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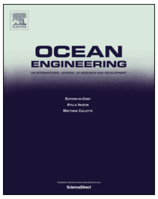

Simplified methods for efficient seismic design and analysis of water-surrounded composite axisymmetric structures

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ABSTRACT

Available simplified formulations for the seismic analysis of axisymmetric structures address materially homogeneous solids with uniform cross-sections, while generally neglecting the effects of higher vibration modes and soil flexibility. In this paper, we develop original simplified procedures that remove these restrictions for practical seismic design and safety evaluation of axisymmetric structures vibrating in contact with water. The procedures proposed take account of higher vibration modes, water compressibility and flexibility of underlying foundation of the structure. For practical purposes, the formulations are first derived while neglecting the effects of surface gravity waves, and are then extended to account for these effects when required. Composite axisymmetric structures made of different materials as well as those with non-uniform hollow cross-sections due to geometric irregularity of interior wall are covered. Step-by-step flowcharts are provided so that the calculations can be easily implemented in a daily practical engineering environment. Application of the proposed techniques is illustrated through the examples of homogeneous and composite axisymmetric tower–water systems with rigid and flexible foundations. The obtained results are successfully validated against advanced coupled fluid–structure finite element solutions.

1. Introduction

Axisymmetric structures surrounded by water are commonly encountered in several civil engineering applications such as offshore platforms, bridge piers, and wind farms. When subjected to earthquake loads, the interaction between an axisymmetric structure and the surrounding water induces hydrodynamic loads while affecting the structural dynamic properties such as natural periods. Earlier literature devoted to the analysis of the vibration characteristics and dynamic response of immersed axisymmetric structures can be roughly classified into three categories depending on the type of modeling adopted for hydrodynamic loads: (i) added-mass formulations where the effect of surrounding water is approximated by added masses distributed along the height of the structure (Lamb, 1932; Nagaya and Hai, 1985; Chang and Liu, 1989; Barltrop and Adams, 1991; Spyrakos and Xu, 1997; Uowska and Koodziej, 1998; Öz, 2003; Wu and Chen, 2005), (ii) continuum-based solutions where hydrodynamic loads are obtained as analytical solutions of the wave equation governing hydrodynamic pressure (Liaw and Chopra, 1974; Eatock Taylor and Duncan, 1980; Williams, 1986; Tanaka and Hudspeth, 1988; Goyal and Chopra, 1989; Xing and Price, 1997; Wei et al., 2012), and (iii) finite element, boundary element or scaled boundary finite element approaches based on the discretization of the surrounding water (Everstine, 1981; Olson and Bathe, 1985; Chen, 2000; Czygan and von Estorff, 2002; Sigrist and Garreau, 2007; Millán et al., 2009; Lu and Jeng, 2010; Tao et al., 2007; Meng and Zou, 2012; Li et al., 2013a,b; Liu and Lin, 2013).

Although the dynamic response of axisymmetric structures surrounded by water can now be solved using coupled fluid–structure finite or boundary elements, most of these techniques have not yet been fully implemented in day-to-day engineering practice, especially at the early stages of seismic design, as they require specialized software or advanced programming, and may result in extensive modeling and computational efforts, combined with high-level expertise. Simplified formulations are therefore still needed to develop efficient procedures that may expedite design and safety evaluation processes. On the other hand, the need for higher structural performance and durability of marine structures suggests increased recourse to composite construction where the efficiencies of various materials can be combined and advantageously optimized. This need is usually coupled to the requirement of using locally available materials for economic or practical reasons. Recent projects illustrate that, in addition to conventional materials such as concrete and steel, researchers and manufacturers are developing new materials such as fiber

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reinforced polymers that can be used to build composite segments of deep water towers such as wind farms (Gutiérrez et al., 2003; Tricklebank et al., 2007; Seica and Packer, 2007; Rashedi et al., 2012; Sun et al., 2012). However, available simplified formulations generally assume that the designed axisymmetric structure has a uniform cross-section and is materially homogeneous, i.e. made with only one material. These methods also usually neglect the effects of higher vibration modes and the flexibility of underlying soil foundation.

In this work, we develop original simplified procedures that waive these restrictive assumptions for enhanced practical seismic design and safety evaluation of axisymmetric structures vibrating in contact with water. Two types of formulations, i.e. I and II, are proposed depending on the mode shapes of the dry structure, i.e. without water, that are obtained using analytical expressions or finite element analysis, respectively. Both proposed formulations take account of higher vibration modes, water compressibility, and flexibility of underlying soil foundation. Formulation type II can also be applied to composite structures made of different materials as well as those with non-uniform hollow cross-sections due to geometric irregularity of the interior wall. The developed methods are assessed through examples that take account of variations in stiffness and mass densities in structures made of several constitutive materials, and having non-uniform hollow cross-sections with irregular interior walls. The effects of higher vibration modes are also included. Expressions are presented considering compressible or incompressible assumptions of surrounding water, as well as rigid or flexible underlying soil foundation. The proposed equations are first derived while neglecting the effects of surface gravity waves. The procedure steps are illustrated in flowcharts in a manner that calculations can be easily implemented in a daily practical engineering environment, for example using simple spreadsheets, as opposed to more sophisticated methods such as coupled fluid–structure finite elements. The formulations are then extended to account for the effects of surface gravity waves when required.

2. Proposed formulations for seismic response of an axisymmetric structure surrounded by water

2.1. Basic assumptions and notations

We consider an axisymmetric structure such as those illustrated in Fig. 1. The structure has a total height H_s and is surrounded by an infinite water domain of constant depth H_w. The immersed part of the structure has a uniform outer radius R_s. As illustrated in Fig. 1, two systems of axes are adopted to define the geometry of the system studied: (i) a Cartesian system (x, y, z), with origin at the center of the bottom cross-section of the structure, and an axis z coinciding with the axis of axisymmetry and (ii) a cylindrical system (r, θ, z), where r denotes the radial distance and θ the azimuth between the reference x-axis and the line from the origin to the projection of the point of interest on the (x, y) plane. The response of the structure is studied under the effect of a ground motion acceleration $\ddot{u}_g$ applied along the x-direction. The following assumptions are adopted: (i) the axisymmetric structure can be made of one or more materials; (ii) the cross-section of the structure can be solid or hollow, and its internal radius may vary as a function of height; (iii) all constitutive materials have a linear elastic behavior during seismic excitation and convective effects in water are neglected; (iv) water is inviscid but can be compressible or incompressible, with its motion irrotational and small in amplitudes; (v) surface gravity waves are neglected. We note that this last assumption is adopted first for practical purposes, it will be waived later in Section 2.5.

2.2. Coupling between hydrodynamic pressure and structural response

The time–history response for radial hydrodynamic pressure exerted at a point of cylindrical coordinates (r, θ, z) is denoted hereafter as $p(r, \theta, z, t)$. It is governed by the classical wave

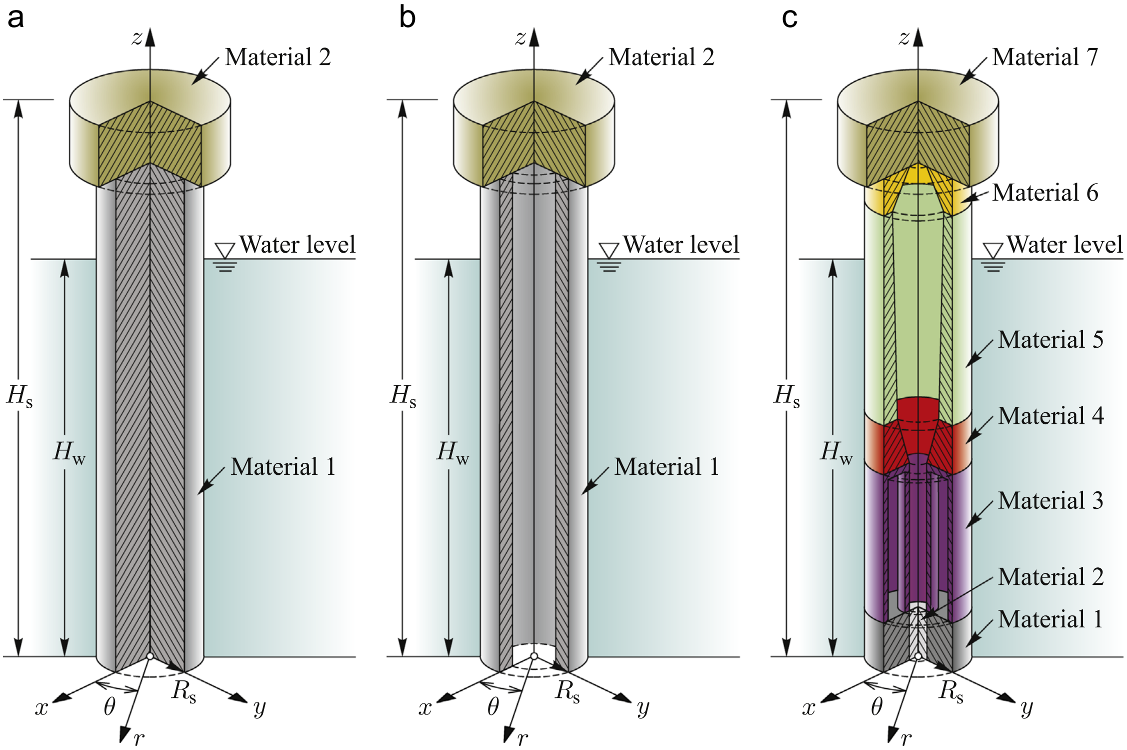

Fig. 1. Examples of axisymmetric towers studied: (a) cylindrical tower with uniform solid section; (b) cylindrical tower with hollow uniform section; (c) axisymmetric tower with non-uniform section and various constitutive materials along the height.