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Theoretical and experimental investigation on wave interaction with a concentric porous cylinder form of breakwater

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ABSTRACT

This paper aims at deriving velocity potential for the regular wave passing through a concentric porous cylinder system, which has an arbitrary smooth section. The wave interaction with the structures, for instance wave force on them and wave elevation, are discussed with different sections and wave properties in this study. The efficiency and accuracy of present method was validated by comparing with the semi-analytical method of SBFEM first. Then an experiment with a quasi-ellipse caisson was also performed to demonstrate the effectiveness and practical potential of present method. Finally, a surface-piercing concentric cylindrical system, which consists of an impermeable inner cylinder and a coaxial single-layered perforated cylinder, was investigated by using present method. The analysis shows that the maximum wave force on the inner cylinder is reduced to some extent with a noncircular perforated cylinder around it, compared with circular cases, while the wave run-up is enlarged by the uneven spacing between the boundaries with the increasing of the wave number.

1. Introduction

Water wave interaction with offshore structures has attracted considerable interest by the scientists and engineers. To reduce the wave action and protect the structures, various types of fixed and floating breakwaters are settled around the structure to against the harsh environmental conditions. Owing to the complex wave-structure interactions, the breakwater tends to significantly affect the hydrodynamic performance of the offshore structure, including the wave diffraction, transmission, energy dissipation, wave run-up. The earliest attempt was performed on a perforated-wall caisson with a perforated front wall backed up by an impermeable wall constructed at Naples, Italy (Jarlan, 1961). Summering from the engineering experience in design and construction of vertical breakwaters for harbor protection, Franco (1994) given a brief description of the major failures and lessons learned from practical engineering.

Because of its effective reduction of wave force and wave run-up on the structures, many researches were carried out to investigate the wave interaction with porous structures like porous plates/walls, slotted walls, perforated wall caisson type breakwaters. Such breakwaters summarized by Xiao et al. (2016) included perforated-wall breakwaters (Jarlan, 1961), spar-buoy breakwater fences (Liang et al., 2004), flexible porous membrane barriers (Suresh Kumar et al., 2007), truss breakwaters (Uzaki et al., 2011), pneumatic floating breakwaters (He et al., 2012), mat-shaped floating breakwaters (Loukogeorgaki et al., 2012), submerged flat plate breakwaters (Lalli et al., 2012) and so on. Various types of the breakwater make the theoretical analysis difficultly be derived in a general formulation for each case. Early theory study was derived by Sollitt and Cross (1972) to predict the wave reflection and transmission with a permeable breakwater. The reflection coefficient introduced by Sahoo et al. (2000) was one of most important parameter for the efficiency of the breakwater. For the single- or multi-chamber perforated caissons, it found that reflection coefficient is grateful affected by the B/L, where B is the chamber width and L is the incident wavelength. A rich literature on the effect of the B/L indicated that it would vary a lot for different practical cases. Detail introduction on this topic can be found from the review of Huang et al. (2011).

The cylindrical structure is free-widely use in the offshore structures, for instance offshore wind turbine, oil platform and bridge foundation. A semi-empirical method called Morison equation (Morison et al., 1950) is widely used to calculate the inline wave force on the small structure in oscillatory flow. For the diffraction problem with a large body, MacCamy and Fuchs (1954) proposed a linear analytical solution of wave action around a bottom mounted cylinder, which neglect the effect of the

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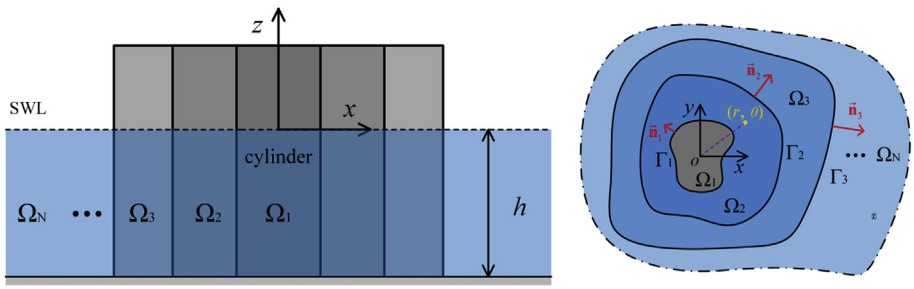

Fig. 1. Schematic for a concentric cylinder system.

viscosity of the water. Interactions of water waves with a porous vertical cylinder or concentric porous cylinder system also have been an active research topic for years. Wang and Ren (1994) performed a theoretical investigation of wave interaction with a concentric surface piercing two-cylinder system, where the exterior cylinder is porous and considered to be thin in thickness and the interior cylinder is impermeable. Later, this method was extended by Darwiche et al. (1994) and Williams and Li (1998) to a similar two-cylinder system case, but with the outer cylinder being porous in the vicinity of free surface and impermeable at some distance below the water surface, and further with the inner cylinder mounted on a storage tank, respectively. For the multi-pile problem, Williams and Li (2000) extended the work of Linton and Evans (1990) to the interaction of water waves with arrays of bottom-mounted, surface-piercing circular cylinders. Chen et al. (2011) revisited this topic by using the null-field integral equation in conjunction with the addition theorem and the Fourier series. The near-trapped phenomenon of multi-pile was also discussed with the effect of porous cylinders and disorder of layout. For the other wave cases, Zhong and Wang (2006) presented the analytical solution on the solitary waves interacting with a surface-piercing concentric porous cylinder system. It showed that the hydrodynamic is much dependent on the annular spacing between the outer porous cylinder and inter solid cylinder. Mandal et al. (2013, 2015) investigated the hydroelastic analysis of a cylinder system, which consists of a rigid cylinder and an outer flexible porous cylinder in water of finite depth. The wave cases for the single-layer and two-layer fluid having a free surface and an interface were considered to evaluate the wave action.

A new semi-analytical method recently, namely scaled boundary finite-element method (SBFEM), which used to solve soil–structure interaction problems (Wolf, 2003), has been successfully induced to deal with the linear wave diffraction problem around a porous structures (Liu and Lin, 2013; Liu et al., 2012; Meng and Zou, 2012; Song and Tao, 2007, 2009; Tao et al., 2009). It also showed that this method can deal efficiently with the diffraction problem around the bottom-mounted cylinder with an arbitrary section (Song et al., 2010). Another method using the dual boundary element method (DBEM) coupled with the dual reciprocity method (DRM) was employed by Chuang et al. (2015) to investigate wave scattering by a concentric porous cylinder system, which consists of a circular inner cylinder and semicircular porous outer cylinder mounted on a conical shoal.

Liu et al. (2016) performed a general method to solve the linear diffraction wave around a uniform bottom-mounted cylinder with arbitrary smooth section by expanding the radius function into a Fourier series. This method can be extended for the concentric porous cylinder system with the boundaries are arbitrary smooth. The formulation of the present method is showed in §2. The efficiency and accuracy of present method was validated by comparing with the semi-analytical method of SBFEM, as shown in §3. Further, an experiment was performed with a quasi-ellipse caisson to demonstrate the practicability of present method in this section. Then a cylindrical system which consist of a circular inner cylinder and a cosine-type outer cylinder was further investigated in §4 with the effect of wave attack angle, layout of the system, wave number and porous parameter. The major found of this study is shown in the last section.

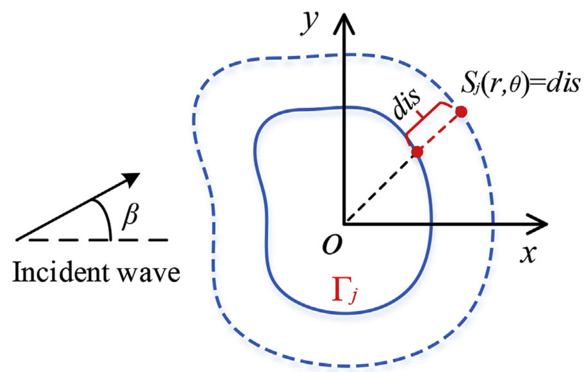

Fig. 2. Schematic for the surface function.

2. Mathematic model

Fig. 1 shows the diagram of the water wave interaction with a concentric porous cylinder system. For the two coordinate systems, the x-y or r-θ planes are all set at the still water level (SWL), and the origin is inside the cross-section of the cylinder. The z-axis is perpendicular to the SWL and positive upward. The whole fluid domain is divided into several subdomains, $\Omega_j \quad (j = 1, 2, \cdots, N)$, with the boundary of $\Gamma_j \quad (j = 1, 2, \cdots, N-1)$. The boundary, which is considered to be thin in thickness, is assumed to be arbitrary smooth and porous. For convenience, the interior subdomain of boundary Γ_j is named as Ω_j and the exterior subdomain of boundary Γ_j is named as Ω_{j+1}. In following analysis, the cylinder is exposed to the plane wave with a frequency ω , wave amplitude A and water depth h.

As mentioned above, the radius function for the cross-section can be expanded into the Fourier series based on the assumption of the smooth cylinder surface. Therefore, the radius function $r_j(\theta)$ of the boundary Γ_i in the polar coordinate can be written as

$$r_j(\theta) = \sum_{n_r=-\infty}^{\infty} b_{jn_r} e^{in_r\theta} \quad (j = 1, 2, \cdots, N-1) \tag{1}$$

where $n_r \in Z$; b_{jn_r} is the Fourier coefficients of $r_j(\theta)$ and N is the number of subdomain.

Then, a surface function, S_j, can be defined by

$$S_j(r, \theta) = dis = r - \sum_{n_r=-\infty}^{\infty} b_{jn_r} e^{in_r\theta} \quad (j = 1, 2, \cdots, N-1) \tag{2}$$

in which dis is the distance between S_j and Γ_j in the radial direction, as shown in Fig. 2. It indicates that boundary Γ_j can be represented by surface function S_j as the value of dis coming to zero.