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Modeling of waves overtopping and flooding in the coastal reach by a non-hydrostatic model

Jingxin Zhang[a,b,*] Hua Liu[a,b]

[a]MOE Key Laboratory of Hydrodynamics, Shanghai Jiao Tong University, Shanghai 200240, China
[b]School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

Abstract

This paper describes a model package that simulates wave transformation, overtopping and flooding in coastal reaches. The present model is extended from the non-linear shallow water equations by means of including the non-hydrostatic pressure terms in the momentum equations. The transformed vertical coordinate, i.e. the σ coordinate, is adopted to fit the free surface and the uneven bottom. When a wave is ready to break, the non-hydrostatic model is locally switched to hydrostatic model by suppressing the dispersive effects. The breaking wave front is handled as a shock, and the shock wave can be simulated by non-linear shallow water equations with conservative numerical strategy. The treatments of the wave breaking and the shoreline motion are validated by experiments. One extensive application of the model to predict flooding induced by large waves or storm surge is presented to verify the efficiency of the present model in modeling of wave transformation and flooding over complex geometry in coastal reaches.

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Keywords: wave breaking; overtopping; flooding; non-hydrostatic mode; nonlinear shallow water equation

1. Introduction

Wave transformations in surf and swash zones, and associated processes, such as wave breaking and run-up, play an important role in the dynamics, which is responsible for the sediment bar evolution in the coastal beaches[1]. Accurate and efficient numerical models are required to predict the wave dynamics, including wave height evolution

* Corresponding author. Tel.: +86-21-34208049; fax: +86-21-34208049.
E-mail address: zhangjingxin@sjtu.edu.cn

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on shoreward and the wave run-up. The wave run-up or the shoreline motion is critical for designs of water breaks, or the assesse of the damage by flooding induced by large waves, for example the tsunami, or the storm surges.

Compared to phase-averaged model, for example SWAN-type models, the phase-resolving models are of good capability in predicting details of fluid motion under waves, especially for wave overtopping and flooding. The Navier-Stokes equations with VOF method used to simulate the free surface is very powerful in simulating wave transformation over complex geometry, but the high computational demand hinders the practical applications for large scale coastal hydrodynamic study. Non-linear shallow water equations (NSW) and Boussinesq-type (BT) models are still widely used to simulate the wave dynamics in the nearshore. The earlier achievements in modeling of the wave breaking by BT models are by means of adopting an extra wave energy dissipation term in the governing equations[2-6]. Recently, a family of fully nonlinear BT model was proposed to simulate wave breaking by means of a splitting scheme[7,8]. The idea is to switch from BT to NSW when the wave is ready to break by suppressing the dispersive property because wave breaking can be described by the shock theory.

In this paper, the in-house codes HydroFlow® was developed as a 3D non-hydrostatic model. By aid of the idea of the splitting scheme used in BT models, the present non-hydrostatic mode is automatically switched to hydrostatic mode in the local wave front when wave breaking happens. Several benchmarks were used to validate the present model in the prediction of the evolution of the breaking waves. Furtherly, the model was applied to simulate flooding induced by tsunami-type waves in one specified coastal reaches.

2. Numerical method

2.1 Model description

The mathematical description of the model are composed by the mass conserved and momentum conserved equations with turbulence closure models. The vertical σ coordinate is used to fit the free surface and uneven bottom. The finite volume method (FVM) is used to discretize the equations based on unstructured meshes. The adopted TVD scheme is capable of suppressing numerical instability and handling shock waves. A collocated, predictor-corrector algorithm is used for the time integration, which is a semi-implicit scheme in time matching. The basic codes have been successfully validated[9]. In this paper, the one-equation turbulence model (SA) is adopted in the simulations.

2.2 Splitting pressure method

A predictor-corrector algorithm is adopted to solve the fully non-hydrostatic model. In the predictor step, the non-hydrostatic pressure is ignored. The temporary governing equations are degenerated to the non-linear shallow water equations, which is summarized as

$$\frac{\partial \boldsymbol{q}^*}{\partial t} = \boldsymbol{B}^n - gD\nabla\zeta^{n+1} \tag{1}$$

where $\boldsymbol{B}$ includes the explicit discretized convective and diffusion terms, g the gravitational acceleration, D the total water depth, ζ the water elevation, and $\boldsymbol{q}$ the flow rate (the supper * indicating temporary variables).

The temporary velocities solved by equation (1) can't guarantee the mass conservative limitation. The velocities need to be updated by the non-hydrostatic pressure justly ignored in the predictor step. In the second corrector step, the new updated velocities $\boldsymbol{q}^{n+1}$ induced by the non-hydrostatic pressure are formulated as Eq. (2), in which the fluid flows are marched based on the temporary variables $\boldsymbol{q}^*$ forced by the non-hydrostatic pressure p_n.

$$\frac{\partial\left(\boldsymbol{q}^{n+1} - \boldsymbol{q}^*\right)}{\partial t} = -C\nabla p_n^{n+1} \tag{2}$$

where the variable p_n is the non-hydrostatic pressure, and C is the summarized coefficient.

The above numerical method can also be taken as one kind of splitting schemes, i.e. the hydrostatic and non-hydrostatic parts being split in the predictor and corrector steps. The present numerical model can be efficiently switched between the two modes. The wave breaking simulation method used in BT models[7,8] is achieved by means of locally degenerating the BT model to nonlinear shallow water equation to suppress the wave dispersive effect in the local breaking wave front. The similar treatment in the present model can be efficiently achieved only by locally