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Wave interaction with a submerged semicircular porous breakwater placed on a porous seabed

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ABSTRACT

In the present study, a coupled eigenfunction expansion-boundary element method is developed and used to analyze the interaction of surface gravity waves with a submerged semicircular porous breakwater placed on a porous seabed in water of finite depth. Two separate cases: (a) wave scattering by the semicircular breakwater, and (b) wave trapping by the semicircular breakwater placed near a porous sloping seawall are studied. Further, as a special case, wave trapping by a semicircular breakwater placed on a rubble mound foundation near a sloping seawall is analyzed in water of uniform depth having an impermeable bed. The wave motion through the semicircular permeable arc of the breakwater is modeled using the Darcy's law of fine pore theory, whilst the wave motion through the porous seabed, rubble mound foundation and the porous seawall are modeled using the Sollitt and Cross model. The friction coefficient defined in Sollitt and Cross model is computed by approximating the spatial dependency of the seepage velocity with the average velocity within the porous media. An algorithm for determining the friction coefficient f is provided. Various physical quantities of interests are plotted and analyzed for various values of waves and structural parameters.

1. Introduction

In recent decades, there is an increasing interests in using porous breakwaters to dissipate a major part of the incoming wave energy for the protection of marine infrastructures in ports and harbors (see Molin [28]). One such effective structure is the semi-circular caisson breakwater which was initially built at Miyazaki port, Japan in early 1990s (see Yuan and Tao [38]). Subsequently, in 1997, a very long semicircular shape breakwater was built in Tianjin port of China and a long submerged semi-circular estuary jetty was constructed in the Yangtze river estuary (see Zhang et al. [39]). Semicircular shaped breakwaters have been also constructed in the harbor of Weihai city in China (see Liu and Li [24]). These types of structures consist of two components, namely an impermeable bottom slab and an permeable semicircular arc. Generally, these types of structures are placed on a rubble mound foundation in the nearshore regions. Different designs of semicircular breakwaters have been proposed by researchers and engineers such as considering the semicircular arc as: (a) impermeable, (b) seaside permeable and leeside impermeable, and (c) both seaside and leeside are permeable in nature (see Dhinakaran et al. [9] and Teh and Venugopal [31]). One of the advantages of these types of structures is that these structures are light in weight and therefore often suitable for soft soil foundation. Moreover, these structures are highly stable against sliding and the overturning moment caused by high incoming wave impact is almost negligible. Due to the aforementioned fact, often these types of breakwaters can act as offshore-detached breakwaters. Due to the presence of the permeable semicircular arc, a major part of the incoming wave energy will be dissipated and as a result, the reflection and transmission coefficients will decrease significantly. This helps to reduce the seabed scouring in front of breakwaters. Moreover, it is effective to create a tranquility zone on the lee side of the breakwater. In general, for the construction of the semicircular breakwaters, the prefabricated caissons are brought to the site and placed on the pre-constructed rubble mound foundations.

Several theoretical and experimental investigations have been conducted by many researchers to study the hydrodynamic performances of submerged semicircular breakwaters of varied configurations. Forbes and Schwartz [10] studied the two-dimensional steady fluid flow over a semicircular obstacle based on linear wave theory and also presented a numerical scheme to deal with corresponding non-linearity. Cooker et al. [5] developed a numerical scheme to analyzed the interaction between a solitary wave and a submerged semicircular rigid cylinder. Further, experimental study is also carried out to validate the numerical results. Using a mixed Eulerian-Lagrangian

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formulation, Lowery and Liapis [27] investigated the interaction of fully non-linear free surface incompressible flow with a semicircular bottom obstruction. Dewi [6] performed a three-dimensional numerical analysis to investigate the effectiveness of a bottom-mounted, submerged and horizontal hemicylindrical flexible shell as a breakwater. In their study, several numerical results are presented and analyzed for various values of waves and structural parameters. Yuan [38] developed a numerical model based on coupled boundary element-finite difference method to study the wave loads acting on the submerged, alternately submerged and emerged semicircular breakwaters. They have validated the numerical results by comparing the same with the laboratory experimental data. In their study, a simplified formula is proposed to calculate the total wave forces on the semicircular rigid breakwaters for practical engineering purposes. Zhang [39] carried out model tests in wave basin to study the wave loads on a surface-piercing semicircular breakwater under the action of irregular waves. By solving the incompressible Navier-Stokes equation numerically, Kasem and Sasaki [15] performed a numerical simulation of the propagation of water waves over a rigid semicircular obstacles. In all the aforementioned works, the semicircular breakwaters are considered impermeable in nature. Recently, Liu et al. [25] studied Bragg reflection of water waves in the presence of multiple submerged semicircular breakwaters.

On the other hand, using the derived time dependent mild slope equation, Tsai et al. [33] studied the wave transformation over submerged permeable breakwater placed on porous seabed. By considering the arbitrary geometry and materials characteristics, Lee and Cheng [21] developed an analytical solution for the problem of wave interaction with submerged porous structures. An experimental investigation was carried out by Dhinakaran et al. [9], Dhinakaran [7] and Dhinakaran [8] to study the hydrodynamic performances of a seaside and fully perforated semicircular breakwater with varied percentage of perforation in regular and random waves. In the aforementioned studies, along with the wave run-up characteristics, various physical quantities of interests such as reflection and transmission coefficients, wave forces acting on the perforated structures etc. are calculated. Teh et al. [32] studied the hydrodynamic performance of a free-surface semicircular breakwater of different porosities in irregular waves through a series of model tests. Based on the linear potential theory of water waves, Liu and Li [23] used multipole expansion method to study the interaction of normal incident waves with a submerged perforated semicircular breakwater. The study has been further extended by Liu and Li [24] to take into account the obliqueness of the incident waves. Teh and Venugopal [31] performed model test in the wave flume to calculate the hydraulic characteristics of the perforated semicircular breakwater model with truncated wave screens under the action of irregular waves. Koley et al. [16] and Koley et al. [20] developed a coupled eigenfunction expansion-boundary element method to deal with the interaction of obliquely incident waves with thick porous structures in uniform and undulated bottom topography respectively. To deal with gravity wave interaction with thin permeable wave barriers, Koley et al. [17], Kaligatla et al. [14] and Koley and Sahoo [18] used system of Fredholm integral equation technique and the structural porosity is modeled using the Darcy's law of fine pore theory. Further, Koley and Sahoo [19] used eigenfunction expansion method as well as coupled boundary element-finite difference method to deal with gravity wave scattering by a flexible permeable vertical membrane wave barrier. Recently, Losada et al. [26] have given a detailed review of the mathematical modeling of water-wave interaction with porous coastal structures. However, there is no study available in the literature on the gravity wave interaction with submerged permeable semicircular breakwater placed on a porous seabed of arbitrary geometry.

In the present context, the interaction of normal incident surface gravity waves with a submerged semicircular porous breakwater placed on a porous seabed of arbitrary geometry is studied based on the linear potential flow theory. Two separate cases namely: (a) wave scattering by a semicircular breakwater and (b) wave trapping by a semicircular breakwater placed at a finite distance apart from a porous sloping seawall are studied. Further, as a special case, the wave trapping by a semicircular breakwater placed on a rubble mound foundation near a sloping seawall in impermeable uniform rigid bottom bed is analyzed. The associated boundary value problems are handled for solution using a coupled eigenfunction expansion-boundary element method. The flow through the perforated semicircular arc is modeled using Darcy's law of fine pore theory, and the wave past porous seabed, rubble mound foundation and the seawall are modeled using Sollitt and Cross model. Equations governing the wave induced motion through the thick and thin porous structures are rederived in which the friction coefficient in Sollitt and Cross model is computed by approximating the spatial dependency of seepage velocity with the average velocity within the porous medium. Moreover, the procedure for determining various physical parameters for flow within the porous medium are briefly reviewed and the details are discussed in the Appendix. An algorithm for determining the modified friction coefficient is provided in Section 4. The convergence of the numerical schemes has been demonstrated for certain wave and structural parameters. The proposed model is compared and validated with some of the known theoretical and experimental results available in the literature in certain limiting cases. The reflection and transmission coefficients, free surface elevations as well as wave forces acting on the breakwater, rubble mound foundation and the seawall are computed and analyzed for realistic values of wave and structural parameters to study the effectiveness of the semicircular breakwater in scattering and trapping of gravity waves. Further, the dissipation of the incoming wave energy due to the presence of permeable semicircular arc, porous seabed, rubble mound foundation and the porous seawall are analyzed.

2. Wave scattering by submerged semicircular breakwater placed on a porous seabed

In this Section, normal incident surface gravity waves scattering by a submerged semicircular porous breakwater placed on a porous seabed of arbitrary geometry is investigated under the assumption of small amplitude water wave theory. The associated boundary value problems are analyzed in the two-dimensional Cartesian coordinate system with x-axis being the horizontal axis and the z-axis is assumed to be positive in the vertically upward direction. The water of density ρ occupies the region $-\infty < x < \infty$, $-\tilde{d}(x) < z < 0$ with $\tilde{d}(x)$ represents the total bottom bed topography and the horizontal plane $z = 0$ coincides with the undisturbed mean free surface. A semicircular breakwater caisson, consists of a permeable semicircular arc of radius a with its center at $(0, -h)$ and an impermeable rigid bottom slab, placed on an undulated porous seabed which finitely extends and occupies the region $-l < x < r\,(l, r > a)$ and $-\tilde{d}(x) < z < -h$ (see Fig. 1). Beyond the porous seabed, the water depths are uniform and the bottom bed is impermeable and rigid in nature. A train of surface

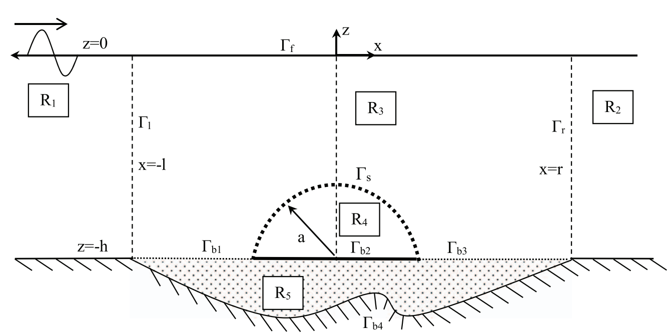

Fig. 1. Schematic diagram of perforated semicircular breakwater placed on a porous seabed.