Ocean Engineering 144 (2017) 203–210

Contents lists available at ScienceDirect

Ocean Engineering

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

Insight into the lateral response of offshore shallow foundations

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ARTICLE INFO

Keywords:
Suction caissons
Densification
Cyclic loading
Impedance
Stiffness

ABSTRACT

Suction caissons are often subjected to cyclic lateral loads caused by the action of wind or waves. As a result of these cyclic loads, excessive lateral deformations may be induced during a caisson's service life. Although soil-foundation response analysis requires information about stiffness and damping at the site, the methods for obtaining this information are still in question. The present study reports non-dimensional frameworks for determining the impedance functions for soil-foundation system at the load reference point along with the results of performance measure parameters that track the response of suction caissons harmonically oscillating on homogeneous soil. The equations are expressed in terms of logarithmic and polynomial models based on a statistical analysis of existing cyclic test results for small-scale Aalborg University Instrumented Suction Caissons, 300 mm in diameter and 300 mm in skirt length.

The variables used in the equations for normalized secant stiffness are load characteristics (ξ_b and ξ_c) and number of load cycles. The present study also identifies critical new findings regarding the local densification and the plastic shake-down at the caisson-soil interface, which are all important factors to consider in a performance based-framework for designing offshore structures.

1. Introduction

By 2004, more than 485 suction anchors had been installed at over 50 different sites (Andersen et al., 2005). Most of these anchors are in clay, but some are in sand or layered soil. Examples of skirted foundations in sand are the offshore platforms at the Draupner E and Sleipner T sites in the North Sea (Tjelta, 1995).

Recently there has arisen a salient trend in the construction of modern wind turbines with a slender design and more than 100 m in tower height; the natural frequencies of these rather novel structures are close to 0.2 Hz. Fig. 1 compares the average water depths for wind farms that are currently in the design phase. The transition to deeper water increases the span between the turbine superstructure and the seabed. Coupled with greater environmental loading from the higher-magnitude wind and waves, the move to deeper water increases the moments applied to the foundations. While monopiles are attractive solutions for developers and designers alike, the increased water depth requires larger diameters with stiffer cross-sections. The monopiles used to date consists of a stiff pile of diameter of 4–6 m and embedment depths ranging from 20 to 30 m. In 2008, Ibsen reported the performance of a bucket foundation installed in Frederikshavn, Denmark as an attractive alternative foundation which can be used to increase the moment capacity (Ibsen, 2008). The bucket foundation, also referred to as “suction caisson”, is a large cylindrical monopod foundation, typically made of steel (Fig. 2) which has the potential to be a cost effective option in certain soil conditions. A bucket foundation typically requires less steel compared to a monopile, but fabrication costs are slightly higher due to the complicated lid structure (Table 1). However, the total cost, steel and fabrication, of a bucket foundation is likely to be less than of a monopile. Typical loading conditions for an offshore bucket foundation are illustrated schematically in Table 2. The loads are shown to be acting at the interface level between the foundation and the turbine shaft. An axial load of approximately 264 t act at this point.

This foundation is an upside-down bucket made of steel with diameter D, skirt length d and skirt wall thickness t. A standard real-scale foundation for a 5 MW wind turbine has $D = 12–18$ m, $t \approx 30$ mm and embedment ratio ranging between 0.5 and 1.

Motion of a bucket foundation will induce forces transmitted through the foundation-soil contact elements into the underlying deformable ground, which produce cyclic strains in terms of displacements and rotation of the foundation. Under a moderate to high amplitude of cyclic loading, most soils change stiffness and damping. In order to study the long-term performance and the uncertainties related to the dynamic response of these structures, the soil stiffness due to these cyclic strains must be taken into consideration. The current codes

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http://dx.doi.org/10.1016/j.oceaneng.2017.08.012
Received 26 October 2015; Received in revised form 28 June 2017; Accepted 8 August 2017

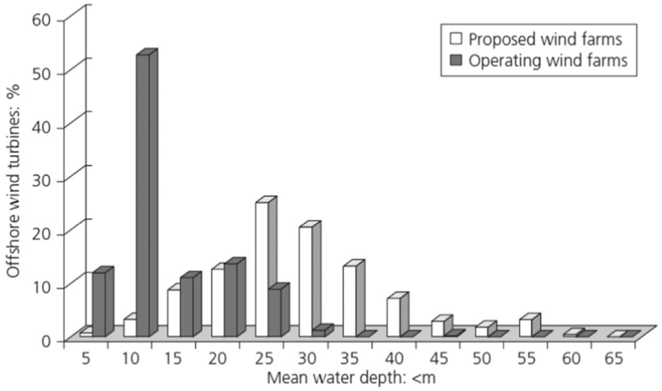

Fig. 1. Water depth for future and in-service wind farms (Doherty and Gavin, 2011).

Fig. 2. Prototype Bucket foundation prior to installation.

Table 1
Cost make up for 8 MW bucket foundation and equivalent monopile (Nielsen, 2014).

Water depth (m)	Steel required for bucket foundation (ton)	Steel required for equivalent monopile (ton)
25	610	820
35	760	–
45	980	–
55	1200	–

Table 2
Details of a typical suction caisson-supported Vestas 3.0 MW wind turbine (Ibsen, 2014).

Component		
Rotor	Diameter	90 m
	Nominal rev.	16.1 rpm
Tower	Hub Height	80 m
Weight	Tower	156 t
	Nacelle	68 t
	Rotor	40 t
	Total	264 t
Foundation	Diameter	12 m
	Height	6 m
	Weight	135 t

of practice (API, ISO and DNV) for the design of offshore foundations provide limited guidance for predicting changes in the foundation stiffness and the resulting changes in damping, which are important design drivers for serviceability limit state (SLS) and fatigue limit state (FLS) requirements.

Experimental studies provided the data necessary to establish combined loading interaction (Bransby and Randolph, 1999; Gourvenec, 2008; Nova and Montrasio, 1991; Houlsby and Cassidy, 2002; Cassidy et al., 2002, 2004; Bienen et al., 2006; Villalobos, 2006; Ibsen et al., 2014a, 2014b, 2015; Barari and Ibsen, 2012, 2014; Larsen et al., 2013). The programmes of Houlsby and Cassidy (2002), Cassidy et al., (2002, 2004) and Ibsen et al. (2014a), (2014b), (2015) resulted in strain hardening models that describe the behavior of circular footings in terms of the combined forces acting on them (V, M, H) and their resulting displacements (w, θ, u). However, in these experiments only monotonic response was studied. To ensure confidence for performance of in-service shallow foundations, further studies on cyclic loading response are required. Modeling significant change in soil-foundation stiffness, derived for the idealized case of a suction caisson fully bonded at the soil surface, is therefore of keen interest in the present study. This paper provides insight into predicting the response of cyclic lateral loading of suction caissons, and presents a complete set of non-dimensional formulas for impedance functions covering the translational mode of cyclic nature of soil-foundation behavior at a given frequency. The procedure is based on a review of previously published general procedures and a statistical analysis of laboratory test data.

To examine the effects of loading shape, load characteristics were defined as in Eq. (1):

$$\begin{cases} \xi_b = \dfrac{M_{\max}}{M_R} \\ \xi_c = \dfrac{M_{\min}}{M_{\max}} \end{cases} \tag{1}$$

where $M_{\max}$ and $M_{\min}$ are the maximum and minimum moment in the load cycle and M_R = static capacity at a given load path. As depicted in Fig. 3, ξ_c distinguishes between one-way and two-way loading. In other words, ξ_c may change in a domain ranging from 0 for one-way loading to −1 for full-two way loading.

1.1. Dynamic considerations of soil-foundation interaction in offshore wind turbines

Wind turbines are designed to have natural frequencies in the range between frequency bands of the rotor rotation and the blade passing, usually denoted by 1p and 3p (for a three-bladed turbine). This may be attributed to the various complex interactions between the structure, foundation, soil and the fluid. In particular, the main source of excitation is the rotor blades passing tower and is very close to the first natural frequency. This hypothesis has also drawn considerable attention in codes of practice. Accurately modeling the dynamic stiffness of the structure is required to predict the dynamic response and the fatigue lifespan of a wind turbine.

For pile foundations, limited previous research using small scale 1 g-tests (Lombardi, 2010; Bhattacharya et al., 2011, 2012) has examined whether the natural frequency of a wind turbine may change with cycles of loading; this research revealed significant change in soil stiffness which changed the first natural frequency of the wind turbine and caused it to approach excitation frequencies. Alteration of the foundation stiffness may be attributed to either strain-hardening or softening, owing to vibration of the soil-foundation systems (LeBlanc et al., 2010). For strain hardening sites where the stiffness increases, the natural frequency of the system will also increase. On the other

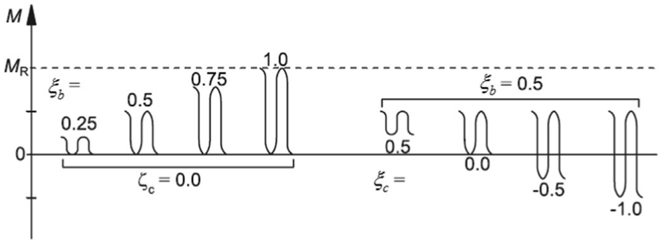

Fig. 3. Cyclic load characteristics.