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An improved method of hydrodynamic pressure calculation for circular hollow piers in deep water under earthquake

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ABSTRACT

Hydrodynamic pressure for cylindrical hollow piers standing in reservoir under earthquake differs from those of offshore structures. Hydrodynamic pressure expressions caused by outer water and inner water are so complicated that their solutions are difficult to calculate. Modification and simplification are performed to improve their adaptabilities in the paper. Added mass and added damping extracted from the hydrodynamic pressure expressions are incorporated into standard forced vibration governing equation, the modified governing equation and the modified numerical calculation model for a whole deep water pier considering hydrodynamic pressure are obtained. Free surface wave and its resulting added damping are proved to be negligible, added mass caused by elastic vibration can be approximately substituted by one caused by rigid motion of pier, and the expressions of the latter are further substituted by simple expressions obtained by curve fitting. Comparison studies show that the simplified expressions are not only convenient but also accurate enough for practical application. Also application is presented and how added mass intensifies seismic response of pier is revealed.

1. Introduction

The estimation of hydrodynamic force on an offshore structure has received considerable attention from scholars and designers. An accurate prediction of the wave loads on the structures is exactly important to design offshore structures. The problems of incident wave, scattering wave and radiation wave have been investigated by many researchers. Miles and Gilbert (1968) studied the problem of scattering of surface waves by a circular dock, and Garrett (1971) studied the horizontal and vertical forces and moments on the dock. Williams and Demirbilek (1988) investigated the hydrodynamic interactions caused by wave scattering between the numbers of an array of stationary truncated cylinders. Both analytical and numerical results of the wave loads exerted on a floating circular cylinder heaving in water in the presence of an incident wave have been presented by Bhatta and Rahman (1995). Also Bhatta and Rahman (2003) studied the wave loadings due to scattering and radiation for a floating vertical circular cylinder in water of finite depth. The wave loadings were derived from the total velocity potential which was decomposed as four velocity potentials, one due to scattering in the presence of an incident wave on fixed structure, and the other three due to radiation respectively by surge, heave and pitch motion on calm water. Wu et al. (2006) studied the diffraction and radiation problems for two cylinders in water of finite depth by using the method of separation of variables and method of matched eigenfunction expansion, analytical expressions of the potentials are obtained. Also Wu et al. (2004) investigated the diffraction and radiation problems for a cylinder over a caisson (a wave power device) in water in finite depth, eigenfunction expansion approach is again used to derive the velocity potentials, a set of theoretical added mass, damping coefficients and exciting force expressions are obtained. Bhatta (2011) presented the computation of hydrodynamic coefficients, displacement–amplitude ratios and loadings on floating vertical circular cylinder due to diffraction and radiation. In his study, Java Mathematical and Statistical Library (JMSL) is used to compute special functions and solve complex matrix equations. Although numerical methods, such as finite element method and boundary element method, can be applied to the diffraction and radiation problems, their calculation efficiency is relatively low and programming for them is complex.

Always the resulting hydrodynamic forces by analytical methods may then be expressed conveniently in terms of added masses and damping coefficients corresponding to the force components in phase with the acceleration and velocity of the structure, respectively. So many studies have been performed to investigate these coefficients in recent several decades. Kim (1974) studied the hydrodynamic coefficients for ellipsoidal bodies oscillating at the free surface. Bai and Yeung (1974) calculated added mass coefficients

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for horizontal and vertical cylinders. Bai (1976) gave the added mass and damping coefficients for axisymmetric ocean platforms. Sabuncu and Calisal (1981) studied hydrodynamic coefficients for vertical circular cylinders at finite water depth, which are obtained and presented for different depth to radius and draft to radius ratios. Venkataramana and Yoshihara (1989) discussed the wave forces on flexible offshore columns by taking into account the vibration mode shapes, and the hydrodynamic coefficients that are derived using linear diffraction theory. Isaacson and Mathai (1991) investigated the calculation of added masses and damping coefficients of a large surface-piercing vertical cylinder of arbitrary section extending to the seabed and undergoing harmonic oscillations. Venugopal et al. (2009) studied the wave and current induced forces on a rectangular section of the cylinders with different breadth–depth ratios, and the coefficients derived in combined waves and currents are presented.

Another phenomenon worthy of concern is that in recent years, lots of deep water piers have been built in China. Many of these piers are seated in the reservoirs of gigantic hydroelectric power station in western mountainous areas, such as Mangjiedu bridge in Xiaowan hydropower station reservoir, Miaoziping bridge in Zipingpu hydropower station reservoir, Yunyang Yangtze River bridge in the Three Gorges hydropower station reservoir and so on. These bridges are always built prior to water storage of reservoirs, so the largest depth of piers can reach up to 168m, and the depth of submerged part of the pier can even exceed 100 m. The western mountainous areas of China are characterized by high seismic hazard levels, these deep water bridges are under threat of earthquake and resulting hydrodynamic pressure. Lai et al. (2004) and Liu et al. (2008) studied the hydrodynamic pressure due to outer water and inner water respectively, and presented hydrodynamic pressure expressions for cylindrical hollow pier based on radiation wave theory, using the method of separation of variables and eigenfunction expansion approach. The radiation wave theory and the method employed in their study are widely used in many references, such as in the paper by Wu et al. (2006). And the hydrodynamic pressure expressions proposed by Lai and Liu are so complicated that self-made programs based on special math software are required in the calculation. This defect becomes an obstacle to practical application, so simplifications of those complicated expressions by Lai and Liu are studied and simplified added mass coefficients are presented in this paper. Unlike those presented in above references, the coefficients here have distinctive features detailed as: (1) diameter or side length of piers can reach up to several meters or even exceeds 10 m, deep water piers are always hollow ones which are full of water, hydrodynamic pressure caused by outer water and inner water should be taken into consideration simultaneously, so added mass coefficients for both outer water and inner water of circular hollow pier are studied. (2) Deep water piers stand in the reservoirs of gigantic hydroelectric power station, the water is basically calm before earthquake. Hydrodynamic pressure applied on piers is different from the one applied on offshore structures, only radiation wave is involved in the study of added mass. (3) The study is mainly focused on simplification of the added mass and added damping coefficients, simplification approaches are unique.

Hydrodynamic pressure should be taken as external load to analyze the dynamic response of whole bridge. Added mass and added damping extracted from the expressions are incorporated into the standard forced vibration governing equation of structure, then the modified forced vibration governing equation and numerical calculation model for deep water bridge are achieved. Simplifications on expressions of added mass and added damping are performed by ignoring secondary causes and by curve fitting. As a result, simple expressions of hydrodynamic pressure in terms of added mass are proposed for commonly used deep water piers. Compare studies show that the simplified expressions are convenient and accurate enough for practical application. Calculation process of application reveals the reason why the response of deep water pier is intensified under earthquake, compared with the one standing in air.

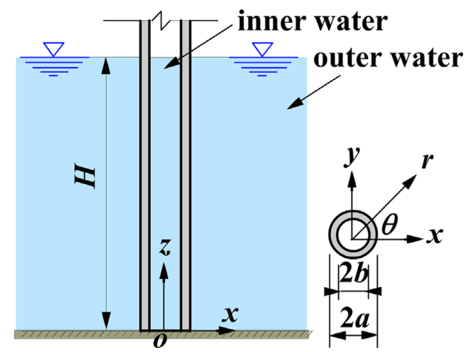

Fig. 1. Geometry of circular hollow pier.

2. Mathematical formulation

Water is assumed to be incompressible and inviscid, the motion of water is irrotational. At the beginning of earthquake, the water is calm, only radiation wave would be stimulated under earthquake. Furthermore, amplitude of wave is so small that the linear wave theory can be used. The deep water pier is simplified as a circular hollow flexible cylinder partially submerged in water, with the bottom fixed at the rigid ground. The water depth is H, outside and inside radius of the pier are a and b respectively, which is shown in Fig. 1. A Cartesian coordinate system $oxyz$ as well as the cylindrical coordinate system $or\theta z$ is defined with the origin at the bottom center of the pier. Axis z is vertically upward from the water bottom and r measures radically from z axis and θ from the positive x axis. The earthquake excitation is assumed to propagate along x axis, the pier can be characterized by translational motion in the x direction and rotational motion about y axis (namely bending vibration). In this study, the fluid is divided into two parts, namely inner water and outer water. The hydrodynamic pressure caused by them should be investigated separately.

Under the above assumptions and the arrangement of the coordinate systems, the radiation velocity potential is set as $\Phi_R(r,\theta,z,t)=\phi_R(r,\theta,z)e^{i\omega t}$, no matter it is caused by inner water or outer water. Here supposing pier vibrates with circular frequency ω, and stimulated water makes movement with the same circular frequency ω. Φ_R should satisfy the Laplace's equation, that is

$$\frac{\partial \phi_R^2}{\partial r^2}+\frac{1}{r}\frac{\partial \phi_R}{\partial r}+\frac{1}{r^2}\frac{\partial^2 \phi_R}{\partial \theta^2}+\frac{\partial^2 \phi_R}{\partial z^2}=0 \tag{1}$$

According to the complete and non-singular set of Trefftz functions (Sun and Nogami, 1991), $\phi_R(r,\theta,z)$ can be expressed as

$$\phi_R(r,\theta,z)=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}R_{mn}(r)\Theta_m(\theta)Z_n(z) \tag{2}$$

Putting Eq. (2) into Eq. (1) and using the method of separation of variables, we can get

$$\Theta_m''+b_m^2\Theta_m=0 \tag{3}$$

$$Z_n''-k_n^2 Z_n=0 \tag{4}$$

$$r^2R_{mn}''+rR_{mn}'+(r^2k_n^2-b_m^2)R_{mn}=0 \tag{5}$$

And also ϕ_R should satisfy the following boundary conditions at the surface and bottom of water respectively:

$$\frac{\partial \phi_R}{\partial z}-\frac{\omega^2}{g}\phi_R=0, \quad z=H \tag{6}$$