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Modeling a solitary wave interaction with a fixed floating body using an integrated analytical–numerical approach

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ABSTRACT

This paper presents the development of an integrated analytical–numerical model to simulate a solitary wave propagating past a fixed and partially immersed body. The velocity potentials of the inner fluid region beneath the structure are determined analytically with unknown coefficients evaluated from a system of newly formulated matching equations with the uses of continuous velocity and velocity potential as well as the orthogonal properties of the eigenfunctions. For the outer region, the propagation of an incident solitary wave and its subsequent wave reflection and transmission after the wave–body interaction are modeled by solving the generalized Boussinesq (gB) equations. Time variations of the wave profiles and hydrodynamic forces for various wave and structural conditions are computed. A series of experimental measurements of wave elevations were carried out for verification of the model performance. The wave elevations obtained from the model simulations are found to agree closely with the measured data. The parametric studies were performed to examine the effects of wave amplitude, structural submergence, and structural width on the transmitted and reflected waves. An increase of structural submergence results in a decrease of the transmitted wave amplitude. Also, with an increase in structural width, the transmitted wave amplitude decreases.

1. Introduction

Study of wave and structure interaction with determined wave transformation and wave induced hydrodynamic forces is practically important to coastal and offshore engineering applications. For example, the uplift forces on a horizontal deck or other floating structures under the action of large shallow-water waves are critical to the design of coastal structures. Over the past decades, modeling propagation of linear or nonlinear waves and their interactions with structures, especially the prediction of wave loading on bottom-mounted structures, has been one of the focused topics to hydrodynamic engineers. For the study of wave interaction with partially submerged floating structures, as a result of divided flow regions in vertical direction, the approach is generally more challenging.

Using a linear diffraction solution, Isaacson (1983) studied the diffraction of solitary waves by a bottom mounted vertical cylinder. The solutions describing reflection of a planar solitary wave by a vertical wall was derived analytically by Power and Chwang (1984). Solving Boussinesq type equations numerically was commonly followed to model propagation and transformation of nonlinear shallow water waves and their interactions with structures. Along this stream of wave model development, Wu (1981) proposed a set of equations of Boussinesq class, which was called generalized Boussinesq (gB) model. Layer-mean velocity potential and free surface elevation were used as the unknown variables. The "generalized" model equations as referred by Wu (1981) can be applied to describe the spatial and temporal variations of various nonlinear long waves in two horizontal dimensions in water of variable depth. The classes of linear dispersive, linear nondispersive and nonlinear nondispersive waves are included as subsystems. The incident solitary wave solutions to Boussinesq equations were investigated by Schember (1982) and Teng (1997). Nonlinear solutions obtained from solving the gB equations for a solitary wave interacting with a bottom mounted cylindrical structure were reported by Wang et al. (1992) and later by Zhong and Wang (2008). Other studies on interaction of nonlinear shallow-water waves with bottom mounted vertical structures were given in Jiang and Wang (1995), Cooker et al. (1997), Basmat and Ziegler (1998), Wang and Ren (1998), etc. For waves propagating past a submerged structure, Seabra-Santos et al. (1987) conducted experiments to investigate the transformation of a solitary wave over a shelf and an isolated obstacle. Patarapanich and Cheong (1989) examined the reflection and transmission coefficients of regular or random waves past a submerged horizontal plate numerically and experimentally. Other linear wave solutions for wave transformation over different breakwater

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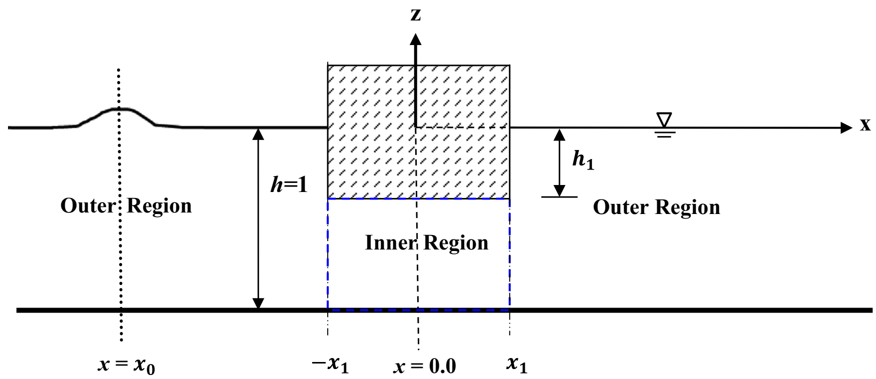

Fig. 1. Schematic diagram showing the fluid domains for an incident solitary wave approaching a floating body of rectangular section.

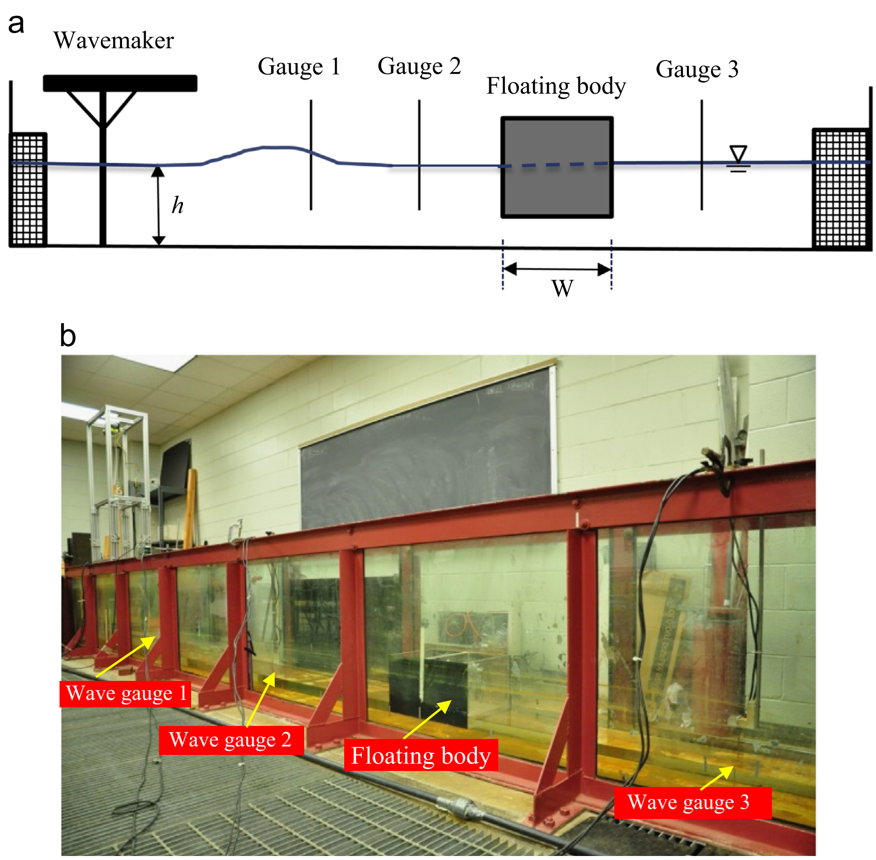

Fig. 2. (a) Experimental measurements of wave elevation for the case of an incident solitary wave propagating past a floating body of rectangular section. (b) A picture showing the setup of experiments with placed wave gauges and a floating body.

systems of submerged structures can be found in Yu and Chwang (1993), Wu et al. (1998), and Hu et al. (2002). Nwogu and Demirbilek (2006) developed a coupled Boussinesq-boundary integral method to simulate nonlinear water wave interaction with submerged porous structures in coastal region. Three-dimensional modeling of propagation and transformation of cnoidal waves through a rectangular breakwater was performed by Wang et al. (2008) using a three-equational Boussinesq model. Recently, through numerical investigation, Guerber et al. (2010) presented results on hydrodynamic interaction between nonlinear waves and a submerged moving two-dimensional circular cylinder.

Studies of nonlinear long waves interacting with structures have been mostly focused on the bottom-mounted and surface-piercing structures. As a result of extended interests on design of new types of offshore structures and protection of coastal bridge structures, the studies of interaction between nonlinear or weakly nonlinear long waves and floating structures have become increasingly important. Interactions between a solitary-wave like tsunamis with a floating elastic plate were investigated numerically by Takagi (1996). Williams et al. (2000) presented the theoretical solutions for linear waves propagating past a pair of partially restrained long floating pontoon breakwaters of rectangular section. Later, the hydrodynamic behavior of a 2-dimensional (2-D) fixed or heave motion floating body under the action of regular waves was examined numerically by Koutandos et al. (2004). Recently, Lin (2006) developed a 3-dimensional multiple-layered volume-of-fluid model to simulate solitary wave interaction with various types of structures including submerged, immersed, and floating structures. Use of the matched eigenfunction expansion method, Bhattacharjee and Soares (2011) investigated analytically