be carefully considered during the design phase to prevent resonance.

Fig. 1 illustrates the excitation frequencies of a typical wind turbine system as presented by LeBlanc [10]. The system is excited by the applied loading from wind and waves, but also by loading from the aerodynamic changes occurring during rotation of the blades. The frequency of rotational loading is termed the 1 P frequency, with the blade-passing frequency being to three times the rotational frequency of the turbine (3 P). The wind gust frequency is typically less than 0.1 Hz, whereas the frequency of high-energy wave loading ranges from 0.05 to 0.5 Hz [11].

During design, the selected system natural frequency needs to lie outside these excitation frequencies in order to avoid resonance and to reduce fatigue damage. Therefore, to ensure that the first natural frequency (f_n) of the system is consistent with all of these excitation frequencies, three options can be considered in the design phase: 'soft-soft', 'soft-stiff' or 'stiff-stiff' design, as shown in Fig. 1. To avoid resonance, f_n needs to be kept 10% away from both the 1 P frequency and 3 P frequency [12]. As shown in Fig. 1, for a soft-stiff system, f_n needs to be fitted in a very narrow band; thus, changes in the foundation stiffness due to cyclic loading may result in f_n entering either the 1 P frequency or 3 P frequency ranges. Although a soft-stiff design is the most cost effective and practical, the foundation stiffness and changes in the foundation stiffness due to cyclic loading need to be carefully determined to avoid resonance during the long design life of the structure.

To understand the dynamic response of the monopile foundation, Zaaijer [13] developed a dynamic model to predict the natural frequency of offshore wind turbine foundations and studied how sensitive the natural frequency is to the input parameters. Alexander [14] estimated the nonlinear resonant frequency of a single pile in nonlinear soil by determining analytical expressions for the natural frequency of the fundamental mode of a pile and Arany et al. [15] presented a methodology to calculate the natural frequency of an offshore wind turbine structure on a flexible foundation using Euler-Bernoulli beam theory and a three-spring model. Bhattacharya et al. [16] experimentally conducted a series of 1:100 scale 1 g model tests of a V120 Vestas turbine supported on monopiles and tetrapod suction caissons in kaolin clay and sand and Prendergast et al. [17] developed an experimental program to examine the effect of scour on the natural frequency of a scale-model monopile at a dense sand test site. Although small-scale tests on the natural frequencies of pile-soil systems have been conducted by Bhattacharya et al. [16] and Prendergast et al. [17], these tests were conducted at 1 g with a stress-state within the soil substantially different from that for a full-size foundation. As soil is a very non-linear material, the effects of this incorrect stress state on the system natural frequency is not easily quantified.

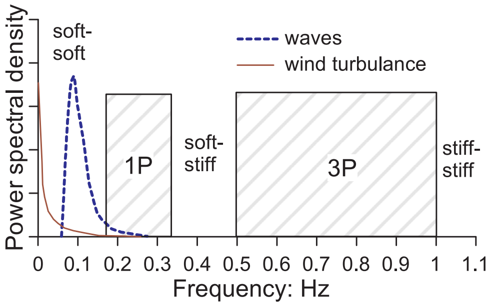

Fig. 1. Excitation frequencies acting on a typical wind turbine system (Leblanc, 2009).