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Scattering of oblique waves by permeable vertical flexible membrane wave barriers

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ABSTRACT

The interaction of obliquely incident surface gravity waves with a vertical flexible permeable submerged membrane wave barrier is investigated in the context of three-dimensional linear water wave theory. From the general formulation of the submerged membrane barrier, the performance of bottom-standing, surface-piercing and fully extended membrane wave barriers are analyzed for various values of wave and structural parameters. The analytic solution of the physical problem is obtained using eigenfunction expansion method and a coupled boundary element-finite difference method has been used to get the numerical solution. In the boundary element method, since the boundary condition on the membrane barrier is not known a priori, the membrane response and velocity potentials are solved simultaneously using appropriate discretization with the help of finite difference scheme. The convergence of the analytic and numerical solution techniques is discussed. The study reveals that for suitable combination of wave and structural parameters, approximately (45–50)% incident wave energy can be dissipated irrespective of membrane barrier configurations. Further, in certain situations, nearly full wave reflection and zero transmission occur for all barrier configurations. The study will be useful in the design of flexible permeable membrane to act as an effective wave barrier for creation of tranquility zone in the marine environment.

1. Introduction

In recent decades, flexible porous breakwaters have been considered as better alternatives to the conventional fixed rigid breakwaters for providing protection from wave attack at locations where protection is required on temporary basis. These types of structures are more suitable where bottom soil foundation is poor as these types of structures do not require proper foundation or strong supports. Moreover, flexible permeable barriers are cost-effective, quickly deployable, lightweight, portable, reusable and environmental friendly. Due to the porosity, these structures can dissipate wave energy at a higher rate which in turn reduces wave forces on the structure. Moreover, a characteristic of flexibility is usually included in these temporary barriers in order to minimize the wave impact on them. In addition, partial flexible barriers allow the free water circulation, transportation of sediment and safe passage of ocean current. Often, permeable and flexible structures are used to reduce wave resonance inside the harbor along with both the reflected and the transmitted wave heights during wave scattering.

Williams et al. [1] investigated the performance of a flexible, floating beam-like structure anchored to the seabed and having a small buoyancy chamber at the top of structure. They have solved the physical problem numerically by using the boundary integral equation method and validated the results by carried out small-scale physical model tests. Kim and Kee [2] studied the interaction of water waves with a vertical flexible membrane barrier in the context of two-dimensional linear water wave theory. Cho et al. [3] have studied the interaction of oblique incident waves with a tensioned vertical flexible membrane barrier hinged at the sea floor and attached to a rigid cylindrical buoy at its top. By using Darcy's fine-pore model, Cho and Kim [4] studied the interaction of monochromatic incident waves with a horizontal flexible porous membrane barrier in the context of 2D linear hydroelastic theory. Lee and Lo [5] have used least square approximation method to solve the physical problem associated with the oblique wave scattering by surface-penetrating flexible membrane wave barriers of finite draft floating in water of finite depth. To restore the wetlands habitat, Williams and Wang [6] proposed to use flexible porous wave barrier to protect cordgrass seedlings form wave

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action during the initial stage of growth following plating. Kumar and Sahoo [7] have analyzed the performance of a vertical flexible porous breakwater in two-layer fluid of finite depth. Further, Kumar et al. [8] have carried out an analysis to investigate the scattering of water waves by a vertical flexible porous membrane barrier pinned both at the free surface and the sea bed in a two-layer fluid of finite depth. Karmakar et al. [9] used least square approximation method to study the scattering of surface gravity waves by multiple surface-piercing flexible permeable membrane wave barriers. Using system of Fredholm integral equation technique, Koley et al. [10] and Kaligatla et al. [11] studied the interaction of surface gravity waves by a floating flexible porous plate in water of finite and infinite depths. Recently, using the same approach as used in [10], Koley and Sahoo [12] analyzed the hydroelastic response of a floating horizontal flexible porous membrane barrier. Most of the methods used to deal with wave–structure interaction problems in the literature as discussed above are suitable for structures of regular geometries in water of uniform depths. Although certain attempts have been made previously to take obliqueness of the incident waves into account but the modeling of the flexible membrane was inappropriate for oblique waves. Therefore, an appropriate model is required to take the obliqueness of the incident waves and the porosity of the membrane into account.

In the present study, scattering of obliquely incident surface gravity waves with a submerged permeable vertical flexible membrane barrier in water of finite depth is investigated in the context of three-dimensional linear water wave theory. As special cases of the submerged barrier, the effectiveness of the bottom-standing as well as surface-piercing and complete membrane barrier are analyzed. The solution of the boundary value problem associated with each barrier configuration is obtained (i) analytically by using eigenfunction expansion method and (ii) numerically by using a coupled boundary element-finite difference method. The eigenfunction expansion method is a semi-analytic tool and is used to validate the computational results obtained by the numerical method i.e., the coupled boundary element-finite difference method. The present numerical method is robust in nature. It can effectively handle the arbitrary shape and configurations of the membrane barrier, and the bottom undulation in the seabed. In this regard, it is worthy to be mentioned that because of the presence of the flexible membrane barrier, only boundary element method can not handle the physical problem as the boundary condition on the membrane barrier is not known a priori and therefore membrane barrier motions and velocity potentials are solved simultaneously using appropriate discretization on the membrane boundary with the help of finite difference scheme. As a result, an appropriate coupling is required between the boundary element method and the finite difference method and the same is demonstrated well in the present study. Further, the convergence of the present method of solution is demonstrated using the approach used in [13,14]. To understand the efficiency of the proposed system, the reflection and transmission coefficients, the wave forces acting on the membrane barrier and its displacement have been plotted and analyzed for various values of wave and structural parameters. Thus, the main contribution in the present study is to develop an appropriate eigenfunction expansion method and a coupled boundary element-finite difference method to handle the problems of obliquely incident surface gravity wave interactions with flexible porous membrane wave barriers.

2. Mathematical formulation

In the present manuscript, oblique wave scattering by a submerged flexible porous membrane barrier is studied in water of finite depth under the assumption of small amplitude water wave theory and structural responses. The physical problems are analyzed in the three-dimensional Cartesian coordinate system with the positive y-axis being vertically downwards and the horizontal plane $y = 0$ represents undisturbed free surface. The fluid domain is infinitely extended in the x–z horizontal direction as $-\infty < x, z < \infty$ and vertical direction as $0 < y < h$ except the flexible porous membrane barrier as in Fig. 1a. A thin vertical flexible porous membrane barrier occupies the region $x = 0$, $a < y < b$, $-\infty < z < \infty$ in the fluid domain. For notational convenience, $L_m = (a, b)$ refers to the barrier segment and $L_g = (0, a) \cup (b, h)$ refers to the gap region. The fluid is modeled using the Airy's water wave theory, and the motion of the fluid is assumed to be of simple harmonic in time with the angular frequency ω. Further, it is assumed that surface waves are incident upon the vertical membrane barrier by making an angle θ with the x-axis. These assumptions ensure the existence of velocity potential $\Phi(x, y, z, t)$ and is of the form $\Phi(x, y, z, t) = \text{Re}\{\phi_j(x, y)e^{i(\beta_0 z - \omega t)}\}$ with $\beta_0 = k_0 \sin\theta$ being the z-component of the plane progressive wave incident upon the membrane barrier and the subscripts $j = 1$, 2 referring to the fluid domains 1 and 2 as shown in Fig. 1a. In the jth fluid region, the spatial velocity potential ϕ_j satisfies the partial differential equation

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} - \beta_0^2\right)\phi_j = 0. \tag{1}$$

The free surface boundary condition is given by

$$\frac{\partial \phi_j}{\partial y} + K\phi_j = 0, \quad \text{on} \quad y = 0, \tag{2}$$

where $K = \omega^2/g$ with g being the acceleration due to gravity. The bottom boundary condition is given by

$$\frac{\partial \phi_j}{\partial y} = 0, \quad \text{on} \quad y = h. \tag{3}$$

The membrane barrier is modeled as string of uniform mass density m_m acting under uniform tension with both the ends being fixed. The motion of the membrane barrier is assumed to be uniform in the longitudinal direction and the barrier is deflected horizontally with a displacement of the form $\zeta(y, z, t) = \text{Re}\{\chi(y)e^{i(\beta_0 z - \omega t)}\}$ with $\chi(y)$ being the complex deflection amplitude and is assumed to be small compared to the water depth. The equation of motion of the membrane barrier deflection $\chi(y)$, acted upon by the dynamic pressure is given by

$$\overline{T}\left(\frac{d^2}{dy^2} - \beta_0^2\right)\chi + m_m\omega^2\chi = -i\rho\omega[\phi_1(0, y) - \phi_2(0, y)],$$
$$\text{for} \quad x = 0, y \in L_m, \tag{4}$$

where $\overline{T}$ is the membrane tension, ρ is the density of the water and $m_m = \rho_m d_m$ is the uniform mass per unit length of the membrane with thickness d_m and density ρ_m. Eq. (4) is rewritten as

$$\left(\frac{d^2}{dy^2} - \beta_0^2\right)\chi + {\lambda_m}^2\chi = -\frac{i\rho\omega}{\overline{T}}[\phi_1(0, y) - \phi_2(0, y)],$$
$$\text{for} \quad x = 0, \quad y \in L_m, \tag{5}$$

where $\lambda_m = \omega\sqrt{m_m/\overline{T}}$. Now, the dynamics of a tensioned membrane is similar to the dynamics of a spring mass system. From Eq. (5), it is clearly seen that the dynamics of a flexible membrane is satisfying an one-dimensional wave equation with celerity $\sqrt{\overline{T}/m_m}$. However, when the membrane is floating in the water, due to the effect of the added mass, the celerity of the membrane wave motion is expected to be lower and is $\sqrt{\overline{T}/m_a}$ where m_a is the added mass. In case of rigid-body hydrodynamics, it is possible to separate the added mass from the mass of the body. But, in the present problem, it is not straightforward to separate added mass term. Further, the