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Surface gravity wave interaction with a submerged horizontal flexible porous plate

S.C. Mohapatra[a], T. Sahoo[b], C. Guedes Soares[a,*]

[a] Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[b] Department of Ocean Engineering and Naval Architecture, Indian Institute of Technology Kharagpur 721 302, India

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ABSTRACT

An analytical study for surface gravity wave interaction with submerged flexible porous plate based on small amplitude water wave theory and structural response is presented. The flexible porous plate is modeled based on the thin elastic plate theory and wave past porous plate is using generalized Darcy's law to incorporate both frictional force and inertia force. The dispersion relation is analyzed to determine the wave motion characteristics of two propagating wave modes in the presence of free surface and flexural waves at the submerged horizontal porous plate in specific cases. Further, the linearized long wave equation under shallow water approximation is derived in a direct manner and the limiting cases are compared. The integral forms of Green's functions are derived using the fundamental solution associated with the two-dimensional Laplace equation. Using Green's identity, the generalized expansion formulae for the wave-maker problem associated with the surface wave interaction with the submerged flexible porous plate are obtained in both the cases of finite and infinite water depths. The usefulness of the expansion formula is demonstrated by analyzing a physical problem associated with the surface gravity wave interaction with a moored finite submerged horizontal elastic porous plate in finite water depth. In the numerical results, the accuracy of the numerical computations are checked and the combined effect of mooring stiffness and porous-effect parameter are analyzed on the reflection coefficients, wave energy dissipation coefficients, and vertical forces. It is observed that the wave energy dissipation/absorption depends significantly on the mooring stiffness, porous-effect parameter, and suitable positing of the submerged plate.

1. Introduction

In recent decades, there is an increasing demand in the multi-use of floating/submerged flexible porous structures for wave energy conversion and breakwaters in order to meet the world energy demand and protection of coastal areas. The effectiveness of these structures is due to the fact that they are able to reflect, absorb, and dissipate wave energy, and are cost-effective and environmental friendly. Moreover, the use of flexible porous structure has great advantages compared to the rigid impermeable structures as the structural porosity helps in dissipating a large amount of wave energy and flexibility of the structure provide the additional feature of wave attenuation through structural (Liu and Li [1].).

Thus, these types of flexible porous structures can be explored to widen the effective analysis of parametric range for wave attenuation and coastal protection. There has been a considerable progress in the literature on the study of wave interaction with submerged structures based on analytical methods. Burke [2] investigated analytically the surface wave scattering by a submerged horizontal plate based on Green's function technique in an infinitely deep fluid. Siew and Hurley [3] employed the method of matched asymptotic expansion to obtain the first-order reflection and transmission coefficients of the problem of wave scattering by a submerged horizontal plate in shallow water. Patarapanich [4] had shown the maximum and zero reflection characteristics of a submerged horizontal plate in deep to shallow water limits depends on the plate width to the wavelength and the submergence depth ratio. McIver [5] obtained the solutions to the diffraction of water waves by a moored horizontal flat plate using the matched eigenfunction expansion method and observed that the motion response of the plate depends on the mooring stiffness. Parson and Martin [6] solved the problem of wave scattering by a submerged horizontal plate using a hyper-singular integral equation for the discontinuity in the potential across the plate and presented results on the variation of reflection coefficients with angle of inclination and depth of submergence. Hassan et al. [7] analyzed the surface wave interaction with submerged flexible plates of finite and semi-infinite length in the

* Corresponding author.
E-mail address: c.guedes.soares@centec.tecnico.ulisboa.pt (C. Guedes Soares).

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absence of compressive force in two-dimensional as well as the three-dimensional problems involving a circular plate by the method of matching. Williams and Meylan [8] presented a solution for the interaction of normally incident linear waves with a submerged semi-infinite elastic plate using Wiener-Hopf technique and residue calculus method in finite water depth. All these studies are meant for gravity wave interaction with submerged horizontal elastic plate of finite or semi-infinite length.

On the other hand, there is a significant interest in the study of wave interaction with submerged horizontal porous structures as these structures can act as effective coastal protection structures. Wu et al. [9] applied eigenfunction expansion method to analyze the porous-effect parameter on the wave loads on the plate and wave reflection by a vertical wall with a horizontal submerged porous plate and observed that the wave loads on a porous plate is smaller than the impermeable plate. Neves et al. [10] obtained the analytical solution for waves propagating through a horizontal porous plate of finite thickness by using eigenfunction expansion method and further investigated the short-wave energy and the long wave energy reduction by the porous plate. McIver [11] demonstrated the difficulties in the dispersion relation and eigenfunction expansions arising in the problems of wave interaction with porous structures. Yip et al. [12] investigated the trapping of surface waves by submerged vertical porous and flexible barriers near the end of a semi-infinitely long channel of finite depth by using matching the velocity and pressure along with edge conditions at the end points of the structure. Molin [13] proposed a hydrodynamic model of perforated or slotted structures based on theoretical assumptions to study the hydrodynamic coefficient. Liu et al. [14] studied analytically wave interaction with a submerged horizontal porous plate based on linear potential theory using eigenfunction expansion method. Further, Liu et al. [15] examined the hydrodynamic performance of a horizontal submerged plate breakwater by studying the reflection and transmission coefficients, wave forces acting on the plate based on matched eigenfunction method. Evans and Peter [16] presented the asymptotic oblique wave reflection by a semi-infinite submerged horizontal porous plate in finite water depth based on Wiener-Hopf technique and residue calculus method. Liu et al. [17] derived a new analytical solution for wave scattering by a submerged horizontal porous plate breakwater based on linear potential theory. Liu and Li [18] studied analytically the wave interaction with a submerged porous plate breakwater under linearized water wave theory using eigenfunction expansion method. Cho and Kim [19] investigated analytically the oblique wave interaction with a submerged horizontal porous plate and analyzed the reflection and transmission coefficients using eigenfunction expansion method. Behera and Sahoo [20] studied wave trapping by a submerged horizontal elastic porous plate located near a rigid wall based on matched eigenfunction method associated with non-moored submerged elastic porous plate. Recently, Mohapatra et al. [21] derived and compared the expansion formulae associated with surface gravity wave interaction with submerged flexible structures between the Green's function technique and eigenfunction expansion method in both the cases of finite and infinite water depths.

Although there has been a little progress in the literature on the surface wave interaction with submerged flexible porous plate based on linearized small amplitude theory, the investigations of the effect of porous-effect parameter and associated plate parameters on phase and group velocities associated with the linearized dispersion relation in both the cases of deep and shallow water depths has not analyzed to the best of the knowledge of the authors till date. Furthermore, although the method is not new, but the derived expansion formulae in the presence of porous-effect parameter based on Green's function in finite and infinite water depths and the application of expansion formulae are new to the present study. Therefore, in the present study, characteristics of the two propagating modes due to the presence of the free surface and submerged flexural waves are studied by analyzing the complex dispersion relation in specific cases. Moreover the linearized long wave equations are derived and the results are compared with the results obtained using small amplitude wave theory. The Green's functions associated with wave interaction with submerged elastic porous plate are derived using the fundamental source potentials associated with the two-dimensional Laplace equation in both the cases of finite and infinite water depths. Using the derived Green's functions along with Green's identity, expansion formulae for the velocity potentials associated with the interaction of surface wave with a submerged horizontal elastic porous plate are derived in both the cases of water of finite and infinite depths.

As an application of the expansion formula, surface gravity wave interaction with a moored finite submerged elastic porous plate is formulated and their solution procedure are presented under the consideration of geometrical symmetry of the boundary value problem (BVP) using the matched eigenfunction expansion method. The accuracy of the numerical computation for different mooring stiffness and porous-effect parameter is checked. The combined effect of mooring stiffness and porous-effect parameter of submerged elastic plate are analyzed from the computed results on reflection coefficient, wave energy dissipation, and vertical force in different cases. It is observed that the wave energy dissipation/absorption by the submerged horizontal elastic porous plate depends strongly on the mooring stiffness, porous-effect parameter, and suitable positing of the submerged plate.

2. Mathematical formulation

The present problem is considered in two-dimensional Cartesian coordinate system with x-axis being in the horizontal direction and y-axis being in the vertically downward positive direction. An infinitely horizontal flexible porous plate is submerged at $y = h$ in the fluid domain with $y = 0$ being the mean free surface. The fluid occupy the region $0 < y < h, -\infty < x < \infty, h < y < H$ in case of finite water depth and $-\infty < x < \infty, h < y < \infty$ in case of infinite water depth (as in Fig. 1). It is assumed that the fluid is inviscid, incompressible, motion is irrotational and simple harmonic in time with angular frequency ω. Thus, the fluid motion is described by the velocity potential $\Phi(x, y, t)$ of the form $\Phi(x, y, t) = \mathrm{Re}\{\phi(x, y)e^{-i\omega t}\}$ where $\phi(x, y)$ is the spatial component of the velocity potential with Re denoting the real part. Further, it is assumed that the free surface elevation $\eta(x, t)$ and the submerged flexible porous plate deflection $\zeta(x, t)$ are of the forms $\eta(x, t) = \mathrm{Re}\{\eta(x)e^{-i\omega t}\}$ and $\zeta(x, t) = \mathrm{Re}\{\zeta(x)e^{-i\omega t}\}$ respectively. Thus, the velocity potential satisfies the two-dimensional Laplace equation as given by

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\Phi = 0 \text{ in the fluid domain,} \tag{1}$$

The linearized kinematic condition at the mean free surface is given by

$$\frac{\partial \eta}{\partial t} = \frac{\partial \Phi}{\partial y} \text{on } y = 0. \tag{2}$$

The linearized dynamic free surface boundary condition at the mean

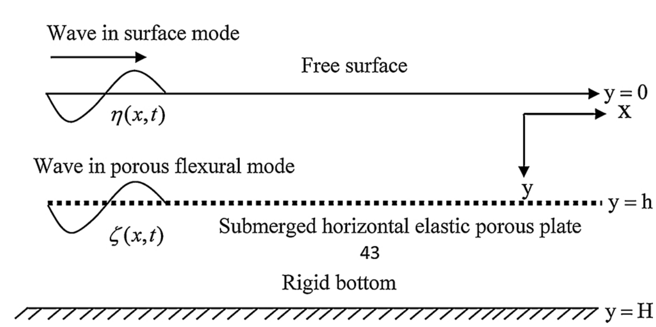

Fig. 1. Definition sketch: wave interaction with submerged flexible porous plate.