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Hydroelastic analysis of gravity wave interaction with submerged horizontal flexible porous plate

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ABSTRACT

The present study deals with the surface gravity wave interaction with submerged horizontal flexible porous plate under the assumption of small amplitude water wave theory and structural response. The flexible porous plate is modeled using the thin plate theory and wave past porous structure is based on the generalized porous wavemaker theory. The wave characteristics due to the interaction of gravity waves with submerged flexible porous structure are studied by analyzing the complex dispersion relation using contour plots. Three different problems such as (i) wave scattering by a submerged flexible porous plate, (ii) wave trapping by submerged flexible porous plate placed at a finite distance from a rigid wall and (iii) wave reflection by a rigid wall in the presence of a submerged flexible porous plate are analyzed. The role of flexible porous plate in attenuating wave height and creating a tranquility zone is studied by analyzing the reflection, transmission and dissipation coefficients for various wave and structural parameters such as angle of incidence, depth of submergence, plate length, compression force and structural flexibility. In the case of wave trapping, the optimum distance between the porous plate and rigid wall for wave reflection is analyzed in different cases. In addition, effects of various physical parameters on free surface elevation, plate deflection, wave load on the plate and rigid wall are studied. The present approach can be extended to deal with acoustic wave interaction with flexible porous plates.

1. Introduction

In the last decades, there is a significant study on wave interaction with submerged structures for wave attenuation in the marine environment. Unlike the case of attenuation of surface waves with the help of vertical breakwaters leading to large wave loading on the structure and blockage of current, the submerged horizontal breakwater does not block the incoming waves and can be properly tuned for attenuating the wave height. Further, the horizontal submerged structures do not hamper the sea scape. The interaction of surface waves passing over and beneath the plate creates a phase difference which when interacts with the incoming waves leads to the destructive interference of the waves. Apart from the destructive interference of the waves through phase change, the use of perforated structures helps in dissipating a large portion of the wave energy and flexible structures provide the additional feature of wave attenuation through structural

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deformation compared to a rigid structure. Further, flexible structures are light in weight, cost-effective, reusable and environmental friendly compared to its rigid counter parts.

The study on surface gravity wave interaction with submerged plate started since Heins (1950). Heins (1950) studied the gravity wave interaction with a finite submerged plate in finite water depth using Wiener–Hopf technique and using Green's identity derived explicit relations for the reflection and transmission coefficients. Burke (1964) studied the interaction of surface waves by a submerged horizontal barrier in infinite water depth and reproduced the results for wave scattering by semi-infinite barrier and finite dock as limiting cases. The effective use of submerged horizontal structure for wave control in the coastal region started since Ijima et al. (1970). Using matched asymptotic expansion method, Siew and Hurley (1977) analyzed gravity wave scattering by a submerged horizontal plate in shallow water. Patarapanich (1984) analyzed the reflection characteristics of a submerged horizontal plate from deep to shallow-water limits. Wu et al. (1998) studied the wave reflection by a vertical wall with a submerged horizontal porous plate using the eigenfunction expansion method. Yu (2002) reviewed the performance of a submerged and essentially horizontal plate for offshore wave control.

Cho and Kim (2008) developed a wave absorbing system using inclined submerged horizontal perforated plates with a vertical wall which is based on linear potential theory and Darcy's law for flow past porous structure. The theoretical model is examined using matched eigenfunction expansion method and validated via boundary-integral equation method. Further, the theoretical and computational results are verified through full-scale experiments. Liu and Li (2011) studied the gravity wave motion over an offshore submerged horizontal porous-plate breakwater under the assumption of linear potential theory using matched eigenfunction-expansion method. Evans and Peter (2010) analyzed the gravity wave interaction with a submerged semi-infinite porous plate by Wiener–Hopf technique and finite porous plate by using the residue-calculus technique in water of finite depth under the assumption of linear water-wave theory. Hu and Wang (2005) analyzed the wave past a combined submerged horizontal plate and a vertical porous wall, and demonstrated that a suitable combination of the submerged plate and the vertical porous wall can effectively reduce wave transmission. Further, the study on suitable arrangements of submerged porous plates can be found in Liu et al. (2007) and the literature cited therein.

On the other hand, Cho and Kim (1998) studied the oblique wave interaction with submerged horizontal flexible membrane using the boundary element method and eigenfunction expansion method. Later, Cho and Kim (2000) studied the wave diffraction by submerged porous flexible membrane using eigenfunction expansion method for understanding the relevant physics and compared the solution with the one derived based on boundary integral equation method. In both the cases, the analytical and numerical results were supported by experimental validations. In all these studies, mode expansion method is used for the structural component whilst eigenfunction expansion method is used for the fluid part. Appropriate matching conditions are applied to obtain the unknowns in the expansion method. In these problems, the fluid and structures are treated separately. On the other hand, Hassan et al. (2009) analyzed the surface wave interaction with submerged flexible plates of finite and semi-infinite length in two-dimensional as well as the three-dimensional problem involving a circular plate using a direct method. In the direct method, the dynamic and kinematic conditions at the interface of the submerged plate are combined together and the physical problem is converted into a boundary value problem associated with Laplace equations satisfying certain higher order boundary conditions on the structural boundary (as in Fox and Squire, 1994; Manam et al., 2006; Kohout et al., 2007). Recently, Williams and Meylan (2012) analyzed the surface wave interaction with semi-infinite submerged elastic plate using Wiener–Hopf technique.

In the present study, a general mathematical condition on the submerged flexible porous plate is derived by combining the dynamic and kinematic conditions on the fluid–structure interface under the assumption of small amplitude water wave theory and structural response. Here, the kinematic and dynamic conditions on the submerged perforated flexible structure are combined together as in Hassan et al. (2009) to derive the combined condition on the submerged flexible porous plate. Three physical problems, such as oblique wave (i) scattering by a submerged flexible porous plate, (ii) trapping by a submerged flexible porous plate near a rigid wall and (iii) reflection by a wall in the presence of a submerged flexible porous plate, are studied in finite water depth. Numerical results associated with wave scattering by flexible plate having free, simply supported and clamped edge are compared and most of the results are analyzed for plate having fixed edges. Characteristics of the gravity wave interaction with the flexible perforated plate is studied by analyzing the roots of the complex dispersion relation which are computed using contour plots. Using the orthogonal property of the vertical eigenfunctions of the open water region and matching the velocity and pressure at interface boundaries, a linear system of equations is derived to determine the unknown constants in the velocity potentials. Various numerical results are computed to understand the effectiveness of the submerged flexible porous plate in dissipating wave energy and creating a tranquility zone.

2. Wave scattering by horizontal flexible porous plate

In this section, oblique wave scattering by submerged horizontal flexible porous plate is investigated. Under the assumption of the linearized water wave theory and small amplitude structural response, the problem is considered in three dimensional Cartesian co-ordinate system with x and y-axis being in the horizontal direction and z-axis in the vertically downward negative direction (as in Fig. 1). A finite submerged flexible porous plate of length b is kept horizontally at $z=-h$ in water of finite depth H. The whole fluid domain is divided into four regions: regions 1, 2, 3 and 4. Assuming that the fluid is inviscid, incompressible and irrotational, the fluid motion is described by the velocity potentials $\Phi_j(x,y,z,t)$ for $j=1,2,3,4$

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