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# Oblique wave scattering by a floating elastic plate over a porous bed in single and two-layer fluid systems

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ABSTRACT

An analytical study is presented in this paper for oblique wave scattering by a floating elastic plate in a one or two-layer body of water over a porous seabed of infinite depth. The solution procedure adopted, under the assumption of small-amplitude surface waves and structural response, is the eigenfunction expansion method. The study aims to look into the interaction between oblique waves and a floating elastic plate that serves as an effective breakwater. Effects of three types of edge conditions, viz. (i) free edge, (ii) simple-supported edge, and (iii) clamped edge are analyzed. Numerical results for the reflection and transmission coefficients are computed and examined for various values of the wave, porous bed and structural parameters. Results for wave interaction with an elastic plate over a non-porous bed are obtained as special cases and compared with results available in the literature. The study reveals that for various combinations of wave and structural parameters, zero reflection and full transmission may occur in case of rigid bottom and real porous-effect parameter of the porous bed. However, for complex porous-effect parameter, zero reflection and full transmission do not occur. Moreover, due to the energy dissipation by porous bed, wave transmission decreases significantly with increase in length of the floating plate in case of complex porous-effect parameter. The results will be useful in the design of breakwaters for the protection of harbors, inlets and beaches against attacks from surface waves.

## 1. Introduction

Over the past few decades, marine floating structures have been extensively investigated, by researchers as well as practicing engineers, for a wide range of applications in ocean and coastal engineering. The main advantage of floating structures is that they allow free passage of currents, thereby avoiding undesirable problems such as sediment deposition near the structures. In particular, there has been an increasing interest in the use of flexible floating structures as breakwaters, since flexible structures may enhance wave attenuation through wave–structure interaction, and most importantly, these structures are light in weight, cost-effective, reusable and environmental friendly. A variety of mathematical techniques have been developed for wave interaction with floating or submerged structures. Various aspects of wave interaction with very large floating structures have been examined by, among many others, Fox and Squire (1994), Meylan and Squire (1996), and Chen et al. (2006). Using Fourier analysis and a newly developed inner product, Sahoo et al. (2001) studied the scattering of surface waves by a floating semi-infinite elastic plate in a two-dimensional water domain of finite depth. Meanwhile, Teng et al. (2001) applied a modified eigenfunction method to wave interaction with a semi-infinite elastic plate. Sturova (2009) developed the time-domain mode-expansion method for hydroelastic analysis of the heterogeneous plate floating on shallow water of variable depth. Oblique scattering of waves by a moored finite floating elastic plate with changes in bottom topography was recently examined by Karmakar and Soares (2012). Papathanasiou et al. (2015) developed model based on finite element method for two-dimensional problems concerning the response of large floating elastic bodies, in an inhomogeneous shallow water environment, characterized by variable bathymetry and thickness distribution. An experimental validation of theoretical models of regular-water-wave transmission through arrays of floating disks is investigated by Bennetts and Williams (2015). Moreover, the presence of thermal strain, surface friction due to wind and water flow beneath the ice are the natural sources of compressive stress on a floating ice sheet. In case of a large compressive force, buckling phenomena occurs and details of this phenomena has been studied by

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Mohanty et al. (2014) in case of flexural-gravity wave motion over rigid bed. Apart from wave interaction with floating structures, there has been a parallel interest in the problems of wave interaction with submerged structures. Hassan et al. (2009) analyzed the surface wave interaction with submerged flexible plates of finite and semi-infinite length in two- and three-dimensional fluid domains. Williams and Meylan (2012) presented an analytical study on the surface wave interaction with a semi-infinite submerged elastic plate using the Wiener-Hopf technique.

There is a sizeable body of literature on the study of full/partial (i.e., fully or partially extended across the water column) porous breakwater of finite width, using the model of Sollitt and Cross (1972). Oblique wave transmission by fully extended porous structures was studied by Dalrymple et al. (1991), followed by Losada et al. (1996) who studied wave interaction with submerged porous structures. A thorough review on wave interaction with various perforated breakwaters can be found in Huang et al. (2011). To avoid the complex dispersion relation within the porous medium, Liu and Li (2013) developed an alternative analytic solution method for wave past a porous structure. Koley et al. (2015) used a boundary element method to study wave interaction with bottom-standing submerged structures that have a perforated outer-layer and are placed on a sloping bed.

In coastal waters, density stratifications often happen as a result of solar heating or the meeting of fresh water with salty water in estuarine regions. Recently, there has been a growing interest in studying wave–structure interaction in a two-layer fluid system by considering an upper lighter fluid of density $\rho_1$ overlying a heavier fluid of density $\rho_2$. Various aspects of wave motion in a two-layer fluid have been studied by Linton and McIver (1995), Sherief et al. (2004), Kashiwagi et al. (2006), and the references cited therein. Bhattacharjee and Sahoo (2008) looked into problems of flexural gravity waves in a two-layer fluid. Xu and Lu (2010) and Lin and Lu (2013) also presented analytical models for interaction between waves and a floating elastic plate in a two-layer fluid. Recently, oblique wave interaction with flexible and porous barriers in a two-layer fluid was examined by Behera et al. (2013).

Unlike wave propagation over impermeable rigid bed, in the case of water wave propagation over a permeable seabed various dissipation mechanisms associated with the porous medium contribute to wave damping and thus transforms the wave characteristics. An enhanced coupled-mode system is developed by Belibassakis (2012) for modeling wave-induced pressure and groundwater flow in variable bathymetry coastal regions, in the layer under the permeable seabed. On the other hand, to study wave motion over a porous seabed, a special type of porous bed condition was used by Martha et al. (2007) and Maiti and Mandal (2014), in which the fluid flow within the porous bed is not taken into consideration and the porosity parameter is similar to the porous-effect parameter introduced by Yu and Chwang (1994) with the resistance effect being predominant. In this model, the rigid bed condition is replaced by a boundary condition which is assumed to be a porous bed. The bed depth is assumed to be infinitely extended. The fluid motions are such that the resulting boundary condition on the sea-bed used holds good agreement and depends on a known parameter $G$ which has a dimension of $(length)^{-1}$, called the porous-effect parameter. This assumption ensures the existence of plane wave solution that will decay otherwise at the far field in the open-water region. To the authors' knowledge, there exists no study in the literature that considers oblique wave scattering by a floating elastic plate in a single or two-layer fluid over such a seabed.

The present work aims to look into the problem of oblique wave scattering by a floating flexible plate over a porous bed as discussed above in both the cases of single and two-layer fluids with the assumption that there exist an interface in case of the two-layer fluid. It may be noted that the physical problems for single and two-layer are different from practical point of view. For example, in case of a homogeneous fluid, a single plane progressive wave will propagate due to the presence of the free surface. On the other hand, in two-layer fluid, plane progressive waves in surface and internal modes will propagate due to the presence of the free surface and interface. As a result, incident, reflected and transmitted wave characteristics in surface and internal modes are discussed in case of two-layer fluids which is not the case for homogeneous single-layer fluid. The mathematical problems are formulated under the assumption of small amplitude water wave theory and structural response. It is also assumed that the flexible plate is under the action of a uniform compressive force. Effect of three different types of edge conditions, namely, clamped edge, simply-supported edge, and free edge are analyzed in the present study. The roots of the dispersion relation in the open-water and plate-covered regions over a porous bed are analyzed using contour plots. In case of two-layer fluid, due to the presence of the interface, there exist waves modes in the surface and internal modes in both the cases of the open water region and plate covered region. Thus, in the case of two-layer fluid, the reflection and transmission coefficients exist in surface and internal modes. Moreover, in the present study, the porous-effect parameter which signifies the bed porosity is assumed to be a complex number to account for the both the inertia and resistance effects. Various numerical results for the reflection and transmission coefficients are computed and analyzed to study the effects compressive force, length of the plate, porous-effect parameter of the porous bed, oblique angle of incidence, structural rigidity of the plate, position of the interface and density ratio. The computed results are compared with those available in the literature for the special case of wave scattering by a floating elastic plate over a non-porous/porous bed in a single/two-layer fluid system.

## 2. Wave scattering by a floating elastic plate in a single-layer fluid system

In this subsection, wave scattering by a floating elastic plate over a porous bed is studied for a homogeneous fluid.

### 2.1. Mathematical formulation

Three-dimensional Cartesian coordinates are chosen wherein the $z$-axis is taken vertically downward positive into the fluid region with ($z = 0$) being the undisturbed free surface, and the $x$-$y$ plane is considered as a horizontal plane. It is assumed that a thin elastic plate having length $b$ and uniform thickness $d$ floats on the mean free surface $z = 0$ of a fluid medium of uniform density $\rho$ and water of finite depth $H$. In the present study, for dealing with more realistic physical situation in which both the resistance and inertia effects will contribute for energy dissipation by the seabed, the porous-effect parameter is assumed to be complex in nature unlike in the work of Martha et al. (2007) and Maiti and Mandal (2014) in which the porous-effect parameter was assumed to be a real number to ensure progressive wave at the far field. Moreover, in the present study, the fluid motion inside the porous bed is not considered. Since water depth is finite, only boundary condition at interface between fluid and porous bed is used to handle the physical problem under the assumption that the porous seabed is infinitely extended in the horizontal direction.

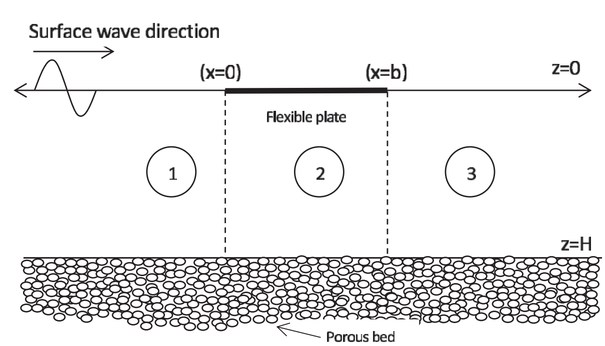


**Fig. 1.** Schematic diagram of wave scattering by floating elastic plate over a porous bed in single-layer fluid.