Applied Ocean Research 55 (2016) 48–58

Contents lists available at ScienceDirect

Applied Ocean Research

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

Elastic rocking vibration of an offshore Gravity Base Foundation

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ARTICLE INFO

Article history:
Received 12 July 2015
Received in revised form 6 October 2015
Accepted 20 November 2015
Available online 22 December 2015

Keywords:
Coupled seawater-seabed half-space
Rigid disc
Rocking vibration
Gravity Base Foundation

ABSTRACT

Gravity Base Foundation is one of the main foundations in offshore wind turbine structure, and the foundation rocking stiffness mostly controls the structure fatigue life. This study models the rocking vibration of a rigid disc foundation on a poro-elastic seabed, covered by a compressible inviscid seawater half-space. The coupled rocking problem is solved using the 3-dimensional elastic wave theory. The behavior of seawater and soil are depicted with the Euler equations and the Biot's theory, respectively. The contact surface of the disc foundation with the soil and the water is assumed to be smooth. The solutions are expressed in Fredholm integral equations of the second kind and solved numerically. The obtained dynamic impedances are used to study the dynamic behavior of Gravity Base Foundations of offshore wind turbines, which are very sensitive to dynamic moments. It is found that foundation with a permeable surface has much smaller dynamic amplitudes, compared to the one with an impermeable surface. The existence of seawater half-space will also alleviate the dynamic amplitudes, but decreasing the natural frequency of the foundation.

1. Introduction

Wind energy generation by means of turbines has proven to be of great value for large scale future investment worldwide. A continuous search for greater wind potential has pushed the industry to offshore solutions with superior wind conditions. The market for offshore wind turbines (OWTs) foundations is currently dominated by monopile (74%) and Gravity Base Foundations (GBFs, as shown in Fig. 1a) (16%) according to 2012 data [1]. From the projects constructed until today it can be seen that the application of Gravity Base Foundations is mainly for shallow water (as shown in Fig. 1b). The current application of GBF's is primarily for water depths ranging from 4 to 15 m. The industry is exploiting the possibility to employ GBFs for the water depth up to 50 m [1,2].

The dynamic loads on an OWT are complex and with various frequencies [3]. Typical first-order natural frequencies of OWTs are within 0.3–0.9 Hz. The loading frequencies that are close to the natural frequency of the turbine support structure can be classed as dynamic loading which requires special consideration [4]. One of the key factors affecting the natural frequencies of OWT structure is the foundation stiffness, so the soil–structure dynamic interactions of the foundation is becoming the main research topic in offshore wind turbine structure design. The dynamic stiffness of foundations and the influences of the stiffness of foundations on the eigen-frequency of OWTs have been widely studied [5–11]. However, most of the foundations studied are offshore pile foundations, very limited studies have focused on GBFs.

For a wind turbine on a GBF subjected to various external dynamic forces (Fig. 2a), including winds, waves, currents, and seismic waves, with the impedance functions (stiffness and damping functions) known, we can study 4 kinds of problems using the lumped parameter approach: if we focus on the whole wind turbine, we can study two kinds of dynamic problems, one is the forced vibration problems of the system (Fig. 2b, the dashpot is not plotted in the figures below for simplicity) to obtain dynamic responses (moments, shear forces, stresses, strains, and displacements), the other is the free vibration problem of the system (Fig. 2c) to obtain the eigen-frequency and vibration modes; if we focus on designing the foundation, the external forces acting on the whole system should be changed to 3 kinds of resultants on the foundation (Fig. 3a) at first, and then also two kinds of dynamic problems could be studied, one is the forced vibration of the GBF (Fig. 3b), and the other is the free vibration of the GBF (Fig. 3c).

It is worth pointing out here that although there are complicated forces on a wind turbine or on a GBF, within the frame of the classical elastic vibration theory, the natural frequencies and vibration modes of a structure (a wind turbine or a GBF) are the internal characteristics of the structure, which will not be affected by the external forces [12].

As suggested in DNV [13], impedance functions for ideal conditions should refer to the classical results of a rigid disc vibrating on the surface of an elastic half-space, and the classic impedance functions are obtained by considering the dynamic interaction of a

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0141-1187/$ – see front matter © 2015 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2015.11.006

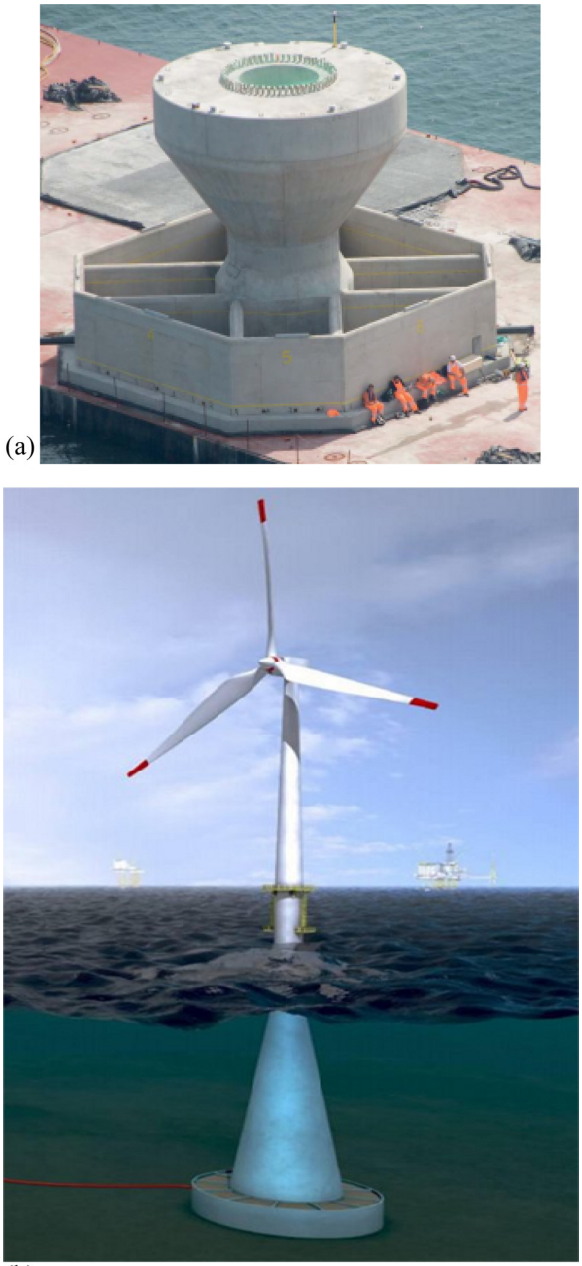

Fig. 1. Images for a GBF and an OWT on a GBF. (a) A Gravity Base Foundation (www.scotsrenewables.com) and (b) offshore wind turbines on GBFs (www.4coffshore.com).

massless rigid disc with elastic soils. Decomposing a real foundation to a foundation with mass and a massless disc (Fig. 4) is a very common and widely accepted method used in foundation vibration problem [14]. Using this method one can obtain the response of a foundation corresponding to only the added forces, and a real foundation with mass could be easily considered by using the Newton's second law. Besides, it is often assumed the problem of a massless disc subjected to vertical, horizontal forces and moments could be decomposed to 3 simple problems (Fig. 5), and studied separately[14], which is not like a bearing capacity problem, where the coupled H-V-M model is widely used.

Luco and Westman [15] considered the dynamic response of a rigid disc under rocking vibration on an elastic solid half-space. Veletsos and Wei [16] considered a disc subjected to a horizontal force and an overturning moment at the surface of an elastic half-space. Veletsos and Verbic [17] studied a rigid disc supported at the surface of a viscoelastic half-space that was subjected to horizontal or vertical forces or a moment. However, all of these studies have focused on cases in which the disc is resting on the surface of a single phase elastic half-space, but most soils in the offshore engineering are not single phrase elastic materials, but two-phase porous elastic materials, which are more suitable to be depicted by Biot's theory [18]. Using Biot's poroelastic theory, Refs. [19–22] studied the vertical, horizontal and rocking vibration of a rigid disc on the surface of a saturated poroelastic half-space.

To obtain a more accurate stiffness of a disc in offshore engineering, it will not be enough to just considering the soils as poroelastic materials. There are still two aspects to improve, the first one is totally permeable disc is used to obtain the rocking impedance function in [19–22], while GBFs in offshore engineering are all impermeable, which will be depicted more precisely by an impermeable disc; the second one is seabed is often covered by seawater in offshore engineering, and it is pointed out that the seawater overlying the seabed might have a strong effect on the dynamic response of the foundations embedded nearby the water–soil interface because of the interface waves [23]. It would be reasonable to take the interface effect into consideration here. Numerous researchers have studied the interaction of a fluid half-space with an elastic medium due to various types of loads, and a review of these studies can be found in [23]. Refs. [23,24] studied a surface rigid disc vibrating vertically and horizontally on a poroelastic half-space in contact with a fluid half-space and found that the existence of a fluid half-space has a remarkable effect on the vertical dynamic characteristics of the disc, but a negligible effect on the horizontal dynamic characteristics. To the best of the authors' knowledge, there are no published results on the rocking vibration of a rigid disc on a poroelastic medium in contact with a seawater half-space, which will be studied in this paper. This work solves a 3D boundary value problem related to poro-dynamics. In this work, by the use of potential functions with boundary conditions, the governing dual integral equations are obtained. Then with the help of Sonine's integrals, the coupled dual integral equations are changed to Fredholm integral equations of the second kind, and solved numerically, and a flow cart of the steps is given in Fig. 6. Such results would be helpful for the design of offshore Gravity Base Foundations. In this work, the main idea is to give the rocking impedance function, and show its importance using a simple model, so we choose the GBF vibration problem in Section 6 to make it as simple as possible. Hopefully the related works about the use of impedance functions to the other problems will be given in the near future. It is worth pointing out here within the elastic vibration theory [25]: when the water depth is larger than the diameter of the foundation, the seawater layer could be treated as a half-space.

2. Problem definition

This section will consider the problem of the time-harmonic rocking vibration of a rigid, massless disc and without friction at the interface between seawater and seabed (Fig. 7). The surface of the soil is permeable, and both permeable and impermeable discs will be considered. The radius of the disc is a. In this study, only small vibrations under still water are considered, and water waves are treated as an external force on the foundation, which means the effects of water waves on the impedance functions of a disc foundation are ignored. Small vibration assumption is based on the finding given by Damdarrd et al. [26] that for wind turbines on norm operating conditions, soils are almost elastic and the elastic vibration theory is suitable. Still water assumption is based on two principles:

(1) the principle of superposition of elasticity, as pressure/force caused by winds, waves, currents can be considered external forces (Figs. 2b and 3b);