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Non-hydrostatic finite element model for coastal wave processes

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ABSTRACT

This paper presents the application of the depth-integrated non-hydrostatic finite element model, CCHE2D-NHWAVE (Wei and Jia, 2014), for simulating several types of coastal wave processes. Specifically, the model is applied to (1) predict the swash zone hydrodynamics involving wave bore propagation, (2) resolve wave propagation, breaking, and overtopping in fringing reef environments, (3) study the vegetation effect on wave height reduction through both submerged and emergent vegetation zones using the drag force term technique, and (4) simulate tsunami wave breaking in the nearshore zone and inundation in the coastal area. Satisfactory agreement between numerical results and benchmark data shows that the non-hydrostatic model is capable of modeling a wide range of coastal wave processes. Furthermore, thanks to its simple numerical formulation, the non-hydrostatic model also demonstrates a better computation efficiency when comparing with other numerical models.

1. Introduction

In the past decades, increasing emphasis has been placed on the coastal wave process because of the rapid development of the coastal area and the tremendous impact of natural hazards (e.g., storm surge and tsunamis). Accurate prediction of wave and hydrodynamic processes in the coastal zone is essential to investigate coastal morphology, protect coastal structures, and mitigate coastal hazards. With the increment of our understanding about wave mechanics and the advancement of computer science and technology, the numerical model has become more and more popular for simulating nonlinear and dispersive wave propagation from deep water to shallow water.

Nonlinear shallow water (NLSW) equations have been widely used for simulating different kinds of wave processes owing to their simplicity. In particular, they are well suitable to simulate the so-called long waves (e.g., tide and tsunami wave) (e.g., Titov and Synolakis, 1998; Wei et al., 2006). In addition, NLSW equations with appropriate conservation properties are able to ensure accurate results for large gradient flows over rapidly varying topography (Stelling and Duinmeijer, 2003), so they could also be applied to the shallow water region from the surf zone to the shore. However, due to the lack of frequency dispersion, NLSW equations are not applicable for modeling waves in deep water.

With the rapid expansion of computer power, there has been a trend to solve the three-dimensional (3D) Reynolds–averaged Navier–Stokes (RANS) equations for water waves (e.g., Higuera et al., 2013; Hsiao and Lin, 2010, among others). With various free surface tracking methods, the free surface elevation could be accurately captured by the RANS model. This property makes the RANS model capable of simulating the 3D wave breaking process and detailed wave–structure interaction. In addition to the RANS model, the mesh-free Lagrangian method of Smoothed Particle Hydrodynamics (SPH) also demonstrates a good capability to resolve wave breaking and wave–structure interaction (e.g., Dalrymple and Rogers, 2006). Furthermore, both approaches are able to simulate the flow turbulence in an elaborate way. Although RANS and SPH models are valuable to simulate coastal waves on a small scale, it is still very challenging to apply them to the real-life coastal wave process because of their high computational cost.

In coastal engineering practice, several simplified but practical approaches are widely used to simulate the dispersive waves. Built upon the linear wave theory, the mild-slope equation (e.g., Berkhoff, 1976) describes the combined effects of diffraction and refraction for monochromatic wave propagation by assuming the water depth varies slowly over a wave length (i.e., $|\nabla h|/kh \le 1$, here ∇ is the horizontal gradient operator, h is the water depth, and k is the wave number). This equation is useful and accurate for predicting reflection from depth transitions having slopes up to 1:3 (Booij, 1983). Continuous efforts have been made to extend the mild-slope equation to account for substantial depth variation (e.g., Suh et al., 1997), random waves, and wave breaking (Kubo et al., 1992). However, it is rare to apply the elliptic-type mild-slope equation in the swash zone, as one encounters the difficulty of specifying boundary conditions along the

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shoreline, which are essential for solving the elliptic equation (Liu and Losada, 2002).

Another popular approach for modeling wave transformation from deep water to shallow water is to solve Boussinesq-type equations. The classical Boussinesq equations of Peregrine (1967) lay the foundation for several well-known Bounssinesq-type equations used today. In general, improvements have been obtained to alleviate, if not eliminate, the restrictions of weak dispersion and weak nonlinearity. To increase the frequency dispersion, the classical Boussinesq equations could be extended by either adding a third-order term to consider the dispersion in deep water (Madsen et al., 1991) or using the velocity at a reference depth instead of the depth-integrated velocity (Nwogu, 1993). In addition, use of high-order terms (e.g., Madsen et al., 2002) and multiple layers (Lynett and Liu, 2004) in Boussinesq-type models could also improve the frequency dispersion approximation. Meanwhile, the so-called highly or fully nonlinear Boussinesq-type equations have also been derived in various ways (e.g., Madsen et al., 2003; Wei et al., 1995). Recent research of Boussinesq-type models focuses on development of the shock-capturing capability by locally switching back to the NLSW model and treating the wave breaking with a shock-capturing numerical scheme (e.g., Roeber et al., 2010; Shi et al., 2012, among others). However, Boussinesq-type models still suffer from some well-known issues, e.g., complicated numerical discretization, use of an extra dissipation term for energy dissipation due to wave breaking, and complex wetting and drying algorithm due to the high-order dispersive terms.

A relatively new approach for modeling water waves is the so-called non-hydrostatic method. The non-hydrostatic model still makes use of the RANS equations, and it explicitly utilizes non-hydrostatic pressure to describe the vertical acceleration of flows (Casulli and Stelling, 1998). The distinction between the non-hydrostatic model and the aforementioned RANS models is that the former tracks the free surface elevation using a single value function in terms of horizontal coordinates. As a result, it requires much fewer vertical grids than those of free surface tracking methods. This improvement makes the non-hydrostatic method particularly attractive to the large-scale coastal wave process in terms of computation efficiency. With the zero non-hydrostatic pressure boundary condition accurately specified at the free surface using an edge-based compact difference scheme, the non-hydrostatic model is able to predict the short wave propagation with only one or two vertical layers (Stelling and Zijlema, 2003). To deal with wave breaking, the non-hydrostatic method treats it as a hydraulic jump and is able to predict correct free surface elevation after the breaking process by ensuring mass and momentum conservation (e.g., Zijlema and Stelling, 2008; Zijlema et al., 2011). Furthermore, the transition of the steep front of a breaking wave into a bore-like shape could also be facilitated by locally switching the non-hydrostatic model into a hydrostatic model (Smit et al., 2013). In the past decade there have been several non-hydrostatic models reported in the literature; see, e.g., the depth-integrated finite difference non-hydrostatic model of NEOWAVE (Yamazaki et al., 2008), the open-source non-hydrostatic wave-flow model of SWASH (Zijlema et al., 2011), and the σ-coordinate based Godunov-type finite volume non-hydrostatic model of NHWAVE (Ma et al., 2012). Because of the simplicity and efficiency of non-hydrostatic model, it has gained more and more attention in coastal wave modeling community. See recent work of Ma et al. (2013), Rijnsdorp et al. (2014), and Smit et al. (2014), among many others.

Recently, we incorporated the non-hydrostatic method into an existing finite element free surface flow model, CCHE2D (Jia and Wang, 1999, 2001; Jia et al., 2002), and developed a depth-integrated non-hydrostatic model, CCHE2D-NHWAVE (Wei and Jia, 2013, 2014), which solves the conservation form of NLSW equations with the non-hydrostatic pressure to account for the dispersion, and together with a depth-integrated vertical momentum equation. By ensuring the momentum is conserved at the discretized level and developing a simple but efficient wetting and drying algorithm by considering global mass conservation, the model has demonstrated a good capability to simulate a wide range of nearshore wave processes, including propagation, breaking, and run-up of nonlinear dispersive waves by validation against analytical solutions and benchmark experimental data. In this study, continuous effort is made to enhance and apply the model to address several types of more challenging coastal wave processes which are widely encountered in engineering practice. The selected four benchmark tests cover topics involve different wave phenomena (e.g., wave propagation, breaking, and run-up), different coastal areas (e.g., the surf zone, the swash zone, and fringing reef environments), and different periods of waves (e.g., short waves and long waves). Consequently, the model can be carefully evaluated from different aspects. Furthermore, for each of the topics considered, two scenarios or conditions are provided to confirm the robustness and the flexibility of the model, and we also show the superiority of the non-hydrostatic model over other models in modeling coastal waves through these numerical experiments.

In the following sections, we first briefly review the numerical formulation of CCHE2D-NHWAVE, and then we present numerical investigations of four types of coastal wave processes using the model. Each of the four sections is structured as follows. A brief introduction presenting the importance of the physical process analyzed is given first. Then the physical experiment and numerical model setup is described. Next, the numerical results are presented and compared with existing experimental data. Finally, a short conclusion is drawn for the test case.

2. Numerical model

CCHE2D-NHWAVE was developed on the basis of an existing finite element free surface flow model that solves the NLSW equtions (Jia and Wang, 1999, 2001; Jia et al., 2002). The newly developed wave module decomposes the total pressure into hydrostatic and non-hydrostatic components, and it utilizes extra non-hydrostatic pressure terms and a depth-integrated vertical momentum equation to account for weakly dispersive waves (Wei and Jia, 2014). Although the readers can refer to Wei and Jia (2014) for the governing equations of CCHE2D-NHWAVE, we briefly review them here to make this work self-explanatory. In a Cartesian coordinate system the computation domain is vertically bounded by the free surface elevation $\eta(x, y, t)$ and the bed elevation $\zeta(x, y)$, and the governing equations are given by:

$$\frac{\partial \eta}{\partial t}+\frac{\partial (HU)}{\partial x}+\frac{\partial (HV)}{\partial y}=0 \tag{1}$$

$$\begin{aligned}H\frac{\partial U}{\partial t}+\frac{\partial (HUU)}{\partial x}-U\frac{\partial (HU)}{\partial x}+\frac{\partial (HUV)}{\partial y}-U\frac{\partial (HV)}{\partial y}= \\ -gH\frac{\partial \eta}{\partial x}-\frac{1}{2\rho}\left(H\frac{\partial q}{\partial x}+q\left(\frac{\partial \eta}{\partial x}+\frac{\partial \zeta}{\partial x}\right)\right) \\ -\frac{gn^2U}{H^{1/3}}\sqrt{U^2+V^2}+\left(\frac{\partial (HT_{xx})}{\partial x}+\frac{\partial \left(HT_{xy}\right)}{\partial y}\right)\end{aligned} \tag{2}$$

$$\begin{aligned}H\frac{\partial V}{\partial t}+\frac{\partial (HUV)}{\partial x}-V\frac{\partial (HU)}{\partial x}+\frac{\partial (HVV)}{\partial y}-V\frac{\partial (HV)}{\partial y}= \\ -gH\frac{\partial \eta}{\partial y}-\frac{1}{2\rho}\left(H\frac{\partial q}{\partial y}+q\left(\frac{\partial \eta}{\partial y}+\frac{\partial \zeta}{\partial y}\right)\right) \\ -\frac{gn^2V}{H^{1/3}}\sqrt{U^2+V^2}+\left(\frac{\partial \left(HT_{yx}\right)}{\partial x}+\frac{\partial \left(HT_{yy}\right)}{\partial y}\right)\end{aligned} \tag{3}$$

$$\frac{DW}{Dt}=\frac{q}{\rho H} \tag{4}$$

where t is the time; U, V, and W are the depth-integrated velocity components in the x, y, and z directions, respectively; the water depth is