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Wave transmission by partial porous structures in two-layer fluid

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ABSTRACT

The present study deals with oblique surface gravity wave scattering and trapping by bottom-standing and surface-piercing porous structures of finite width in two-layer fluid. The problems are analyzed based on the linearized water wave theory in water of uniform depth. Both the cases of interface piercing and non-piercing structures are considered to analyze the effect of porosity in attenuating waves in surface and internal modes. Eigenfunction expansion method is used to deal with wave past porous structures in two-layer fluid assuming that the associated eigenvalues are distinct. Further, the problems are analyzed using boundary element method and results are compared with the analytic solution derived based on the eigenfunction expansion method. Efficiency of the structures of various configuration and geometry on scattering and trapping of surface waves are studied by analyzing the reflection and transmission coefficients for waves in surface and internal modes, free surface and interface elevations, wave loads on the structure and rigid wall. The present study will be of significant importance in the design of various types of coastal structures used in the marine environment for reflection and dissipation of wave energy at continental shelves dominated by stratified fluid which is modeled here as a two-layer fluid.

1. Introduction

In recent decades, porous structures are introduced into the art of energy dissipation and reduction of wave load acting on various marine facilities. Apart from energy dissipation, these porous structures change the phase of the incoming and reflected waves which in turn creates a tranquility zone. Further, porous structures are often used as wave absorbers in laboratories for removing unwanted waves during experiments. In addition, wave motion in two-layer fluid having a free surface and an interface is very common in continental shelves and estuaries leading to the generation of plane progressive waves in surface and internal modes. Gravity wave interaction with porous structures in a two-layer fluid has assumed significance in the recent decades to understand the role of permeability of the structure in attenuating waves in surface and internal modes. Partial porous structures are preferred for various coastal engineering applications instead of complete structures extending from the bottom to the free surface. Bottom-standing structures are more suitable near navigational channels/harbors as these structures allow free passage of vessel over it. Often these bottom-standing structures are used as (i) sheltered region by marine habitats from high wave attack and (ii) artificial fish reef in coastal fishery. On the other hand, surface-piercing porous structures are more appropriate at location where bottom soil condition is poor and water depth is large.

The interaction of surface gravity wave with various coastal structures involves various physical processes such as reflection, refraction, diffraction, wave breaking, scattering and trapping etc. However, for creating a tranquility zone in the marine environment with the introduction of coastal structures, two major class of problems such as wave scattering by barriers and wave trapping by barriers near a wall are considered in the literature. The efficiency of the coastal structure as a wave barrier is measured from the reflective and dissipative characteristics of the structure. Apart from the reflective and dissipative characteristics, the structural longevity is analyzed by measuring the wave load acting on the structure. In case of wave scattering, the fluid domain is assumed to be infinitely extended and the structure, as a wave barrier, is assumed to be located at the center. The reflection and transmission coefficients are computed to understand the amount of wave energy that is reflected and transmitted by the barrier when a monochromatic wave of known amplitude and frequency is incident upon the structure. On the other hand, in case of wave trapping, the wave barrier is assumed to be located at a finite distance from the coastal infrastructure (say a rigid wall) which is to be protected. Thus, in case of wave trapping, the transmitted wave is confined to a finite region between the wave barrier and the rigid wall. Unlike the case of wave scattering where reflection and transmission coefficients play dominating role in the understanding of the efficiency of the wave barrier, the reflection coefficient plays a significant role in measuring the efficiency of the

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wave barrier. On the other hand, one of the unique aspects of study for wave trapping is in the determination of the structural configuration and characteristics of the wave barrier for obtaining optimum wave reflection by the barrier and load on the wave barrier/rigid wall. In these study, emphasis is not only given on finding the trapped modes by relating the wave wavelength with the distance between the wall and the barrier but also analyzing the effect of these trapped modes in attenuating/absorbing the outgoing waves for protecting coastal facilities (see Wang and Ren [1], Sahoo et al. [2] and Behera et al. [3]). However, there is a significant progress in the literature emphasizing the existence of trapped modes in infinitely oscillatory systems whose details can be found in the review paper of Linton and McIver [4].

Gravity wave scattering with partial rigid structures as breakwaters in a single layer fluid is well studied in the literature (see Newman [5], Mei and Black [6] and McIver [7]). Sollitt and Cross [8] developed a model to study wave motion within porous structure using Lorentz's principle of virtual work. On the other hand, Chwang [9] developed the porous wavemaker theory to study the wave past porous structure using Darcy's law. Dalrymple et al. [10] studied the scattering of obliquely incident surface waves by a porous structure in fluid of constant density. Yu [11] generalized the porous wavemaker theory of Chwang [9] to account for both inertia and frictional force to deal with wave past thin porous structure. Losada et al. [12] studied wave scattering by submerged porous structures. Huang et al. [13] reviewed the performance of perforated structures as a wave barrier. Koley et al. [14] investigated oblique wave scattering by a vertical flexible porous plate. Behera and Sahoo [15] studied gravity wave interaction with submerged horizontal flexible porous plate. Liu and Li [16] analyzed the wave scattering by porous structures by decomposing the velocity potentials within the porous structure and avoided the use of the complex dispersion relation within the porous medium which are commonly used in the classical method (as in Dalrymple et al. [10]). On the other hand, Sahoo et al. [2] investigated the trapping and generation of surface waves by thin partial porous barriers in finite water depth. Koley et al. [17] studied the oblique wave trapping by partial porous structures of finite width kept near a wall in a homogeneous fluid medium using boundary element method and compared the results with the solution obtained using eigenfunction expansion method. The advantage of the boundary element method used in the paper is that it does not require the determination of the complex dispersion relation within the porous medium. Further, the boundary element method is free of structures with special regular shapes, such as rectangular bars or circular cylinders, whilst the analytic methods only work for rectangular or circular bars. Most of these studies are related to wave-structure interaction problems in homogeneous fluid medium having a free surface.

However, due to solar heating or mixing of fresh river water with salty water in the estuary regions, density stratifications are observed at various locations in the coastal areas. In many situations, often the fluid is idealized as a two-layer fluid by considering the upper lighter fluid of density ρ_1 is lying on the top of the heavier fluid of density ρ_2. Various aspects of wave motion in a two-layer fluid medium separated by a common interface with the upper fluid having a free surface is discussed in Lamb [18] and Wehausen and Laitone [19]. Ten and Kashiwagi [20] pointed out various cases associated with ship motion in which the viscosity effect can be neglected and the stratified fluid can be modeled as a two-layer fluid having a free surface and interface. Apart from waves in surface modes, waves in internal mode carry huge amount of energy and can seriously damage ocean structures (see Yuan et al. [21]). In case of wave motion in two-layer fluid, two propagating waves exist in surface and internal modes. The mutual interaction of these waves with ocean structures is an interesting branch of study and is likely to be of significant importance in ocean engineering. Barthélemy et al. [22] studied the scattering of surface waves by a step bottom in a two-layer fluid. Linton and McIver [23] developed a general theory for a two-dimensional wave scattering by the horizontal cylinders in an infinitely deep two-layer fluid and calculated the amount of energy that was converted from one wave number to the other for the case of circular cylinders in either the upper or lower fluid layer. Sherief et al. [24] studied the axisymmetric forced motion produced by a vertical cylindrical porous wave maker immersed vertically in two-layer fluid. Manam and Sahoo [25] used a generalized orthogonal relation to study wave scattering by porous structures in a two-layer fluid. Kashiwagi et al. [26] analyzed the wave diffraction by a floating body and relevant wave-induced motion in a two-layer fluid using boundary element method. Kumar et al. [27] studied the scattering of surface and internal waves by partial rectangular dykes in a two-layer fluid. Behera and Sahoo [28] studied gravity wave interaction with thick porous structures of various configurations in two-layer fluid in which the porous structures are extended from the free surface till the bottom. Both the cases of wave scattering and trapping by porous structures of various configurations are analyzed. Behera et al. [3] studied the oblique wave trapping by partial porous and flexible structures kept near a rigid wall in two-layer fluid using least square approximation method. However, to the authors knowledge, there is no study in the literature to analyze wave interaction with thick partial porous barriers in two-layer fluid having free surface and interface.

In the present paper, both the cases of oblique wave (i) scattering by partial porous structures and (ii) trapping by partial porous structure near a rigid wall are analyzed in two-layer fluid under the small amplitude water wave theory in water of finite depth. In the present study, the porous structures are assumed to be of finite width. Further, both the cases of interface piercing and interface non-piercing structures are considered in the present study. Using the eigenfunction expansion method, system of equations are obtained for the determination of various hydrodynamic quantities of interest. Further, the results are obtained using boundary element method and compared with the analytic results based on the eigenfunction expansion method. The efficiency of the porous structure in creating a tranquility zone and reducing the wave height is analyzed by studying the reflection and transmission coefficients for waves in surface and internal modes in case of wave scattering by partial porous structures. On the other hand, the role of the porous structure in trapping the incident waves is studied by analyzing the reflection coefficient, free surface and interface elevations and forces acting on the porous structure and the rigid wall in different cases. The present study is assumed to be significant help in the development of cost-effective wave attenuation system for protecting various coastal facilities.

2. Wave scattering by partial porous structures

In this section, scattering of surface gravity waves by partial porous structures are investigated in two-layer fluid having a free surface and an interface in water of depth H. The upper fluid of density ρ_1 has a free surface at $z=0$ occupies the region $-h<z<0, -\infty<x,y<\infty$ whilst, the lower fluid of density ρ_2 occupies the region $-H<z<-h, -\infty<x,y<\infty$ with $z=-h$ being the mean interface and $\rho_1<\rho_2$. The flow field is divided into four regions as in Fig. 1(a) and (b). The notations L_b and L_g represent the structural length and gap along the depth of the structure respectively with b being the width of the porous structure. For the bottom-standing structure as in Fig. 1(a), $L_b=(-H\le z\le -H+a)$ and $L_g=(-H+a\le z\le 0)$, whilst for the surface-piercing structure as in Fig. 1(b), $L_b=(-a\le z\le 0)$ and $L_g=(-H\le z\le -a)$ where a is the height of the porous structure. Further, the submerged interface of the structure is denoted as $L_w=(0\le x\le b)$ with $z=-H+a$ for the bottom-standing structure and $z=-a$ for the surface-piercing structure. The fluid is assumed to be inviscid and incompressible, the flow is irrotational and simple harmonic in nature with angular frequency ω out side and inside of