NUMERICAL MODEL STUDY OF MORPHODYNAMICS OF A COASTAL INLET DUE TO STORM SURGE AND WAVE

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Abstract: This paper presents an application study of a process-based two-dimensional model with the shock-capturing capability to investigate morphodynamic changes of a coastal inlet and adjacent areas due to hazardous storm attack. Because supercritical flows may occur in an inlet channel due to surge waves, a shock capturing method is incorporated in the coastal flow model, which is integrated with the existing wave spectral and morphodynamic models. By including the radiation stresses obtained from the wave spectral model, the current model solves the two-dimensional shallow water equations explicitly using finite volume method considering the effects of Coriolis force, wind stresses, bottom irregularities and nearshore short wave actions. The integrated model is applied to study the morphology changes that take place due to a severe storm attack on a medium size idealized coastal inlet. The complex flow hydraulics and morphodynamics are successfully simulated by the present model and expected results are obtained. The simulation shows that the model can predict the development of ebb and flood shoals, scour holes and sediment deposition and erosion in the inlet channel. Through this preliminary investigation of the morphodynamics of a coastal inlet, it is found that the model is applicable to predict morphodynamic processes driven by hazardous storm surges and waves in coastal and estuarine zones.

Keywords: Shock-capturing Model, Roe scheme, Morphodynamics, Coastal inlet, Storm Surge.

Introduction

Coastal barrier/levee breaching during hazardous storm/hurricane surges can be devastating by causing flooding and inundations, severe coastline erosions, damage of coastal properties, structure failure, and casualties. However, the mechanisms of coastal barrier breaching 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 mechanism and accurate prediction of coastal barrier breaching process is vital to flood water management, water infrastructure protection planning, and environmental impact assessment in coasts. Physical or laboratory studies of breaching process may not be feasible due to huge expenditure. The cheaper alternative is the mathematical model that can simulate the physical processes with reasonable accuracy. Such models can also be used in a cost effective way comparing to physical model study to refine and optimize designs of coastal structures.

Simulation of coastal barrier breaching processes has to take into account the multi-scale water motions due to waves, tides, river flows, etc. During extreme hydrological and meteorological conditions supercritical flows may be developed through breached barrier islands or coastal inlets. Therefore, the hydrodynamic models should be capable of simulating multiple flows such as subcritical, transcritical, or supercritical. However, most of the existing

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coastal models without appropriate shock-capturing numerical techniques generally fail to simulate coastal barrier breaching flows due to extreme waves and surges attack during storms or hurricanes.

The numerical models for simulating tides and short wave-induced currents as well as short and long term morphological changes must have capabilities to represent short-period waves, long-period tides and nearshore currents with different temporal and spatial scales. Some commercially available models such as MIKE21 [1, 2], DELFT3D [3], SHORECIRC [4], CMS-M2D [5, 6] have shown some of these capabilities to deal with flows and morphodynamic changes in coasts.

In this paper, an advanced explicit finite volume flow model in two-dimensions (2D) is presented. It is for simulating flows induced by extreme conditions such as river flood flows, storm waves, surge tides, winds, etc. The model is based on the solution of the conservative form of the non-linear shallow water equations with the effects of the Coriolis force, wind stress and short wave averaged radiation stresses. The forward Euler scheme is used for the unsteady term; and the convective term is discretized using Godunov-type shock-capturing scheme along with the Roe’s approximate Riemann solver on non-uniform rectilinear grids. The hydrostatic flux is calculated using an equivalent water depth at each cell interface; and the bed slope source term is treated in such a way that exact balance between hydrostatic flux and bed slope source terms is preserved under still water condition. This model is validated carefully by simulating an experimental dam-break flow and its advance over a triangular obstacle; and then the integrated model is applied herein to investigate simulation capabilities of severe storm surge, wave-induced currents and subsequently bathymetry changes in a hypothetical coastal inlet. The inlet typically represents basic geometry and configuration of a natural inlet with offshore slope, wave and storm forcings. The numerical results correctly reproduce expected trends in hydrodynamic behaviour and morphological changes. Through the preliminary investigation, it is found that the developed model in conjunction with wave and morphodynamic process models can be used in planning for barrier island protection, flood and sediment management and shoreline stabilization.

**Model Description**

The computational model used here is developed for simulating the coastal hydrodynamic processes driven by various hydrological conditions such as tides, surges, wave-induced currents, surface wind friction, turbulence by tidal currents and wave breaking in the surf zone, the Coriolis force, etc. This coastal hydrodynamic model is implemented to support the data structures and the rectangular grid system of the coastal models in the Surface water Modeling System (SMS) [7]. In addition, the wave simulation results such as wave heights, periods, and directions, which are computed by the CMS-Wave model [8], can directly be transferred into this hydrodynamic model and the model can be run together with morphodynamic models. The hydrodynamic model for long wave tidal and shortwave-averaged longshore currents is governed by the depth- and shortwave-averaged shallow water equations in conservative form as given below.

\[
\begin{align*}
\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot (\mathbf{V} \mathbf{F}) &= \nabla \cdot \mathbf{F}^d + \mathbf{S} \\
\end{align*}
\]

where \( \mathbf{U} = [H, H_u, H_v]^T \) = vector of conserved variables; in which \( H = h + \eta \) = total water depth; \( h \) = still water depth; \( \eta \) = deviation of the water surface from the still water level (Figure 1); \( u \) and \( v \) = depth- and wave-averaged (over a period) velocities parallel to the \( x \)- and \( y \)-directions; \( \mathbf{F} = (E, G) \), \( \mathbf{F}^d = (E^d, G^d) \), wherein \( E \) and \( G \) = convective fluxes in the \( x \)- and \( y \)-directions, respectively; \( E^d \) and \( G^d \) = diffusive fluxes in the respective directions, \( \mathbf{S} \) = source terms which contain bed slope, the Coriolis term, bottom friction stresses, surface wind stresses, and radiation stresses by waves. The bottom friction stresses take into account the bottom friction forces driven by long period tidal currents and shortwave-averaged wave-induced currents. The former can be calculated by the quadratic bottom shear stresses with Manning’s roughness coefficient; the latter can be computed by Nishimura’s approximation [9] about the shortwave-averaged bottom stresses under combined currents and waves. Surface wind stresses are given by the empirical wind shear stress formulations in which the wind drag coefficient is calculated by Buttolph et al. [10]. The depth-averaged eddy viscosity coefficient is assumed to be horizontally homogeneous, which contains three parts
calculated in three different zones, i.e. deep water, surf zone, and transition zone. The wave stresses responsible for wave-induced currents are given by the gradients of wave radiation stresses, which, in the present model, are computed by the CMS-Wave model available in SMS [8]. One may refer to Kuiry et al. [11] for the detailed descriptions of the mathematical formulations.

**Numerical Solution**

The shallow water equation, Eq. (1), is discretized by cell-centered finite volume method. Each cell in the computational domain represents a control volume and the conservative variables are assumed to be stored at the cell center. In order to introduce integral form of the equations over a fixed control volume $\Omega$:

$$
\int_{\Omega} \frac{\partial U}{\partial t} d\Omega + \int_{\Omega} (\nabla \cdot F) d\Omega = \int_{\Omega} S d\Omega
$$

A discrete approximation to Eq. (2) is applied to every cell so that the volume integrals represent integrals over the area of the cell with the dependent variables represented as piecewise constants and the surface integrals represent the total flux through the cell boundary. By applying divergence theorem to the convective and diffusive flux terms, on a Cartesian grid with spacing $(\Delta x, \Delta y)$, the discrete form of Eq. (2) can be written as

$$
U^*_{i,j} = U_{i,j} - \frac{\Delta t}{\Delta x} \left( E_{i+1/2,j}^* - E_{i-1/2,j}^* \right) + \frac{\Delta t}{\Delta y} \left( G_{i,j+1/2}^* - G_{i,j-1/2}^* \right)
$$

where $n =$ time step index, the indices $i$ and $j$ locate the cell center at which the physical variables (i.e. velocities and water elevation) are defined; the index $i+1/2$ denotes the location of the cell interface at half of a cell size ($\Delta x/2$) away from the cell center. Eq. (3) is evaluated for all the cells with suitable initial and boundary conditions and the solution is advanced explicitly with respect to time. To calculate the convective flux, Roe’s Riemann solver [12] is used to develop a shock-capturing scheme to simulate supercritical flows such as dam-break flows and levee breaching flows. Since the diffusion fluxes are parabolic, play a stabilizing role in the flow movement. So the discretization is carried out in a simple way following a centered-type scheme [11].

However, the source terms need to be paid a special attention. First, the implicit treatment for a linearized bottom friction stresses is implemented so that the stability condition can be relaxed. Second, the discretization of the bed slope source terms has to be treated in a way, which satisfies a compatibility relation with the hydrostatic flux term [11]. The exact treatment of bed slope terms for triangular cell can be found in Kuiry et al. [13]. The time
The integration scheme adopted is explicit and must satisfy the stability condition so that no wave resulting at an interface can travel beyond the extent of its stencil. The stability criteria adopted is:

$$\Delta t = C_r \min \left[ \min \left( \frac{\Delta x}{u + \sqrt{gH}} \right), \min \left( \frac{\Delta y}{v + \sqrt{gH}} \right) \right]_{i,j}$$

where $C_r = \text{Courant number between zero and one}$. For the problems considered here, if not mentioned, a constant value of $C_r = 0.75$ is used.

**Boundary Conditions**

Boundaries surrounding a computational domain consist of offshore boundary, upstream river inlets, and upstream and downstream of longshore currents induced by offshore oblique wave actions. Several types of boundary conditions provided by the coastal models in SMS are also available in the present model, which are to specify tidal elevations at offshore boundary, wave-adjusted boundary condition to the upstream and downstream of longshore currents, and hydrographs at upstream river inlets. All the boundary conditions for the coastal hydrodynamic model in SMS are implemented in the present model. For the details of the boundary conditions for SMS, one may refer to [10, 6, 14]. In addition to the implementation of a wave-adjusted boundary condition, Kuiry et al. [11] found that a free outflow boundary condition is sufficient if that boundary is not subjected to any external boundary condition and the results are consistent with the interior solutions. Therefore, this free outflow boundary condition is also available for the simulation of longshore currents driven by oblique incident offshore waves.

**Model Applications**

The model is first validated with experimental results obtained from a laboratory dam break study. Then the model is applied to simulate hydrodynamic and morphodynamic responses in a hypothetical coastal inlet due to a storm surge.

**Flow over a triangular obstacle due to Dam break**

This model validation case is to simulate the dam break and flow advance over a triangular obstacle, and to compare the results with experimental data obtained from the Recherches Lab Châtelet together with the University of Bruxelles (Belgium). The channel geometry is shown in Figure 2. This experimental test case was established to investigate the dam break and flow advance over a triangular obstacle. The dam site is located at $x = 15.5m$; and the reservoir has depth of 0.75m and width of 15.5m. A triangular obstacle (6 m long, 0.4m high) is located 13m downstream the dam over the bed of the channel. The slopes of the obstacle are symmetric. The initial downstream condition is dry bed. Brufau et al. [15] reproduced this dam-break flow over the obstacle. By using the present model with exclusion of wave action effects and turbulence mixing, a 40s long dam break flow is carried out successfully, in which the time step is 0.01s. In this case, the calibrated Manning’s roughness $n = 0.00625$ is used which is slightly different from that adopted by Brufau et al. [15].

Figure 3 shows the comparisons of the water depth evolutions with time computed and measured at the gauging points: G4, G10, G13, and G20, in which the first two stations are located at the upstream of the obstacle, the third one at the peak of the obstacle, and the last one at the downstream. This figure compares the water depths computed by the present model with the measurements. For reference purpose, the numerical results by Brufau et al. [15] are also plotted in the same figure. The present model produces the results similar to those of Brufau et al. [15]. In G4, the computed results reproduced two reflective waves of the dam-break wave which are bounced back from the triangular obstacle. In G10, the computed water depths are slightly higher than the measurements. In G13, the peak of the obstacle, the computed water depths are lower than the measurements. In downstream, G20, the computed water depth by the current model is closer to the experimental observation, and is better than the results of Brufau et al. [15].
Figure 2: Geometry and gauge locations in the experimental model for simulation of dam break

Figure 3: Computed and measured water depths at different gauge points
Morphological changes due to a storm surge in a coastal inlet

The present coastal hydrodynamic model is integrated with the existing CMS-Flow models in SMS, and therefore can be operated through the SMS interface. The CMS-Flow model package provides users with two different hydrodynamic models, an explicit model [10] and an implicit model [6, 14]. These models are verified and validated and are designed to simulate coastal hydrodynamic responses to tides, waves, river inflows, surface winds, and Coriolis force. In addition, a set of sediment transport models based on empirical formulations are also available in the package [10].

To apply the present model to demonstrate the model’s capabilities of simulating supercritical flows possibly created by storm surges, waves, and/or surge tides, a hypothetical coastal inlet in a barrier island is considered in this application study. The coast is designed such that it represents the basic geometry, inlet entrance configuration, offshore slope, wave and storm forcings at a medium size inlet (Figure 4). The flow domain has a bathymetry varying from 30 m at offshore to 3 m deep at the bay.

![Figure 4: Idealized coast with initial bathymetry](image)

Initially, a M2 tide with amplitude 0.5 m is imposed at the offshore boundary and the simulation is continued for several cycles so that a suitable initial condition is developed. An irregular spectral wave with significant wave height $H_s = 3.5m$, a peak period $T_p = 9s$, and mean incident angle $= 30^\circ$ (JONSWAP spectrum) is imposed at the offshore boundary (Figure 5a). A storm surge with a peak of 10 m is imposed at the offshore boundary (Figure 5b). This surge may create a supercritical flow in the inlet channel. The other ocean boundaries are specified as free flow boundaries. The radiation stress gradients calculated from the specified wave is held constant throughout the simulation.
Figure 5: Imposed offshore boundary conditions (a) incident wave (b) storm surge

Figure 6(a) plots the flood current at 18 hr and 6(b) shows two profiles of the water elevations during flood and ebb tides respectively along a transect passing through the center of the inlet channel. In the flood tide, the water elevations drop down from 10m at offshore to 6 m at bay; in the ebb tide, the tidal elevation at offshore falls to 2.1m, and a water jump can be found outside the inlet channel. From the computed currents, it is found that the surge tide at t = 18hr is a subcritical flow, but the ebb tide at t = 24hr is a supercritical flow as the Froude number at that time is greater than 1.0 (Figure 7). In the flood tide, the longshore currents are developed due to oblique incident waves.
Figure 6: (a) Flood current at \( t = 18 \) hr due to combined surge-wave input (The arrow indicates the incident wave direction at offshore) in a hypothetical coastal inlet in a barrier island; (b) Profiles of water surface elevations during a flood and an ebb tide.

![Figure 6](image)

Figure 7: Froude number observed at 24 hrs along the longitudinal transect during ebb tide.

![Figure 7](image)

The sediment median size around the inlet and its adjacent coast is set as \( d_{50} = 0.2 \) mm. A Lund-CIRP total load sediment transport model is used to compute the sediment transport and morphological changes [10]. Figure 8 presents two pictures of computed bed elevations at the peak of the surge tide and an ebb tide after the surge tide, respectively. Due to the supercritical flows through the inlet channel induced by the surges, a large amount of sediment from offshore is conveyed through the channel. These sands are deposited in the bay and an ebb shoal inside the bay is created. During the ebb tide, the flow carries certain amount of sediments back to the offshore. This ebb current with sands create a flood shoal outside the inlet. A strong flood current induced by the surge has created a huge scour at the entrance of the inlet channel as shown in Figure 8(a). In addition, the ebb current in 8(b) has developed another scour hole at the opposite side of the inlet channel. However, the scour created by the flood tide is refilled by the sands carried from the ebb tide.
Figure 8: Computed bed elevations around the inlet (a) at t = 18 hr and (b) at t = 24 hr

Conclusions

In this paper, an advanced explicit finite volume flow model in two-dimensions is presented for simulating flows induced by extreme conditions such as river flood flows, storm waves, surge tides, winds, etc. The model is based on the solution of the conservative form of the non-linear shallow water equations and the effects of the Coriolis force, wind stress and shortwave-averaged radiation stresses are included. The forward Euler scheme is used for the unsteady term; and the convective term is discretized using Godunov-type shock capturing scheme along with the Roe’s approximate Riemann solver on non-uniform rectilinear grids. The present model was successfully validated by simulating a dam-break flow and its advance over a triangular obstacle in a laboratory flume. The model’s capabilities of simulating the supercritical flows induced by a hypothetical surge tide and storm wave in an idealized inlet at a barrier island were demonstrated. The computed flows and morphological changes due to the surge and wave conditions are physically reasonable. Further applications of the model to simulate a real barrier breaching are planned to be done in the near future. In addition, the developed model for simulating the supercritical flows under waves and tides can be used together with the coastal models available in SMS.

References


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