Soil Dynamics and Earthquake Engineering 95 (2017) 138–152

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Vertical elastic dynamic impedance of a large diameter and thin-walled cylindrical shell type foundation

Rui He[a,b], Lizhong Wang[c], Ronald Y.S. Pak[d], Zhen Guo[c,*], Jinhai Zheng[a,b]

[a] College of Harbor, Coastal and Offshore Engineering, Hohai University, Nanjing 210098, China
[b] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China
[c] College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, PR China
[d] Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, CO 80309-0428, USA

ARTICLE INFO

Keywords:
Offshore wind turbine
Dynamic impedance
Elastic shell
Poroelastic seabed
Vertical vibration

ABSTRACT

This paper studies the vertical vibration of a large diameter and thin-walled cylindrical shell type foundation embedded in a fully saturated porous seabed in contact with a seawater half-space. The solution of the coupled fluid-shell foundation-soil vibration problem is obtained using the ring-load Green's functions for both the shell and the layered fluid-seabed half-space. By considering the fully coupled boundary conditions at the shell-soil interface, the shell vibration problem is reduced to Fredholm integral equations. Through an analysis of the corresponding Cauchy singular equations, the intrinsic singular characteristics of the problem are rendered explicit. With the singularities clear, an effective numerical method involving the Gauss-Chebyshev method is developed to solve the governing Fredholm equations. Selected numerical results for the dynamic contact load distributions, displacements, and dynamic impedance functions are examined based on different shell lengths, soil materials, shell properties, and frequencies of excitation. Moreover, the results are analysed for cases in which there is and is no fluid overlying seabed to examine the effect of fluid.

1. Introduction

Wind power generation is a clean method of energy utilisation. Compared to on-land wind power, its offshore counterpart shows significant advantages, including better wind speed, not occupying valuable land, and less visual and noise pollution. In China, the implementation of the ocean energy strategy has accelerated the development of offshore wind power. In recent years, an increasing number of offshore wind turbines (OWTs) have been built in the field or have been planned to be built. However, there is a lack of understanding of the dynamic performance of OWTs. Zania [1] notes that the dominant load conditions for wind turbines are dynamic load. Accurately calculating the natural frequencies of OWTs is the key to avoiding structural damages from external loads at various frequencies. Besides, under the normal operating conditions, soils around the foundation are almost elastic and the elastic vibration theory is suitable [2].

The dynamic impedance (stiffness and damping) of OWT foundations directly affects the natural frequencies and dynamic responses of turbines. As widely used foundation options for OWTs, both suction buckets and mono-piles are large-diameter and thin-walled cylindrical shell type foundations. Compared to traditional slender piles, these shell type foundations have a smaller length-diameter ratio, typically 0.5–6 for bucket foundations [3], which may be more suitable to be depicted using shell theory than beam theory. Most foundations made of steel could be considered shell type foundations, since they are built as an assembly of tubular steel profiles or flat/curved steel panels. Shell type foundations can be used as foundations for both shallow water and deep sea, as shown in Fig. 1. For OWTs with tripod pile/bucket foundations (Fig. 1(a)), the shell foundation vibrates vertically under the dynamic moment caused by lateral dynamic loads. For deep-sea OWTs (Fig. 1(b)), a bucket foundation is also subject to dynamic vertical forces transmitted by the tension legs, model tests have shown that there is no suction between the bucket top disc and the seabed under small tension load, the side shear developed first and reached its peak before significant suction was measured under the top cap [4,5], which means bucket foundations in normal tension load can be simplified as alone shell foundations. However, we do not adequately understand the vertical dynamic characteristics of cylindrical shell type foundations. There have been a lot of excellent pioneering works on bucket foundations, especially on “installation process”, “bearing capacity”, “cyclic loading”, and “transient loading” problems [6–9]. Besides, Doherty and Deeks [10] studied the static stiffness of bucket foundations in non-homogeneous elastic soil medium using the scaled

---

* Corresponding author.
E-mail address: nehzoug@163.com (Z. Guo).

http://dx.doi.org/10.1016/j.soildyn.2017.01.034
Received 27 August 2015; Received in revised form 13 November 2016; Accepted 26 January 2017
0267-7261/

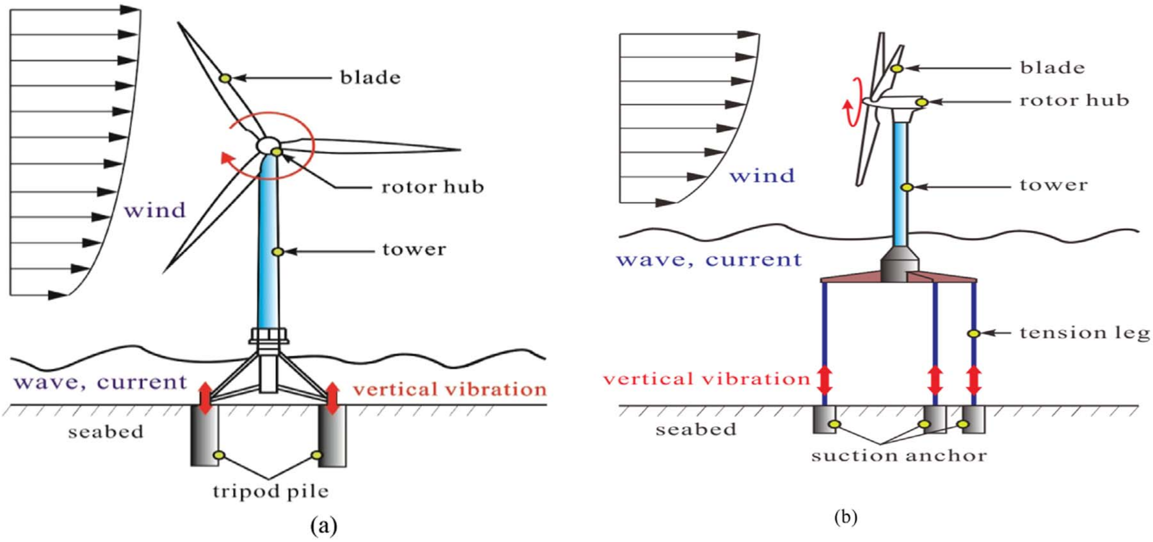

Fig. 1. (a) The image of a wind turbine in shallow water; (b) The image of a wind turbine in deep sea.

boundary finite element method. However, it is still not clear about the elastic dynamic impedance of shell type foundations, which has an important effect on the natural frequencies of OWTs. For these new types of foundations for OWTs that engineers can provide estimates using the static stiffness of piles [11], the p-y and t-z curves developed for slender piles [12–16], Novak's simplified method [17,18], experiments [19,20], or numerical methods [21–25] to calculate the stiffness of OWT foundations. However, Versteijlen et al. [26] noted that “Over the recent years, measured natural frequencies of installed OWTs have been found to be higher than designed for.” This inconsistency is mainly caused by the underestimation of the stiffness of OWT foundations. To save costs and make the natural frequency computation more accurate, a new and more realistic model involving dynamic interaction of seawater-shell type foundation-soil is needed.

Therefore, to guarantee the safety of OWTs, it is critical that researchers understand how shell type foundations respond to vertical dynamic forces. Although there are many papers related to the dynamic interaction of traditional slender piles within elastic soil strata due to vertical dynamic forces [27–32], there are few studies on the vertical vibration of cylindrical shell type foundations. Liingaard et al. [33] studied the impedance of bucket foundations in a viscoelastic medium using the coupled BEM-FEM method. For a free open-ended cylindrical shell embedded in soil, Pak and Ji [34] obtained an analytical result by considering the soil as a single-phase elastic solid. Ji [35] studied the vertical dynamic vibration of an impermeable shell in soil using the boundary element method (BEM). However, the shell in a real shell type foundation is not free and open-ended but constrained by a top disc or the tower of OWT, and the seafloor is a natural two-phase medium composed of water and soil skeletons. Thus, the constraint of the top ending and the poroelastic effect of the seabed should be considered. Additionally, He et al. [36] noted that the seawater overlying the seabed might have a strong effect on the dynamic response of foundations embedded near the water-soil interface due to interface waves. It would be reasonable to take the interface effect into consideration because shell-type foundations are assembled very close to the seawater-seabed interface.

In this study, to extend the rigorous analysis of the dynamic problem to offshore applications, a coupled seawater-shell-seabed model is used. In this model (refer to Fig. 2), the seawater half-space is described by the Euler equations for a compressible inviscid fluid [37]; The seabed is modelled as a Biot poroelastic medium [38], whereas the shell type foundation is modelled using an elastic thin shell theory [39]. As noted by Lin et al. [40], when permeability of soil is less than 10^{-6} m/s, relative pore fluid flow is negligible, in which Biot's wave equations may not applicable and saturated soils that consist of fine to medium sands may be described by Biot's theory, so we use a sandy seabed in the numerical analysis part. For the shell problem, the coupled water-shell-porous seabed system is treated as a superposition of an intact water-seabed half-space and a reduced and constrained shell, whose reduced elastic modulus and mass density are defined in Section 4. The Green's functions for the thin shell and the layered seawater-seabed half-space are used to formulate the governing Fredholm equations by considering appropriate boundary conditions on the contact interface of the shell and the seabed. By analysing the corresponding Cauchy kernels, the fundamental singular characteristics of the interfacial reactions acting on the shell are given explicitly. The Fredholm equations are numerically solved by a piecewise linear interpolation of the functions of the interfacial reactions using the Gauss-Chebyshev method. The governing equations for the fluid and the soil are presented in Section 2. In Section 3, the ring load Green's functions for the shell and layered fluid-soil half-space are presented. In Section 4, the coupled dynamic vibration problem is considered. The numerical results are presented and discussed in Section 5. Conclusions are presented in Section 6.

2. Governing equations

2.1. Governing equations for the fluid

The governing equations for the compressible inviscid fluid can be written as [36].

$$c_w^2\nabla^2 P_w = \frac{\partial^2 P_w}{\partial t^2},\ \rho_w\frac{\partial^2 \mathbf{U}_w}{\partial t^2} + \nabla P_w = 0. \tag{1}$$

Considering time-harmonic motion with angular frequency ω, and the relation $P_w = p_w e^{-\mathrm{i}\omega t}$, $\mathbf{U}_w = \mathbf{u}_w e^{-\mathrm{i}\omega t}$, we have [37].

$$\nabla^2 p_w + k_w^2 p_w = 0,\ \mathbf{u}_w = \frac{1}{\rho_w \omega^2}\nabla p_w, \tag{2}$$

where p_w and $\mathbf{u}_w$ are the amplitude of the pressure and the displacement of the fluid, respectively. $k_w = \omega/c_w$ is the wave number of the fluid, $c_w = (\lambda_\mathrm{w}/\rho_\mathrm{w})^{1/2}$ is the speed of sound in the fluid, and λ_w is the compressional modulus of the fluid. Besides, the term $e^{-\mathrm{i}\omega t}$ will be omitted from all quantities below for simplicity.

2.2. Governing equations for the shell

To model the shell type foundation, elastic thin shell theory will be