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Surface Wave Modeling in Coastal Waters

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Introduction

Coastal surface waves are critical in studying the complex marine systems and have large-scale implications on coastal engineering applications. Waves can be observed in all sizes and forms in water open to the atmosphere, depending on magnitude of the forces acting on the water [1]. Therefore, different categories of surface waves exist. One way to characterize them is based on their distinct temporal scales, associated with various generating mechanisms. For example, wind waves have a typical period of 16 seconds or smaller, which are generated locally when wind blowing over the water surface. Swells, with a period of 12-20 seconds, are waves that have traveled away from the area in which they were formed, either from a distant storm or combination of waves from different wind systems. Infragravity waves (also known as surf beat, see [1]) are long, bound waves whose period ranges from 20 seconds to the order of minutes, can be forced by either nonlinear difference interactions between short waves [2-5] or short-waves-induced radiation stresses [6,7]. Tsunami waves, in spite of its non-periodic wave form, appear to be much longer with an effective duration of 15 minutes to 1 hour; and can be induced by earthquakes or landslides in the ocean [8]. There are other types of coastal wave motion, e.g., boat wakes induced by ship motions [9,10], acoustic-gravity waves [11], storm surges due to hurricanes, capillary waves associated with surface tension, continental coastal shelfwaves produced by earth Coriolis force, (for details see [12]). In this review, we confine ourselves to surface waves in the near shore.

Usual approaches to simulate surface wave propagation fall into two categories: wave-resolving and phase-resolving models. Wave resolving models involve using Boussinesq type wave equations with modified nonlinearity and dispersion characteristics for the simulation of wave propagation, especially in shallow water regions [13-15]. A more straight forward method is to solve the Navier-Stokes equations directly with proper free surface tracking techniques, such as the volume-of-fluid (VOF) method [16] and the level-set method [17]. They have been widely applied to wave shoaling and breaking simulations in the surf zone [18-20]. One disadvantage of these methods is that they are computationally expensive therefore cannot be utilized for large-scale simulation. Furthermore, because the free surface normally crosses the computational cell arbitrarily, the pressure boundary condition is difficult to be precisely exerted on the free surface. One approach to simplify the above-mentioned method is to consider the free surface elevation as a single value function of the horizontal coordinates. Under this assumption, the free surface always stays at the upper computational boundary, therefore, can be computed by using the free surface boundary conditions. This treatment leads to a family of non-hydrostatic wave models. Different approaches to discretize the governing equations have been developed, such as finite difference method [21,22], finite element method [23] and finite volume method [24,25]. Another non-trivial problem in non-hydrostatic modeling is to simulate breaking waves in the surf zone and wave run-up in the swash region, because the numerical scheme must treat shock propagation adequately [22]. Shock-capturing schemes based on a Godunov - type approach are suitable for breaking wave simulations because they can deal with discontinuous flow. This approach has been applied to simulate breaking waves in the surf zone [24]. A state-of-the-art nonhydrostatic wave model, NHWAVE [26], also implements this approach to its numerical scheme for simulations of tsunami induced by submarine landslides [20], infragravity waves over fringing reefs [27], and solitary wave breaking over a sloping bed [8].

An alternative approach to simulate wave shoaling, refraction, diffraction, and breaking is developed by the use of phase-resolving models. They are usually more computationally-efficient and more suitable for large-scale wave-field simulation as compared with wave-resolving models, because they solve the governing equations in spectra domain. In deep water (e.g., (kh)2

0:5, where k represents the characteristic wave number and h is the local water depth), the WAM-class of models (e.g., SWAN, Booij et al.[28] WAVEWATCH III, Tolman [29]), which numerically implements the wave action equation, are able to capture bulk second order statistics (wave energy, significant wave height) relatively well. Nearshore wave transformation, however, is associated with wave over varying bathymetry therefore needs different treatment. This problem has been generally solved by the use of the Mild-Slope approximation, which assumes the depth change within one wavelength is small, i.e., Ñh=kh O(1). In the framework of the Mild-Slope approximation, waves are assumed to travel though a flat bottom locally, but have large variations across long distance. The pioneering formulation of Berkhoff [30] has been followed by extensions [31-34]. These linear wave models are insufficient because near shore waves exhibit strongly-nonlinear features. Because the nonlinear resonance condition for a single triad can be satisfied exactly in shallow water, triad interaction dominates nearshore wave-wave interaction. Unidirectional triad-interaction wave models have been developed [2,3] and extended to a directional version [35,36]. Enormous efforts have been made to include various physical processes into phase-resolving models, such as white capping, bottom friction, wave breaking [5], wave-current interaction [37,38], and so on.

In general, two approaches (wave-resolving and phase-resolving) have been implemented to cope with surface wave modeling in coastal waters. Although wave-resolving simulations usually require large computing resources, they conduct direct numerical simulation to the governing equations therefore are able to accurately simulate complicated wave phenomena. Recent development of non-hydrostatic approach with shock-capturing scheme enables the model to simulate wave breaking and run-ups in very shallow water, e.g., swash zone [22,26]. Phase-resolving models, on the other hand, are naturally suitable to simulate large-scale wave propagation due to its computational efficiency. Both deep-water and near-shore wave models have been developed for directional wave spectrum evolution. Physical effects such as windinput, white-capping, and bottom friction have improved the model performance. Future effort will focus on combining wave-resolving and phase-resolving models to integrated wave modeling systems [39-41].

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