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Integrated Coastal and Oceanic Process Modeling and Applications to Flood and Sediment Management

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ABSTRACT

This paper presents an integrated coastal and oceanic process modeling approach and its engineering applications for simulations of flooding and sediment transport in coasts and estuaries. It is demonstrated by a case study on the assessment of long-term morphological changes driven by synthetic events (typhoons/hurricanes and monsoons) in the Danshui River estuary in Taiwan. In addition to spatiotemporal variations of detailed flow circulations in the estuary, long-term simulations of coastal and oceanic processes reveals key features of seasonal morphological changes driven by waves, tides, and river flooding flows. It shows both short-term storms and long-term monsoons are important for management of flood and sedimentation in the region.

KEY WORDS: Coastal and oceanic processes, multi-scale process modeling, long-term assessment, typhoon/hurricanes

INTRODUCTION

During hurricane/typhoon seasons, extreme physical forcing such as river floods, ocean waves, and storm surges causes hazardous flooding and inundation in low-lying lands of coastal regions. When hurricane landfall coincides with astronomical high tides, storm surge waters will inundate much wider area of the coast. High waves and strong currents can cause significant sediment transport, and eventually barrier island breaching, shoreline erosion, and navigation channel filling in inlets and estuaries. River floods also convey a great amount of sediments from upstream to river mouths and estuaries which exacerbate flood water stages in river mouths and sediment filling in navigation channels. Meanwhile, impact assessment of climate change such as sea level rise requires predictions of long-term hydrological forcing responses to sea level changes on a regional (e.g. the Gulf of Mexico or the US East Coast) or global scale. For better management and planning, a holistic impact assessment of flood and sedimentation is needed to take into account spatiotemporally-varying conditions of hydrology, meteorology, and oceanography from a local coast to a regional ocean scale.

Numerical modeling of integrated coastal and oceanic processes driven by various hydrological and atmospheric forcings (e.g. astronomical tide, waves, storm surges, river flood, wind, atmospheric pressure, and rainfall) has become a useful tool for planners and decision-makers to assess socio-economic and environmental impacts of these conditions (Figure 1). Numerical simulations by using integrated coastal and oceanic process models (INTCOM) can facilitate multi-purpose engineering practice in developing coastal flood management plans, as well as designing erosion control structures by considering large-scale and long-term variations of hydrological and meteorological conditions.

Various coastal and oceanic processes of waves, currents, and sediment transport with a wide range of spatiotemporal scales can be found from deepwater to shallow water. At oceans, wind-generated surface waves are dominant, in which the scale of wave length varies from 1m to 1km. However, astronomical tidal waves have a long wave length usually with several hundred kilometers. As far as beach profile changes are concerned, significant impacts to morphological changes happen in a relatively-narrow nearshore zone. But driving forces of shoreline changes essentially include waves, currents, storm surges, sediment transport, and wind in larger coastal areas. Therefore, due to spatially-varying scales of processes, modularized process-integrated models become more effective for computing both hydrodynamic and morphodynamic processes in a long-term duration and a large region.

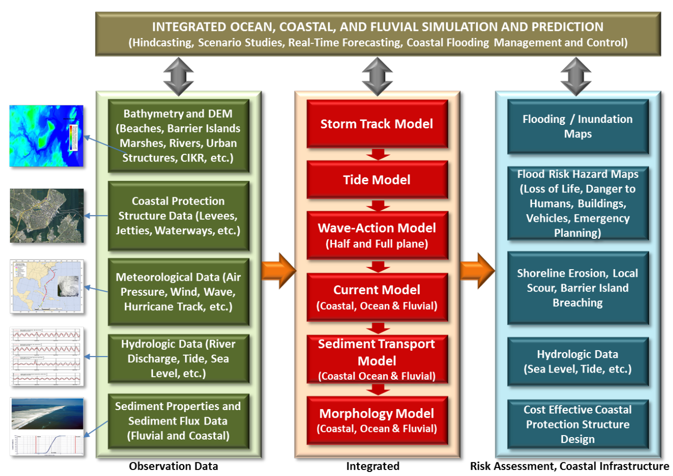

Fig. 1 Integrated coastal and oceanic process modeling (INTCOM) for analysis of flood and morphological changes in coasts and estuaries

In coastal and nearshore zones, including tidal inlets, using coastal process models, simulations of coastal morphodynamic changes and shoreline evolutions have become feasible. In general, these were accomplished by sequentially computing wave fields, flow fields, and bed elevation changes by using wave spectral (action) models, shallow water flow models with wave effects (radiation stresses), and sediment transport models. By this iterative procedure through wave-current-morphology models, it is possible to simulate the morphological process by using an empirical sediment transport model for the fine time-scale morphological process (e.g. Reniers et al. 2004). A number of application software packages are available for computing hydrodynamic and morphodynamic processes in coasts and estuaries such as DELFT3D (e.g. Roelvink 2006), MIKE21, FVCOM (Chen et al. 2006), CCHE2D-Coast (e.g. Ding et al. 2016), and Coastal Modeling System (CMS) (e.g. Sánchez et al. 2014).

Cyclone (hurricane or typhoon)-induced storm surges and high waves are the most devastating hydrological forcings to cause hazardous flooding and erosion in inlets, river mouths, and coastal zones. Generally coastal process models do not integrate modeling of storm surges and waves due to cyclonic wind and atmospheric pressure depression. A few storm surge models are available for computing hydrodynamic variables (water levels and flow velocities) using the shallow water equations, e.g. ADCIRC (Westerink et al. 1993), POM (Blumberg & Meller 1987), SLOSH (Jelesnianski et al 1992), FVCOM (Sun et al. 2013). To compute wave deformation and transformation processes from oceans to coastal areas, all the above-mentioned models need to couple with a “third-party” wave model (e.g. SWAN).

Complex and unsteady flows in coasts, inlets, river mouths, and estuaries usually induce significant temporal/spatial morphological changes in a short storm period. An INTCOM model with multi-scale simulation capability is need to access impacts of extreme hydrological events such as hurricanes, storms, high tides, and river floods.

In the following contents, an INTCOM model (Ding et al. 2016) is used as an example to demonstrate the approach for assessing long-term morphological changes in the Danshui River estuary in Taiwan. Through this case study, a procedure is presented for the assessment of the long-term impact of sediment transport by using synthetic hydrological events which include typhoons, monsoons, and river flooding flows. It demonstrates capability and efficiency of this integrated multi-scale process model to simulate coupled long-term hydrodynamic and morphodynamic processes in coasts and oceans. Spatially-varying grids are available for simulations of geometrically complex coasts, rivers, and estuaries, including interactions among structures, waters, and sediments.

BRIEF DESCRIPTION OF AN INTEGRATED COASTAL AND OCEANIC PROCESS MODEL

In this paper, an integrated river/coastal/oceanic process modeling system (Ding et al. 2016) is used as an example to describe an integrated process modeling approach for assessment and management of flooding and sedimentation in coasts and estuaries. As illustrated in Figure 1, this model integrates a number of submodels for simulating deformations and transformations of irregular/multidirectional waves, tropical cyclonic barometric pressure and wind fields along storm tracks, tidal and wave-induced currents, and morphological changes. For computing irregular waves, a multi-directional spectral wave action equation is adopted in the wave spectral module. It is capable of modeling wave deformation/transformation processes from deepwater to shallow water for nonbreaking and breaking waves, including wind-generated waves and whitecapping effects. For coastal structures, the wave model also takes into account the transmission effect of wave energy through a permeable structure (e.g. rubble mount breakwater). The current model is to simulate multi-scale hydrodynamic processes of free-surface water flows such as river flows, tidal currents, nearshore currents, and storm surges.

In the current module, the two-dimensional (2-D) depth- and shortwave- averaged shallow water equations with wave forcing are employed to simulate flows driven by wave radiation stresses, tides, storm surges, river inflows, the Coriolis force, and turbulence in surf zones, tidal zones, and ocean waters. This hydrodynamic model provides users with two options to calculate wave radiation stresses: one is the traditional wave stress formulations by means of sinusoidal wave assumption by the linear small-amplitude wave theory; another is the improved radiation stresses formulae derived from the non-sinusoidal wave assumption which enables to take into account the three-dimensional (3-D) features of vertical current structures (e.g. surface rollers or undertow currents) in the surf zone.

In the sediment transport submodel, empirical sediment transport models are used to calculate the sediment transport rates of bed materials and suspended sediment under the conditions of combined waves and currents. A unified sediment transport model (Ding & Wang 2008) is used to calculate the sediment flux from upstream rivers to estuaries and coasts to consider seamlessly the sediment transport from a non-wave environment at a river, to a wave-current interaction area at an estuary and a wave-dominant coastal zone. Morphological changes are computed on the basis of the mass balance of sediments in which the wetting and drying process is properly modeled to handle tidal variations and bed changes.

Similar to other integrated models (CMS, DELFT3D, MIKE21, etc.), simulations by using this integrated model are also supported by a user-friendly interface which assists users to generate computational grids, specify boundary conditions and model parameters, and to monitor and visualize simulation results. All the submodels work with the same computational grid. Thus, the wave and flow models run on the same computational cores, passing information between submodels through local memory/cache. It does not need to switch any additional executable codes during computations. All simulations are performed efficiently on a PC.

CASE STUDY: MODELING MORPHOLOGICAL CHANGES IN DANSHUI RIVER ESTUARY DURING TYPHOON SEASON IN 2008

Flowing into the north Taiwan Strait, the Danshui River estuary is the largest estuarine system in Taiwan, and is formed by the confluence of the Tahan Stream, Hsintien Stream, and Keelung River (Figure 2(a)). Its drainage area encompasses 2,728 km^2, with a total river length of 328 km. The tidal effect extends up to 82 km upstream of the river (Liu et al. 2007). A daily-averaged discharge in dry seasons from the three tributaries is 400 ~ 500 m^3/sec. Wave actions influence flow and sediment transport in the estuary, harbors, and adjacent coasts. River flood flows, waves, and storm surges induced by typhoons are major hydrological forcings that cause flooding/inundation and erosion/deposition in a wide area of the estuary. In July and September of 2008, three typhoons, Fung-Wong, Sinlaku, and Jangmi made landfall in Taiwan (Figure 2b), resulting in peak discharges of 3,800, 6,500, and 7,300 m^3/sec respectively, as estimated using CCHE1D, a one-dimensional (1-D) river flow model (Tenth River Management Office 2014). Two bathymetry surveys in this area were carried out in June (before the typhoon season) and October of 2008 (after the typhoons). The bathymetric and topographic data were used to estimate bed changes in the estuary and adjacent coasts. More than 2.0-m sediment deposition was found at the river mouth after the three typhoons, and the some erosion occurred near flood-plains of the river and along coastlines.

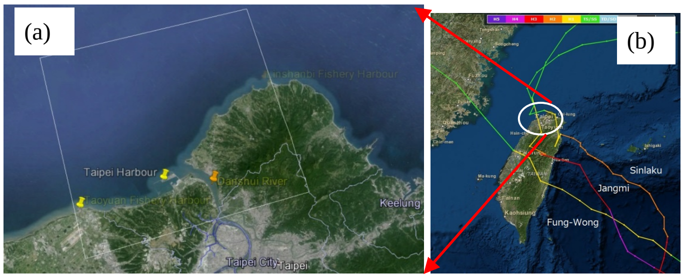

Fig. 2 (a) Danshui River estuary. The rectangular polygon represents the study area. (b) The trajectories of three typhoons in 2008

Within the study area (33 km × 31 km) shown by a polygon in Figure 2a, a non-orthogonal quadrilateral mesh, containing 156,349 nodes, was generated. The grid resolution varies from 20m at the river mouth to 500m in the offshore. The eastern boundary of the computational domain is located at the Lin-Shan-Bi fishery harbor; while the western boundary is approximately at the Tao-Yuan fishery harbor. The upstream boundary of the river is placed at the Kuan-Du Bridge. To calculate the morphological changes due to the three typhoons in 2008, the computation of wave-current-morphology interaction was performed continuously from July to October 2008. In accordance with the dates of the typhoons, Fung-Wong was introduced from 7/26 to 7/30, Sinlaku from 9/10 to 9/18, and Jangmi from 9/26 to 10/1. The observed water surface elevations during the periods of the selected typhoons were used for the boundary conditions of water levels (at the Lin-Shan-Bi tide gauge for the eastern boundary conditions and at the Tao-Yuan tide gauge for the western boundary conditions. The offshore wave parameters (i.e. significant wave heights, peak periods, and mean wave directions are from the observation data at a buoy located at the 3-km offshore of the Taipei Harbor). The observed wind data at the Taipei Harbor were used to reproduce time-dependent wind fields. The hydrograph, i.e. the discharge at the Kuan-Du Bridge during the computational period was used as the discharge boundary conditions at the river upstream. On the offshore boundary, the wave spectral energy density was computed using the observed wave parameters in the offshore. A total of 37 bins were set up to cover wave directions from -180^o to $+180^o$, providing a radical interval of 10^o. In the frequency domain, a total of 21 frequency bins were set up to cover a spectrum from 0.02Hz to 2.0Hz. A depth-averaged parabolic eddy-viscosity model was used for calculating eddy viscosity in the flow model. In the simulations, a time step of 10 sec was used to compute flows and morphological changes. Due to lack of data on bed material properties, a median sediment diameter of 0.2mm is assumed for the sediment grain size on river beds, beaches, and sea-beds. One simulation of waves, flows, and morphological changes through the two-month duration of the typhoons took approximately 40 hours on a standard PC (with a single core of Intel Core i7 CPU@3.20GHz).

The model was spun up by computing tidal flows from 7/23/2008 17:00 to 7/27/2008 17:00 before introducing Typhoon Fung-Wong. The time step in the spin-up period was set to 30 sec. After the spin-up, the wave-current interaction for modeling morphological changes was conducted for 66 days till the end of Typhoon Jangmi at 0:00 10/2/2008. Then, the time step for computing flows was changed to 10 sec. Bed elevations were updated every 100 sec. The wave field was computed every one hour based on the latest flow field.

Figure 3 presents snapshots of flow and wave fields close to the peak time of Typhoon Sinaku during an ebb tide at the river mouth. Multiple circulations can be identified around the breakwaters of the Taipei Harbor and in the river estuary. The offshore waves induced by the storm winds were transferred to the estuary through deformation and transformation processes such as refraction, diffraction, and breaking.

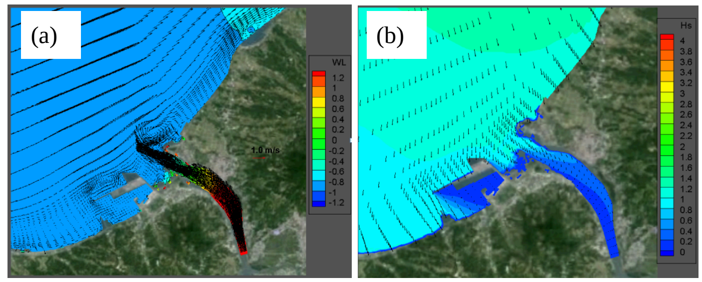

Fig. 3 snapshots of computed velocities and water levels (a) and wave fields (b) in Sinlaku at 15:00 9/14/2008, Q=6,000m^3/sec, ebb tide

Several tide gauges in this area located at Taipei Harbor, the Taipei Harbor offshore, and the river mouth near the Kang-Du Bridge, provided observation data of water surface elevations during the typhoon season in 2008. The ADCP installed in the Taipei harbor offshore provides velocity measurements at the river mouth. One wave buoy at the offshore of the Taipei Harbor measured wave parameters. Model validation has been performed by comparing computed water elevations, velocities, wave heights, directions, and periods with observations at those tide gages and the buoy. Comparisons have shown that the long-term simulation results from July to Oct., 2008 are in good agreement with the observations (Ding et al. 2014).

Figure 4 (a) and (b) presents the computed bed changes after Typhoons Fung-Wong and Jangmi, respective. The results show that sediment deposition in the river mouth was growing from Fung-Wong to Jangmi and moved further toward the offshore (around the area with water depth less than 10 m). The erosion in the river occurred in the reach downstream from the Kuan-du Bridge and the outer bank of the river bend. However, a large amount of sediment deposition in the deep channel of the river can be identified. Inside the Taipei harbor, both deposition and erosion happened. It is quite clear that the morphological changes in the river were caused by the fluvial processes and flood flows during the typhoon season. The bed changes in the river mouth were driven by the combined effects of riverine and coastal processes due to river flows, tides, and waves. The bed changes in the south coast (mainly being eroded) were induced by coastal processes due to wave breaking and longshore currents. Ding et al. (2015) compared the computed bed changes with the observation, and found that the morphological changes in the river estuary show consistent patterns of deposition and erosion.

For assessing long-term impact of morphological changes and flooding in the coastal area including the river estuary, predictions of sediment transport and morphological changes were carried out by repeating a synthetic "one-year" event. As shown Table 1, this event contains a historical three-month-long monsoon and three typhoons. A multi-year simulation of sediment transport and flows was done by repeating this synthetic one-year event. Figure 5 presents variations of the profiles of bed elevations along the center of the river course to the offshore. It indicates that upstream sediments transported by flood flows in typhoons can quickly change the river cross sections in the estuary, and even make a large amount of depositions in the river mouth. However, the monsoon can adjust the morphological changes in the estuary and coastal zones in the south. Due to the limit of the paper, details on the long-term assessment of morphological changes and flooding in the estuary will be described in a separate publication.

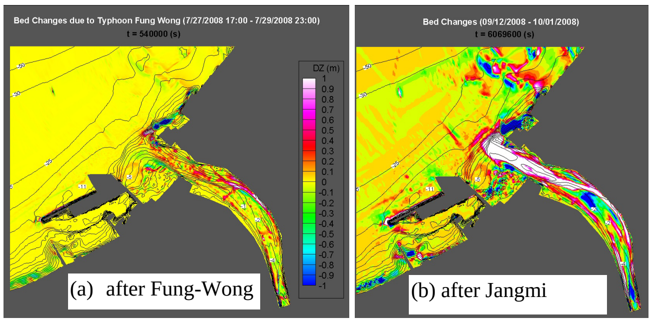

Fig. 4 Computed bed changes after typhoons

Table 1. Selected events for one-year assessment

Event	Start	End	Hours
Monsoon	2009/12/01 0:00	2010/3/1 0:00	2160
Aere	2004/8/24 4:00	2004/8/27 0:00	68
Jangmi	2008/9/28 1:00	2008/9/30 23:00	70
Saola	2012/7/30 21:00	2012/8/4 13:00	112

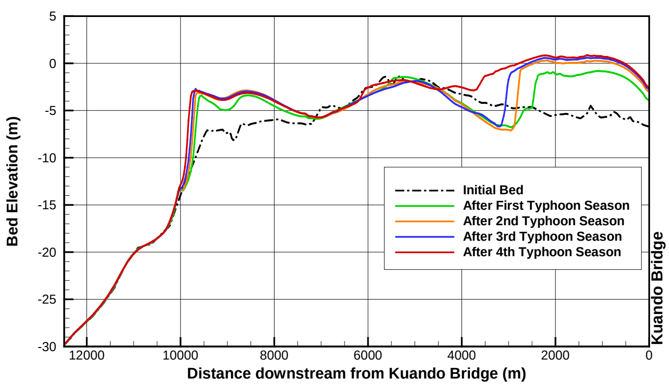

Fig. 5 Predicted profiles of bed elevations at the center of Danshui River after Typhoons

CONCLUSIONS

This paper presents a brief overview of integrated coastal and oceanic process modeling (INTCOM) approach and its engineering applications for simulations of flooding and sedimentation in coastal regions and estuaries. Through the case study of assessment of morphological changes in the Danshui River estuary in Taiwan, it presents a procedure for assessing long-term morphological changes by means of synthetic hydrological events which include typhoons, monsoons, and river flooding flows. Based on the results of model validation and the long-term prediction, the key features of spatiotemporal variations of sediment transport and morphological changes in the estuary and adjacent coasts are investigated. The results show that river floods with sediments from upstream cause significant sedimentation in the estuary, and wave effects and tidal currents in monsoon rebalance sediment transport at the river mouth. Both short-term storms and long-term monsoons are important for management of sedimentation/erosion and flood risks in the estuary and adjacent coasts.

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