Computers & Fluids 39 (2010) 2051–2068

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Modelling coastal barrier breaching flows with well-balanced shock-capturing technique

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ARTICLE INFO

Article history:
Received 30 April 2009
Received in revised form 27 April 2010
Accepted 26 July 2010
Available online 4 August 2010

Keywords:
Shallow water equations
Supercritical flow
Radiation stress
Storm surge
Coastal flow
Process-based Model
Finite volume method

ABSTRACT

This paper presents a coastal hydrodynamic model for simulating coastal barrier breaching flows through an inlet which are mostly induced by extreme hydrological conditions such as storm/hurricane surges, waves and tides. In order to simulate wave field and wave-induced flow field in a coast, a wave action spectral model is coupled with a hydrodynamic model. The Godunov-type shock-capturing technique is used in the hydrodynamic model to simulate the supercritical flows and shocks driven by the extreme storm conditions. The hydrodynamic model is based on the solution of depth-averaged non-linear shallow water equations with all physical forcings common to coastal hydrological conditions so that it is capable of simulating multiple flow regimes, in which subcritical, transcritical, or supercritical flows may happen. The bed slope terms in the system of equations are treated in such a way that exact balance between flux gradient and bed slope terms is achieved under still water condition. The wave model readily provides the radiation stresses that represent the shortwave-averaged forcings in a water column and take into account wave-induced nearshore currents. In the coupled system, the models are operated systematically. The coastal hydrodynamic model is shown to accurately reproduce analytical and benchmark numerical solutions. To further test the accuracy of the model, flow through a coastal inlet with a storm surge is simulated and the results are compared with an established coastal flow model. Finally, the model is examined to simulate a severe storm surge that develops supercritical flows and the results are found to be encouraging.

1. Introduction

In recent years numerical flow models have been increasingly developed and applied to simulate many free surface flows such as flood wave propagations, dam-break events, coastal and estuarine flows. Depending upon flow situations, flow regime can change from subcritical to supercritical. A number of circumstances may contribute to such an event, including dam-break, severe storm and storm surge or a tsunami. Modelling these flows is important for engineering applications and optimum design of hydraulic structures. In this paper, our primary objective is to develop a model that can solve the above mentioned phenomena using finite volume algorithm on Cartesian grids. This category of mathematical models is largely based on numerical solution of the depth-averaged two-dimensional shallow water equations.

Over time, extensive research work has been performed on simulations of supercritical flows such as dam-break and levee breaching flows by solving the non-linear shallow water equations. The shock-capturing upwind methods originally developed for Euler equations have been extended to resolve the discontinuous problems in the shallow water equations. These are, for example, Roe's method [1–3], the Beam-warming scheme [4], the monotonic upstream schemes for conservation laws (MUSCL) [5], the Osher and Salmon scheme [6], the essentially non-oscillatory (ENO) scheme and the Harten, Lax and van Leer (HLL) solver [7]. Most of these solution methods are capable of capturing shocks with high level of accuracy in few computational cells and the flux discretization is based on wave propagation structure. However, most of the resulting models have been applied to dam-break problems on flat bed or to shallow water flows of hydraulics, typically without the challenging requirements of coastal engineering problems. The irregular bottom bathymetry and effect of waves due to tide or storm surge often develop complex flow field. Such flow field may better be described by a shock-capturing flow model combined with a wave transformation model. The use of such combined flow model for coastal flow dynamics is comparatively recent and there is room for considerable improvement.

Godunov-type finite volume solvers of the shallow water equations have a shock-capturing property that is essential to preserve discontinuous or steeply varying gradients that occur in transcritical and sharp-fronted shallow flows. By upwinding the flux within the integral conservation form of the governing

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doi:10.1016/j.compfluid.2010.07.015

equations, Godunov-type methods represent physically correct propagation of information throughout the flow fields by solving sets of Riemann problems over the entire flow domain. Many Riemann solvers now exist, out of which the method due to Roe [8–10] has been widely researched. Although, Roe's Riemann solver is robust, difficulties arise in solving the Riemann problem when source terms are included in the governing equations. Essentially, a numerical imbalance is created by artificially splitting the surface gradient into flux gradient and bed slope terms in order to make the system of equations strictly hyperbolic. These terms are then evaluated by different methods at different locations within computational grids creating numerical imbalance that leads to non well-balanced scheme. Bermúdez and Vázquez-Cendón [11] proposed upwinding of the source terms to achieve equilibrium between flux gradients and source terms. Later, Vázquez-Cendón [12] modified the same idea to solve more general flow problems in the case of one-dimensional channel with longitudinal width variations. LeVeque [13] introduced a Riemann problem inside a cell to account for the propagation of source terms and the method was found to preserve both stagnant and quasi-steady state condition. Though the method is suitable for quasi-steady problems, it has been reported to be less robust when predicting steady transcritical flows that contain shocks. Burguete and García-Navarro [14] proposed conservative schemes with flux adjusted source term discretization technique using either a semi-implicit or upwinding method. Zhou et al. [15] developed the Surface Gradient Method (SGM) and pointed out that the main source of error is caused by inaccurate reconstruction of water depth. Xing and Shu [16] proposed splitting of bed slope into two terms in order to achieve exact balance. Kuiry et al. [17] proposed an analytical approach without the upwinding of the source term to deal with such imbalance, but it was implemented for triangular grids. In this work, the concept proposed by Kuiry et al. [17] is extended to Cartesian grid. This approach is also suitable for nonorthogonal grid. The modified method exactly balances flux gradient and source terms under no flow condition and maintains the conservativeness of the scheme.

Coastal flooding and inundation during hazardous storm/hurricane surges can be devastating, caused by severe coastal erosions, damage of coastal properties, structure failure and casualties. However, the mechanisms of coastal processes are highly complex due to complex hydrological and meteorological conditions driven by storm waves, surges, astronomical tides, wave-induced currents, river flood flows, etc., resulting in multiple spatial and temporal scales of water motions. Full understanding of their mechanisms and accurate prediction of the physical processes is vital for flood water management, water infrastructure protection planning and environmental impact assessment in coasts and estuaries. Because supercritical flows may be developed due to storm waves and surge tides through breached barrier islands or coastal inlets, hydrodynamic models should be capable of simulating multiple flow regimes such as subcritical, transcritical, or supercritical flows. However, most of the coastal flow models used to date without appropriate numerical techniques failed to simulate this kind of supercritical coastal flows due to extreme waves and surges during attacks of storms or hurricanes.

The wave-induced nearshore currents in a coast make flow pattern more complex. An exclusive wave model is necessary to couple with the shallow water flow model in order to simulate both the wave field and the wave-induced flow field. As far as irregular wave models are concerned, wave spectral models are more efficient than the phase-resolving wave models [18]. In the present study, a nearshore spectral wave action model (CMS-Wave) [19] available in the Surface Water Modelling System (SMS) package is systematically used with the shallow water flow model. The wave model readily provides radiation stresses that represent the shortwave-averaged forcing in a water column and take into account the effect of nearshore currents. Also, the wave model calculates the required parameters for the bed friction stress due to the combined effect of wave and current. Therefore, the systematic integration of the wave model with the hydrodynamic model helps to develop a shock-capturing coastal flow model that can simulate wave transformations and deformations together with complex flow scenarios.

The objective of this paper is to present a numerical model which is suitable for simulating flow dynamics of coastal barrier/levee breaching flows. In order to fulfill this goal a shock-capturing hydrodynamic model based on Roe's Riemann solver is combined with a steady state wave transformation and deformation model (CMS-Wave). The gravity source term in the hydrodynamic model is treated in a special way so that the scheme is well-balanced and it can simulate flows over strongly variable topographies without upwinding of the source terms. In order to examine the accuracy of the proposed model numerical and experimental tests are presented. The capability of the model to simulate subcritical and supercritical flows in coastal inlet with all the physical forcings when attacked by severe storm surge is also examined.

2. Model description

In case of coastal hydrodynamic processes, wave–current interaction is a common concern. Therefore, the effect of ambient currents on wave propagation cannot be neglected. Longuet-Higgins and Stewart [20] introduced the concept of radiation stresses and showed the existence of energy transformation between waves and currents. Therefore, the coastal hydrodynamic processes can be simulated considering wave and hydrodynamic models either in a coupled or a decoupled way. In the present study two different models are used to simulate waves and wave-induced currents, i.e. flows. The wave model is readily available in SMS package and the presently developed hydrodynamic model can be operated sequentially under the SMS interface. The wave model is a phase-averaged spectral model named as CMS-Wave [19]. This model is used to simulate wave fields and to calculate radiation stress gradients. The radiation stress gradients represent the wave forces responsible for wave-driven flow. These stress gradients are used as source terms in the wave-induced hydrodynamic model developed in the present study. A brief description of the CMS-Wave model [19] is presented below. The hydrodynamic model which is based on the solution of depth- and shortwave-averaged two-dimensional shallow water equations is described in detail in the following sections.

2.1. CMS-wave model

The CMS-Wave model [19,21] is a two-dimensional spectral wave action model. The model formulation is based on the parabolic approximation equation [22] including diffraction terms and energy dissipation due to wave breaking and bottom friction. The model simulates steady state spectral transformation of directional random waves and waves can propagate from the seaward boundary toward shore and vice versa. The CMS-Wave takes into account the effect of an ambient horizontal current or wave–current interaction and solves the wave-action balance equation as follows:

$$\frac{\partial(v_x N)}{\partial x} + \frac{\partial(v_y N)}{\partial y} + \frac{\partial(v_\theta N)}{\partial \theta} = \frac{\kappa}{2\sigma}\left[\frac{\partial}{\partial y}\left(CC_g \cos^2\theta \frac{\partial N}{\partial y}\right) - \frac{CC_g}{2}\cos^2\theta \frac{\partial^2 N}{\partial y^2}\right] - \varepsilon_b N - R \quad (1)$$

where x, y are the horizontal coordinates in two directions; $N = E(\sigma, \theta)/\sigma$ is the wave-action density to be solved and is a