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Efficient computation of coastal waves using a depth-integrated, non-hydrostatic model

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ABSTRACT

An efficient two-dimensional, depth-integrated, and non-hydrostatic model for coastal waves over varying bathymetries is presented. Through the fractional step procedure, the governing equations are decomposed into hydrostatic and non-hydrostatic parts. The hydrostatic parts are the nonlinear shallow water equations, which are handled using a high resolution Godunov-type finite volume scheme that handles breaking waves efficiently. To enhance the robustness of the model, a central upwind flux evaluation, a well-balanced non-negative water depth construction, and an implicit bottom friction are incorporated. The non-hydrostatic part is treated using a finite difference approach. A new wave breaking approximation is proposed, which is simple, easy to implement, and does not require identifying individual wave fronts. The resulting numerical code is particularly efficient and robust computationally. Numerous numerical validations, which involve one- and two-dimensional cases for both non-breaking and breaking waves, are performed to demonstrate the capability of the model to handle wave propagation, wave breaking, and wet–dry fronts over complex bathymetries.

1. Introduction

Over the past decade, continuous efforts have focused on developing a non-hydrostatic free surface model for simulating water waves. Notable models include the three-dimensional non-hydrostatic model (Young and Wu, 2010; Ai et al., 2011; Zijlema et al., 2011; Choi and Yuan, 2012; Ma et al., 2012; Smit et al., 2014; Bradford, 2014) and the depth-integrated model (Zijlema and Stelling, 2008; Yamazaki et al., 2009; Bai and Cheung, 2013a; Wei and Jia, 2013), just to name a few recently published works. In addition to the rapid growth of computing power, the increasing popularity of this kind of model is mainly due to the following reasons: 1) it efficiently captures free surface elevation by defining the elevation as a single-valued function of horizontal positions (Young and Wu, 2010; Bradford, 2014); and 2) it imposes an accurate non-hydrostatic pressure on the top layer, which allows for use of a very small number of vertical layers to obtain high accuracy in dispersion (Ai et al., 2011; Ma et al., 2012). By contrast, the traditional Navier–Stokes models usually employ complicated free surface reconstruction methods (e.g., marker and cell, volume of fluid, and level set methods) and require a large number of vertical layers to reach an acceptable dispersion accuracy (Stelling and Zijlema, 2003; Wu et al., 2010).

The non-hydrostatic modeling of breaking waves is a challenge, given that the numerical scheme has to be carefully designed to adequately handle discontinuity (Zijlema and Stelling, 2008; Yamazaki et al., 2009; Ma et al., 2012). To date, only a few non-hydrostatic models have this desired feature, and most of these models are implemented according to the finite difference (FD) method using the momentum conservation scheme (Zijlema and Stelling, 2008; Yamazaki et al., 2009; Zijlema et al., 2011; Ai and Jin, 2012; Smit et al., 2014). The finite volume (FV) method is popular because of its conservation property. Thus, the question is why the FV method is not used to develop a shock-capturing non-hydrostatic model. The fractional step method provides such an approach, but this method is mainly designed for decoupling velocity and pressure in Euler or Navier–Stokes equations for efficient numerical solutions (Stansby and Zhou, 1998; Casulli and Stelling, 1998). This method decomposes the total pressure into hydrostatic and non-hydrostatic parts, with the former determined first via numerical implementation and the latter computed through a subsequent step as a hydrostatic solution corrector (Stelling and Zijlema, 2003; Ma et al., 2012). The hydrostatic parts pertain to the nonlinear shallow water (NSW) equations and many FV schemes are available (Toro 2009). This approach ensures that the hydrostatic and non-hydrostatic parts can be solved independently through different numerical methods as noted by previous researchers (e.g., Casulli and Stelling, 1998), but only a few studies follow this approach to solve the non-hydrostatic free surface model using the hybrid FD/FV scheme (Bradford, 2005, 2011, 2014; Ma et al., 2012; Fang et al., 2014). In

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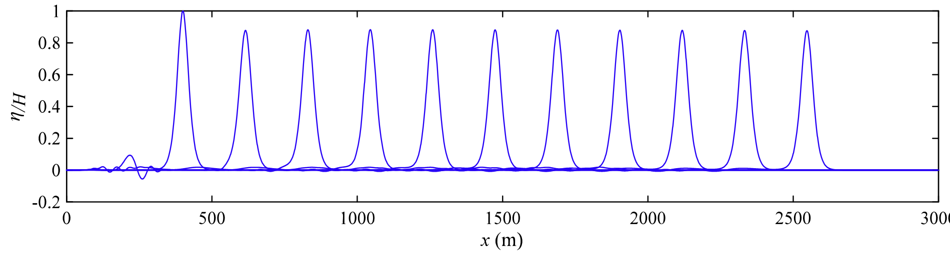

Fig. 1. Computed solitary wave profiles at $t = 0$ s to 200 s (from left to right and with a time increment of 20 s).

these models, the attractive shock-capturing property is attained by solving the hydrostatic parts (or NSW equations) through a Godunov-type FV scheme, which requires constructing a monotone numerical flux. Prior to the flux evaluation, a Riemann problem across each cell face needs to be solved at each time step, which is complex and computationally expensive. This problem is one reason why the FV method is not widely used in shock-capturing non-hydrostatic models (Zijlema and Stelling, 2008), especially for three-dimensional (3D) problems.

Wet–dry fronts are another issue that should be addressed when developing a non-hydrostatic model, which are crucial to correctly describe the moving waterline in the swash zone (Yamazaki et al., 2009; Zijlema et al., 2011; Ma et al., 2012). The capability of handling wet–dry fronts usually coexists with the shock-capturing ability, which only emerges in a few non-hydrostatic wave models (Bradford, 2005, 2011, 2014; Yamazaki et al., 2009; Ma et al., 2012; Zijlema et al., 2011; Ai and Jin, 2012; Fang et al., 2014). Wet–dry fronts need special treatment once the FV scheme is adopted to obtain the hydrostatic solution, where the solution should either satisfy the extended C-property or is well-balanced (Bermudez and Vázquez-Cendón, 1994). In the extended C-property, the model is required to precisely maintain the solution of a still water surface near wet–dry fronts at a discrete level, which is difficult. Thus, tremendous efforts have been made to achieve this goal, as shown in the recent review by Medeiros and Hagen (2013). A well-

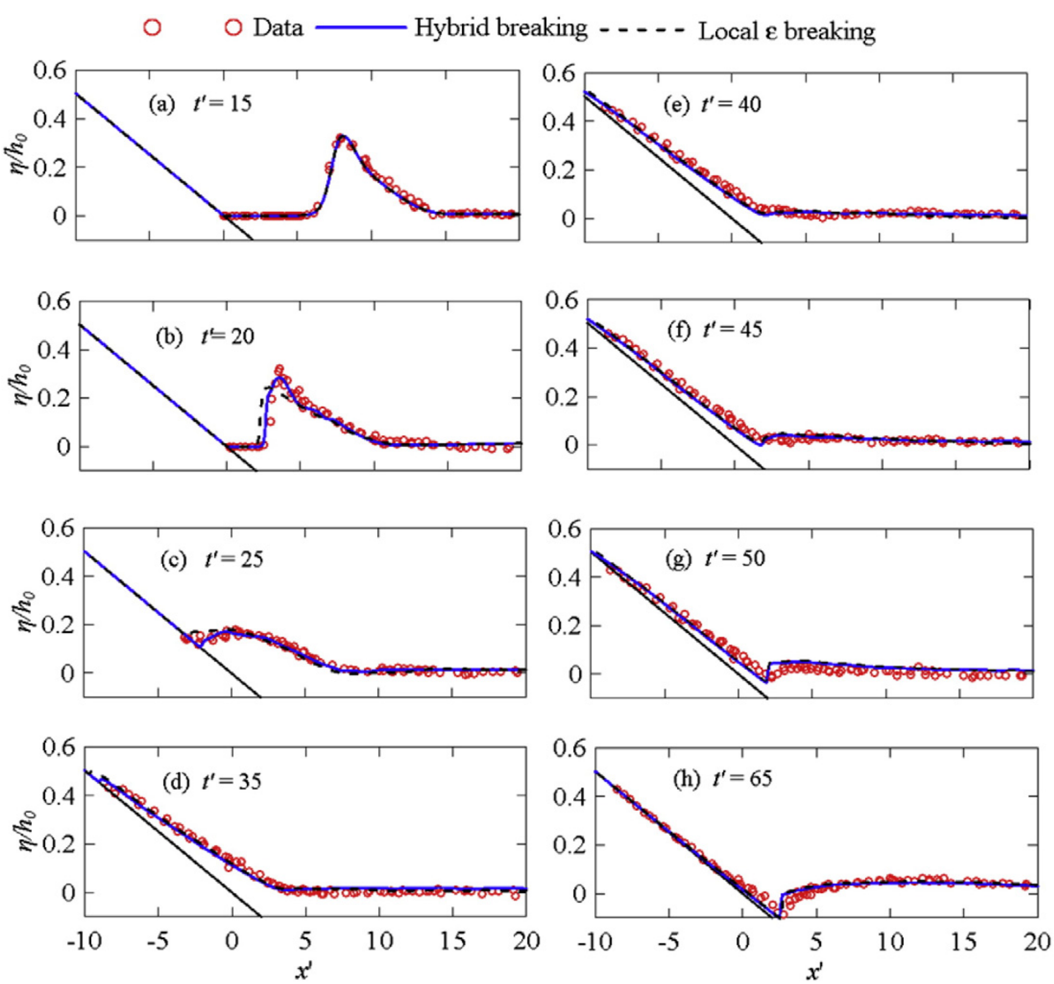

Fig. 2. Comparison between the computed and the experimental free surface elevations for solitary wave breaking, runup, and rundown at various instances on a plane beach.