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Simplified evaluation of earthquake-induced hydrodynamic pressure on circular tapered cylinders surrounded by water

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ABSTRACT

Dynamic response of offshore structures can be influenced due to the water-structure interaction. The water-structure interaction can be simply represented by added mass in earthquake response analysis. The added mass for a circular cylinder can be obtained by analytical method. However, the added mass for an arbitrary shape of structure is rather difficult to be solved by analytical method. In this study, a substructure method for analysis of the seismic response of an arbitrary shape of structure is presented. The finite element technique incorporating the exact artificial boundary condition presented for simulating the far field of the infinite water is applied to the evaluation of added mass for offshore structures, where the exact added mass matrix is fully populated and symmetrical. The structure is idealized as a three-dimensional finite element model system. Firstly, the presented method is to investigate the seismic response of circular tapered cylinder vibrating in water. Secondly, a lumped added mass matrix is adopted to replace the exact added mass matrix. Thirdly, a simplified formula is presented to evaluate the added mass of the circular tapered cylinder.

1. Introduction

Offshore and coastal structures, such as stock tanks, intake towers, bridge piers and offshore wind turbines, may be subjected to great hydrodynamic pressures during severe earthquakes. It has been demonstrated that the earthquake-induced hydrodynamic pressures may have a significant influence on the dynamic response of the structures (Liaw and Chopra, 1974). Interaction with water also modifies dynamic properties of the structures (Han and Xu, 1996). The experiment conducted by Wei et al. (2013) also indicated that water-structure interaction had significant effects on the dynamic response of bridge pile foundations submerged in water. Therefore, it is necessary to study the earthquake-induced hydrodynamic pressures for the seismic design of the offshore and coastal structures.

Many researchers have investigated earthquake-induced hydrodynamic pressure on a circular cylinder. Liaw and Chopra (1974) initially investigated the significance of hydrodynamic pressure on the dynamic response of cantilever circular cylinders. The authors discovered that water compressibility was negligible for slender cylinders. If the water is incompressible, the seismic hydrodynamic pressure is equal to a product of the constant mass of water and the acceleration of cylinder. Dynamic responses of circular cylinders subjected to horizontal ground excitation were also studied by Williams (1986) and Tanaka and Hudspeth (1988). A simple formula for evaluating the natural frequencies of a flexible circular cylinder vibrating in water was presented by Han and Xu (1996). Then, Chen (1997) presented a finite-difference scheme to solve nonlinear hydrodynamic pressures acting on a circular cylinder. Recently, a series of simplified formulas for evaluating the earthquake-induced hydrodynamic pressure on a circular cylinder were developed. Li and Yang (2013) presented an improved method of hydrodynamic pressure calculation for circular hollow cylinders. Yang and Li (2013) proposed the expanded Morison equation to calculate the hydrodynamic force of hollow circular piers caused by inner water. Du et al. (2014) proposed a simplified formula of hydrodynamic pressure on rigid circular cylinders considering water compressibility in the time domain. Wei et al. (2015) developed simplified methods for efficient seismic design and analysis of water-surrounded composite axisymmetric structures with uniform circular cross-section for outside façade. Jiang et al. (2017) developed a simplified formula for the hydrodynamic pressure on a circular cylinder, where the main parameters were radius of the cylinder and water height. In addition, Liao (1985) and Williams (1987) investigated the hydrodynamic interactions between submerged circular cylinders.

However, only a few studies were conducted to investigate the earthquake-induced hydrodynamic pressure on axisymmetric structures. For an arbitrary shape of structure, the earthquake-induced

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hydrodynamic pressure is rather difficult to be obtained by an analytical method. Liaw and Chopra (1975) utilized the finite element method to compute the earthquake response of axisymmetric intake towers surrounded by water. Based on the use of a complete and non-singular set of Trefftz function, Sun and Nogami (1991) presented a semi-analytical and semi-numerical approach to evaluate the hydrodynamic pressure on axisymmetric offshore structures. Park et al. (1991) adopted the finite element technique incorporating the infinite element to evaluate the hydrodynamic pressure on offshore structures. Avilés and Li (2001) studied the effect of the seabed flexibility on hydrodynamic pressures on axisymmetric offshore structures.

The substructure method is a preferable approach for analysis of structures interaction with water (Tsai and Lee, 1991), which is to consider the structure-water system as composed of two substructures, namely the structure and the body of water. This technique avoids direct analysis of the large water-structure system. Firstly, a substructure model is developed for the earthquake response analysis of circular tapered cylinders in Section 2, where the hydrodynamic terms that are the product of added mass matrix and the acceleration of the cylinder are determined by finite element analysis of the fluid system. Secondly, a simplified model for the added mass matrix is proposed in Section 3. Thirdly, the simplified formula for the hydrodynamic pressures acting on circular tapered cylinders is presented by curve fitting method in Section 4.

It should be noted that the present work can be simplified as a cylinder oscillatory in water. Large amount of studies has been conducted to investigate a circular cylinder oscillatory in water (Sarpkaya, 1986, 2002; Meneghini and Bearman, 1995; and Iliadis and Anagnostopoulos, 1998). Comparing with the present work, the work conducted by Sarpkay corresponds to much smaller diameter condition. However, the present model cannot be used to predict the conditions tested by Sarpkaya because the viscous of the fluid is ignored in the present study. In the future work, we will improve the present model to investigate the cylinder oscillatory in viscous fluid.

2. Substructure model of water-cylinder system

A circular tapered cylinder surrounded by water is shown in Fig. 1, which extends from the sea bottom to above the surface along the z-axis. The cylinder whose axis line is coinciding with the z-axis is treated as a three-dimensional structure and the height of the cylinder is H. The water depth is h, the foundation is assumed be rigid, and the earthquake excitation is assumed to propagate along the x-direction. The water-cylinder interaction system is initially at rest. As shown in Fig. 2, to model the fluid domain efficiently, the whole fluid domain is divided into two subdomains: the near field Ω_1 surrounding the cylinder with the outer cylindrical boundary surface at finite distance R (Γ_C) from the origin, and far field Ω_2 outside of Ω_1.

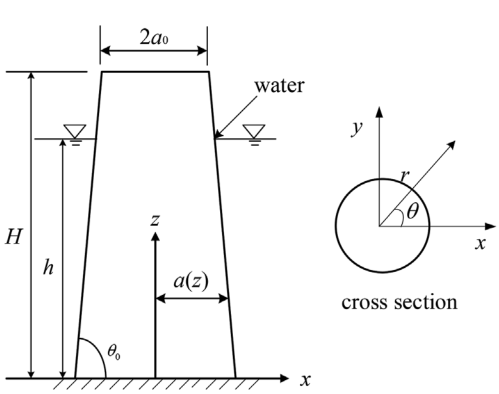

Fig. 1. Definition of the problem.

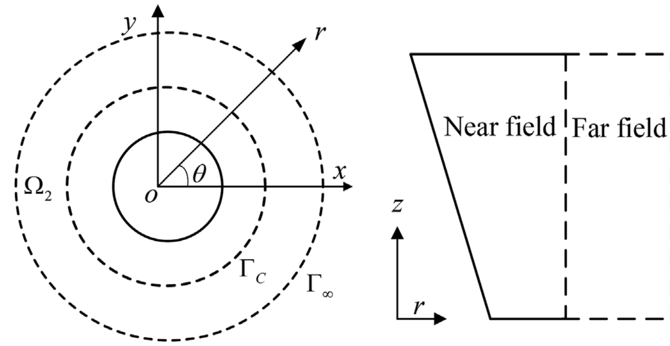

Fig. 2. Analysis model of the fluid domain.

2.1. Equations of motion of cylinder substructure

For the case of dynamic analysis of the water-cylinder system, the cylinder substructure can be discretized by using the FEM. In this study, an eight-node hexahedral element is adopted to discrete the three-dimensional cylinder (Chandrupatla and Belegundu, 2012). Thus, the dynamic equations of motion is given by

$$\mathbf{M}\ddot{\mathbf{U}}(t) + \mathbf{C}\dot{\mathbf{U}}(t) + \mathbf{K}\mathbf{U}(t) = -\mathbf{M}\ddot{\mathbf{u}}_g(t) + \mathbf{F}(t) \tag{1}$$

where $\mathbf{U}(t)$ is the vector of nodal point displacements relative to the ground; $\dot{\mathbf{U}}(t)$ is the vector of nodal point velocities relative to the ground; $\ddot{\mathbf{U}}(t)$ is the vector of nodal point acceleration relative to the ground; $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the symmetrical mass, damping, and stiffness matrices for the cylinder structure, respectively; $\mathbf{F}(t)$ is the vector of hydrodynamic forces acting on the cylinder surface arising from the hydrodynamic pressure of the water; and $\ddot{\mathbf{u}}_g(t)$ is the acceleration of the ground motion.

2.2. Finite element model for the near field of the water

Assuming water incompressible and inviscid, the hydrodynamic pressure distribution is governed by the Laplacian equation. In Cartesian coordinate system, the governed equation is expressed as

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = 0 \tag{2}$$

in which p (x, y, z, t) is the hydrodynamic pressure, and x, y, z are Cartesian coordinates.

The hydrodynamic pressure distributions can be obtained by solving Eq. (2) with the following boundary conditions and zero initial conditions.

(1) Surface at the floor of the water

$$\left.\frac{\partial p}{\partial z}\right|_{z=0} = 0 \tag{3}$$

(2) Surface at the free surface of the water with neglecting the surface wave effect

$$p|_{z=h} = 0 \tag{4}$$

(3) Surface at the interface of the water and cylinder

$$\left.\frac{\partial p}{\partial n}\right|_{r=a} = \rho\ddot{u}\cos(n, x) \tag{5}$$

(4) The initial conditions are

$$p|_{t=0} = 0 \; and \; \left.\frac{\partial p}{\partial t}\right|_{t=0} = 0 \tag{6}$$