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Wave diffraction from a truncated cylinder with an upper porous sidewall and an inner column

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ABSTRACT

An analytical model based on linear potential theory is proposed to predict the three-dimensional wave diffraction from a truncated cylinder with an upper porous sidewall and an inner column in the finite water depth. The velocity potential is analytically derived in the whole fluid domain based on the method of variable separation and eigen-function expansion technique. The continuous conditions of pressure and velocity potential are satisfied on the interface between the adjacent sub-domains. Wave forces are calculated directly from the incident and diffracted potentials. The model is validated in comparison with other published results of wave diffraction from a porous bottom-mounted cylinder and impermeable truncated cylinder, respectively. Then the numerical tests are performed to investigate the effects of the porous coefficient G, the draft ratio h/h_1 (h and h_1 mean the drafts of the porous part and whole cylinder, respectively), the ratio of the inner and outer radii b/a and the water depth d/h_1 (d means the water depth) on the wave forces acting on the structure. It is found that, by introducing an upper porous sidewall, the hydrodynamic loads are improved in comparison with the fully impermeable structure, which may be benefit to enhance the survivability of the relating marine structure.

1. Introduction

Wave exciting forces are key elements to be considered for the safe operation of marine structures, such as breakwaters, wave power devices and offshore platforms (Hirdaris et al., 2014). Effective optimization of the wave loads on the structure may lead to the reduction in the cost of offshore structures. Structures with porous portion constitute an important class of maritime structures. By comparing with the impermeable structure, wave force acting on the porous structures is relatively reduced and the wave reflection is decreased, thus the porous structure is favored while the wave force reduction or excellent wave attenuation performance is needed (Chwang and Chan, 2003; Chandrasekaran et al., 2015; Teng et al., 2000).

There has been a great deal of effort directed towards quantifying wave interactions with porous ocean structures. Generally, the porous structures may be divided into two categories, i.e., bottom-mounted structures and truncated structures. The former was mainly focused on the porous breakwaters and bottom-mounted cylinders. The use of porous structures as breakwaters was extensively investigated both theoretically and experimentally (Jarlan, 1961; Yu and Chwang, 1994; Hu et al., 2002; Williams and Li, 1998; Yu, 1995; Liu et al., 2006, 2008). A detailed review of the studies on the interaction between waves and perforated breakwaters can be found in Huang et al. (2011). Three-dimensional (3-D) wave diffraction from an array of bottom-mounted cylinders with porous sidewalls were investigated by Williams and Li (2000), Park et al. (2014), Sankarbabu et al. (2007) and Li et al. (2004). It was found that the porous sidewall can significantly reduce both the hydrodynamic loads experienced by the cylinders and the wave run-up. Mandal and Sahoo (2015) dealt with the hydroelastic problem of concentric flexible porous cylinder systems in two-layer fluid. The results showed that the full wave reflections in the surface and internal modes may occur for some special cases. However, the investigation of perforation in the truncated structures is still quite rare up to now. Williams et al. (2000) theoretically studied the wave diffraction and radiation from a floating cylinder whose middle part is porous and found that the porous part of the structure has a significant influence on the horizontal hydrodynamic force. However, its influence on the vertical force is relatively weak. Recently, the hydrodynamic characteristics of the porous structures used as the bottom mounted offshore platform and tension leg platform were investigated theoretically (Lee and Ker, 2002; Chandrasekaran and

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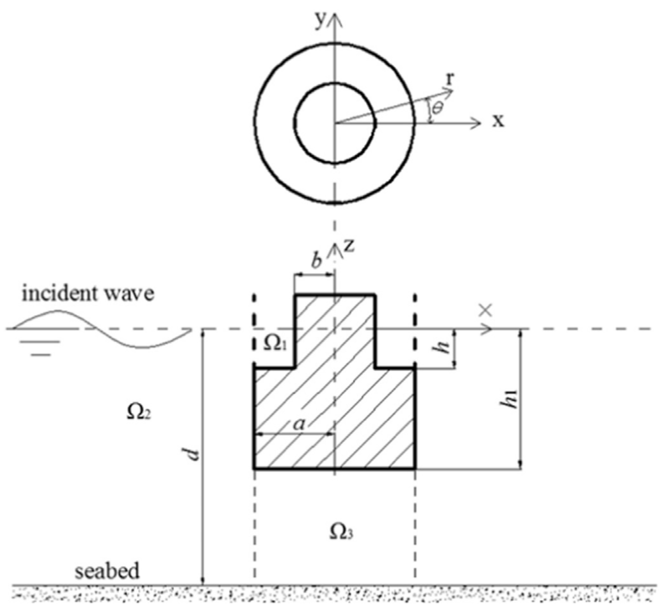

Fig. 1. Definition sketch.

Sharma, 2010; Chandrasekaran et al., 2015).

The porous materials as ocean structures can reduce the wave exciting force, which has been testified in the previous studies (Chandrasekaran et al., 2015). Since the most wave energy propagates nearby the free-surface, a porous sidewall surrounding an inner column as the top part of a truncated structure to dissipate energy (see Fig. 1) is expected to have the potential to efficiently reduce the wave loads. The proposed structure (see Fig. 1) can be regarded as the refit of the traditional impermeable structure or the compound structure. To the authors' best knowledge, there is little research to study the hydrodynamic characteristic of such type of structures. The proposed structure is expected to improve the hydrodynamics in comparison with the impermeable truncated structures. The latters have been extensively investigated by Wolgamot et al. (2012), Göteman et al. (2014), Zheng and Zhang (2015), Kara (2016), Ning et al. (2016), Johanning (2009) and Johanning et al. (2001). This paper aims to study the diffraction problem of a truncated circular cylinder with top porous sidewall and to quantify the effects of various wave and structural parameters on the wave loads. Analytical solution based on linear potential flow theory for wave diffraction from such a truncated cylinder is derived using the eigen-function expansion approach. Different from the analytical solutions of hydrodynamic problem of the general truncated cylinder with porous part (Williams et al., 2000; Lee and Ker, 2002), the effect of the imaginary part of the porous coefficient is considered and the present model can conveniently deal with the diffraction problem of truncated cylinder and the bottom-mounted cylinder with the surface-piercing porous part.

The paper is organized as follows. In Section 2, the governing equation and boundary conditions are described. In Section 3, the analytical derivation of the diffraction problem is given. In Section 4, the results are presented and discussed. Finally, the conclusions are presented in Section 5.

2. Theoretical formulation

The problem of wave diffraction from a truncated circular cylinder with an upper porous sidewall outside an inner cylinder is considered as shown in Fig. 1. Symbols a, b, h, h_1 and d represent outer cylinder radius, inner cylinder radius, draft of the upper porous part, draft of the whole cylinder and the static water depth, respectively. A cylindrical polar coordinate (r, θ, z), combined with a Cartesian coordinate (x, y, z), is built with its origin located at the center of the cylinder on the still-water level.

The structure is subjected to regular surface waves propagating in the positive x-direction with a wave height H (H=2 A, where A is wave amplitude) and an angular frequency ω. Under the frame of linear potential theory, the fluid can be described in terms of a complex velocity potential $\Phi(r, \theta, z, t) = \mathrm{Re}[\phi(r, \theta, z)e^{-\mathrm{i}\omega t}]$, where Re denotes the real part of a complex expression, i the imaginary unit and $\phi(r, \theta, z)$ represents the spatial potential. Subsequently, the common time-dependent term $e^{-\mathrm{i}\omega t}$ can be dropped from all the dynamic variables.

As shown in Fig. 1, the fluid domain is divided into three regions: an interior region defined by Ω_1 ($-h \le z \le 0$, $b \le r \le a$); an exterior region defined by Ω_2 ($-d \le z \le 0$, $r \ge a$) and another region beneath the cylinder, i.e., Ω_3 ($-d \le z \le -h_1$, $0 \le r \le a$). Since the present study is solved in the frequency domain, the velocity potential in each region Ω_j is denoted by ϕ_j, j=1, 2 and 3. Each potential satisfies Laplace equation in the corresponding flow region, namely

$$\nabla^2\phi_j = 0 \quad \text{for} \quad j = 1,\ 2,\ 3 \quad \text{in } \Omega_j \tag{1}$$

The potential also satisfies the appropriate boundary conditions on the free-surface, and sea-bed, namely

$$\frac{\partial \phi_j}{\partial z} = \frac{\omega^2}{g}\phi_j \quad \text{for} \quad z = 0,\ \ j = 1,\ 2,\ 3 \tag{2}$$

$$\frac{\partial \phi_j}{\partial z} = 0 \quad \text{for} \quad z = -d,\ \ j = 2,\ 3 \tag{3}$$

where g is the acceleration due to gravity.

The boundary condition on the impermeable surface of cylinder can be expressed as

$$\frac{\partial \phi_1}{\partial z} = 0 \quad \text{for} \quad b < r < a,\ \ z = -h \tag{4}$$

$$\frac{\partial \phi_3}{\partial z} = 0 \quad \text{for} \quad 0 < r < a,\ \ z = -h_1 \tag{5}$$

$$\frac{\partial \phi_1}{\partial r} = 0 \quad \text{for} \quad r = b,\ \ -h < z < 0 \tag{6}$$

$$\frac{\partial \phi_2}{\partial r} = 0 \quad \text{for} \quad r = a,\ \ -h_1 < z < -h \tag{7}$$

The boundary condition on the porous circular wall can be expressed as follows (Sollitt and Cross, 1972; Yu, 1995):

$$\frac{\partial \phi_1}{\partial r} = \mathrm{i}kG(\phi_1 - \phi_2) \quad \text{for} \quad r = a,\ \ -h < z < 0 \tag{8}$$

where k is the wavenumber, $G = \frac{\gamma}{k\delta}\left\{f - \mathrm{i}\left[1 + \frac{C_m(1-\gamma)}{\gamma}\right]\right\}$, δ is the physical thickness of the porous wall (the thickness is negligible geometrically) and γ, f and C_m are the porosity, the linearized resistance coefficient and the added-mass coefficient of the porous medium, respectively (Yu, 1995). The parameter G can be write as G_r+i G_i, where G_r denotes the real part and G_i the imaginary part. Physically, G_r and G_i represent the drag term and the inertia term, which lead to the wave energy loss and the phase change, respectively (Teng et al., 2000; 2001).

On the cylindrical surface of r=a, the potentials should satisfy the following matching conditions :

$$\phi_2 = \phi_3 \quad \text{for} \quad r = a,\ \ -d < z < -h_1 \tag{9}$$

$$\frac{\partial \phi_2}{\partial r} = \begin{cases} \frac{\partial \phi_1}{\partial r} & \text{for} \quad r = a,\ \ -h < z < 0 \\ 0 & \text{for} \quad r = a,\ \ -h_1 < z < -h \\ \frac{\partial \phi_3}{\partial r} & \text{for} \quad r = a,\ \ -d < z < -h_1 \end{cases} \tag{10}$$

The velocity potentials in the flow region consist of the incident