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Dual boundary element model coupled with the dual reciprocity method to determine wave scattering by a concentric cylindrical system mounted on a conical shoal

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ABSTRACT

In this study, the dual boundary element method (DBEM) is coupled with the dual reciprocity method (DRM) 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. The complex porous-effect parameter proposed by Yu and Chwang [2] is used to describe the permeability of the porous outer cylinder. The effect of topography has been considered by applying the extended mild-slope equation (EMSE) which was proposed by Chandrasekera and Cheung [10] to the entire fluid domain. The wave force, wave amplification, and increased performance configuration are illustrated through examples.

1. Introduction

In recent decades, porous structures have become popular in coastal and offshore engineering because they reduce the wave forces and wave run-up on structures. The porous-effect parameter, known as the Chwang parameter, has been used to describe the permeability of porous thin structures [1]. Yu and Chwang [2] have proposed another derivation that is based on the findings of Sollitt and Cross [3] and used to extend the parameter from a real form to a complex form.

A theoretical investigation of regular wave interactions with a concentric porous cylinder system that consists of a circular porous outer cylinder and impermeable inner cylinder was proposed by Wang and Ren [4]. Their results showed that the presence of the outer cylinder reduced the hydrodynamic force acting on the inner cylinder and wave amplitude around the windward side of the inner cylinder. Since then, many numerical and experimental studies of wave interactions with concentric porous cylinder systems have been published [5–7]. In concentric cylinder systems, the circular outer cylinder was the primary focus of these studies until Liu and Lin proposed two related studies [8,9] that included a single-layer arc-shaped outer cylinder and a double-layer arc-shaped outer cylinder. However, the aforementioned studies primarily included water of uniform depth. Therefore, the effect of topography will be considered in the transformation of waves in the present study.

The extended mild-slope equation (EMSE) proposed by Chandrasekera and Cheung [10] improves upon the results of Berkhoff's [11] mild-slope equation (MSE) for relatively steep and rapidly undulating bathymetry. In addition, the EMSE has been successfully employed in many cases with steep topography [12,13]. However, the EMSE can be rearranged into an inhomogeneous Helmholtz equation (see Eq. (15)) to produce the domain integration in the conventional boundary element method (BEM) procedure.

Recently, a cylindrical island mounted on a permeable circular shoal was researched by using the linear long wave equation (LWE) in Kuo et al. [14]. The first exact analytic solution to the modified mild-slope equation (MMSE) for wave scattering by Homma island was proposed by Liu and Xie [15].

The application of the conventional BEM with the dual reciprocity method (DRM) (DRBEM) was first proposed by Nardini and Brebbia [16] in free vibration analyses for the Laplace operator to circumvent the difficulties associated with domain integration. Later, due to conquering of using Helmholtz operator in the DRBEM, Zhu [17] initiated an application of the DRBEM for wave refraction and diffraction based on the MSE. The combined effects of wave refraction–diffraction and currents were studied by the DRBEM in Hsiao et al. [18]. Recently, Hsiao et al. [12] developed the DRBEM wave model, which is governed by the EMSE. Unlike the finite difference method (FDM) and the finite element method (FEM), the conventional BEM distinguishes itself as a boundary method. Since the

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interior mesh does not have to be dealt with, the mesh preparation of the conventional BEM is more cost efficient. For the advantage of the conventional BEM, the DRBEM is applied to transform domain integrals into the corresponding boundary integrals for the EMSE in this study.

The porous outer cylinder in the concentric porous cylinder system is often viewed as a thin structure (degenerate boundary) that results in an ill-posed problem for the conventional BEM and DRBEM procedures; however, the dual boundary element method (DBEM), which was first proposed by Hong and Chen [19] for a cracked elasticity problem, is a potential solution to this problem. The DBEM has been applied to analyze the interaction between water waves and a submerged horizontal thin plate by Tsaur and Her [20]. In the case with degenerate boundaries, the DRBEM cannot provide sufficient conditions. By introducing the hypersingular boundary integral equation, the DBEM overcomes this problem without subdomains and thereby requires less computer memory. Detailed review can be found in Chen and Hong [21]. Therefore, the problem in this study is addressed by combining the DBEM and DRM and using the advantages of both.

However, when the inverse associated with the approximating functions inevitably is computed, it fails because coincident nodes on the degenerate boundary emerge in the process of combining the DBEM and DRM. Fedelinski et al. [22] proposed a modified matrix associated with the approximating functions to remedy this situation, and they applied the DBEM and DRM in dynamic fracture mechanics. Additionally, Albuquerque et al. [23] proposed an easy adaptation that eliminates the consideration of nodes on the degenerate boundary in the computation of the matrixes associated with the approximating functions and particular solutions.

Following the suggestion proposed by Albuquerque et al. [23], the DBEM and DRM are applied in this study to examine the effectiveness of a semicircular porous outer cylinder in the concentric cylindrical system mounted on a conical shoal. The wave forces and wave amplifications are discussed in terms of various conditions.

Section 2 describes the governing equations, boundary conditions, and numerical implementation. Section 3 presents examples used to verify the model. In Section 4, an examination of the wave forces and wave amplifications is presented. Section 5 presents the conclusions from the study.

2. Formulation

This work applies the DBEM coupled with the DRM technique to investigate the scattering of simple harmonic waves by a concentric cylindrical system mounted on a conical shoal. Fig. 1 shows a sketch of the configuration. The concentric cylindrical system consists of a circular inner cylinder with radius r_a and semicircular porous outer cylinder on the left with radius r_c. The side wall of the outer cylinder is porous and thin. The center axis of the conical shoal that is surrounded by an infinite fluid region of constant depth h_0 is the same as the center axis of the inner cylinder, where h_a and r_b are the water depth of the perimeter of the inner cylinder and radius of the toe of the bottom shoal, respectively. The Cartesian coordinate system defines the three-dimensional problem, where the origin is located at the center axis of the inner cylinder at the still-water level, x and y are measured horizontally and z is measured vertically upwards from the still-water level.

For an inviscid, incompressible fluid and non-rotational motion, a flow velocity potential Φ exists and satisfies the Laplace equation in the fluid region. Furthermore, a monochromatic incident wave with amplitude ζ_0 and angular frequency σ ($\sigma = 2\pi/T$, where T is the wave period) is specified, and it propagates at an angle θ_I to the positive x-axis. The velocity potential of the linearized wave

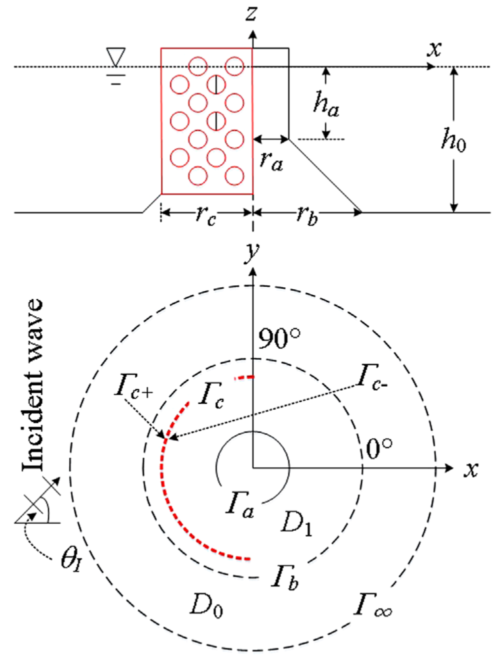

Fig. 1. Definition sketch.

motion is as follows:

$$\Phi(x,y,z,t) = \frac{g\zeta_0}{\sigma}\phi(x,y)\frac{\cosh k(z+h)}{\cosh kh}\cdot \exp(-i\sigma t) \tag{1}$$

where t is time, g is the gravitational constant, ϕ is the complex horizontal spatial velocity potential, $i=\sqrt{-1}$, h represents the water depth and k is the wave number that satisfies the dispersion relation ($\sigma^2 = gk \tanh kh$).

According to the derivation by Chandrasekera and Cheung [10], ϕ satisfies the EMSE as follows:

$$CC_g\nabla^2\phi + \nabla CC_g\cdot\nabla\phi + \left[\sigma^2\frac{C_g}{C} + gf_1\nabla^2 h + gkf_2(\nabla h)^2\right]\phi = 0 \tag{2}$$

where $C=\sigma/k$ and $C_g = d\sigma/dk$ are the phase and group velocities, respectively, $\nabla = (\partial/\partial x, \partial/\partial y)$, $\nabla^2 h$ is the bottom curvature, (∇h) is the bottom slope, and f_1 and f_2 are dimensionless coefficients as follows:

$$f_1 = \frac{-4kh\cosh(kh) + \sinh(3kh) + \sinh(kh) + 8(kh)^2\sinh(kh)}{8\cosh^3(kh)\left[2kh + \sinh(2kh)\right]} - \frac{kh\tanh(kh)}{2\cosh^2(kh)} \tag{3}$$

$$f_2 = \frac{\mathrm{sech}^2(kh)}{6\left[2kh+\sinh(2kh)\right]^3}\cdot\Big\{8(kh)^4 + 16(kh)^3\sinh(2kh) - 9\sinh^2(2kh)\cosh(2kh) + 12(kh)\left[1+2\sinh^4(kh)\right]\left[kh+\sinh(2kh)\right]\Big\} \tag{4}$$

Based on linear wave theory, the free surface elevation η is as follows:

$$\eta(x,y,t) = \mathrm{Re}\left[i\zeta_0\phi(x,y)\cdot\exp(-i\sigma t)\right] \tag{5}$$

The entire fluid domain (see Fig. 1) is divided into two regions by the pseudo boundary Γ_b, where the exterior infinite region D_0 is a constant-depth region between Γ_∞ (at infinity) and Γ_b, and the interior region D_1 is a variable-depth region between Γ_b and Γ_a. To specify the location of the velocity potential ϕ, we define ϕ_0 and ϕ_1 to denote ϕ in the D_0 and D_1 regions, respectively.

Because $k=k_0$ and $h=h_0$, C and C_g are constant in the exterior region D_0, the EMSE, Eq. (2), is reduced to the Helmholtz equation