

Interactions of Waves and River Plume and their Effects on Sediment Transport at River Mouth

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LONG-TERM GOALS

To develop a robust coastal/nearshore modeling system for river plume dynamics, sediment deposition/resuspension and inlet morphodynamics in a wave-dominated, high sediment yield and highly stratified environment.

OBJECTIVES

- To develop a detailed wave-resolving Reynolds-Averaged Navier-Stokes model for wave-current-sediment interactions in well-mixed and salt-stratified conditions.
- To study the interactions between tidal flow, waves and riverine outflow and their effects on mixing and sediment transport using a 3D finite volume coastal modeling system (FVCOM).
- To develop parameterizations of critical intra-wave processes for wave-averaged and/or depth-integrated coastal modeling systems.

APPROACH

The fate of riverine sediment and the morphodynamics of inlet and river mouth are very complex. Inlet and river mouth are essentially very effective sediment traps due to diminishing river flow inertia, frictional effects and stable density stratification (e.g., Wright 1977). Moreover, other dominant oceanic forcing namely waves, tides and ocean currents also play influential roles. When riverine outflow is weak, inlet hydrodynamics and morphodynamics are mainly controlled by interaction between tidal flow and bathymetry (de Swart & Zimmerman 2009; Hibma et al. 2004). In addition, wave effects can further complicated (and sometimes dominates) this problem through wave-induced cross-shore and alongshore transports (Bhattacharya and Giosan 2003). Due to the nonlinear nature of the system, the effects of the tidal currents and waves on the resulting hydrodynamics and sediment transport cannot be simply incorporated through linear additions. In fact, many theoretical, laboratory and field evidences suggest nonlinear interactions among waves, tidal currents, bathymetry, bottom boundary layer and sediment transport processes are the determining factors in coastal morphodynamics. These complex interactions give distinct channel-shoal patterns, river mouth bars and ephemeral deposits that are either very dynamic or in some sort of dynamic equilibrium.

We envision a multi-scale numerical modeling of coastal hydrodynamics, sediment transport and morphodynamics for turbid riverine outflows into a coastal zone with strong tidal flow and wave energy that may be further complicated by bathymetry. The backbone of such modeling framework shall be built upon exiting coastal modeling system. Indeed, in the past decade, there has been significant progress in the numerical modeling of coastal/nearshore circulation, wave field and sediment transport (e.g.,

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Reniers et al. 2004; Warner et al. 2008; Shi et al. 2007; Chen et al. 2008; Kim et al. 2009). However, there remains critical issues, especially related to coupling between wave and circulation, sediment transport in wave-current boundary layer, flocculation, and convective sedimentation (and many others) that need to be investigated in details. Hence, our study can be discussed in terms of modeling at two different spatial and temporal scales, namely, the intra-wave scale and the coastal modeling scale.

Intra-wave scale: Understanding the intra-wave processes is a critical step to further predict large-scale coastal hydrodynamics and morphological evolution. To achieve our long term goal, we address three critical intra-wave processes:

- (1) Wave-current interaction: the interactions between surface waves and tidal flow near inlet/river mouth with episodic large river outflow.
- (2) Initial deposition: Processes affecting vertical sediment flux that may greatly alter the distribution of sediment deposition.
- (3) Resuspension: How interaction between waves and tidal flow can affect resuspension and re-distribution of sediment near inlet/river mouth.

A wave-resolving 2DV numerical model solving Reynolds-Averaged Navier-Stokes (RANS) equations with free-surface tracking scheme based on volume of fluid (VOF) method (e.g., Lin and Liu 1998) is extended by PI's team to study wave-mud interaction. This numerical model is able to resolve continuously and consistently the surface wave propagation, bottom boundary layer fluid-mud transport, and wave attenuation with a single set of governing equation and closures (Torres-Freyermuth & Hsu 2010). Recently, this code is further extended to calculate sediment-induced gravity flow and salinity transport. This code is adopted here for studying interactions between surface waves, currents and sediment resuspension/transport processes. We will also extend our 2DV-VOF modeling effort to 3D-VOF in the later stage of the project.

Coastal modeling scale: To model the hydrodynamics and morphodynamics of the entire estuary and tidal inlet, numerical models that cover a spatial domain of tens of kilometers and temporal evolution of weeks to months are needed. To obtain results within a reasonable amount of computational time, these models are usually based on depth-integrated or wave-averaged formulations. Hence, many key small-scale processes are not resolved and need to be parameterized appropriately. While one of the main focuses of our modeling efforts is the intra-wave processes, it is also critical to carry out large-scale modeling so that critical issues related to morphodynamics can be investigated and more importantly, findings at the intra-wave scale can be directly implemented into the coastal modeling scale. An open-source, unstructured grid, finite-volume, three-dimensional (3D) primitive equation ocean model, FVCOM (Chen et al. 2003) is adopted in this study for coastal modeling.

WORK COMPLETED

We have extended the 2DV-VOF model to study interactions between surface waves and a sediment-laden river plume. For the sediment-laden plume component (no waves), the numerical model is validated with laboratory experiment of Garcia (1993) for turbidity currents and saline currents over a changing slope involving a internal hydraulic jump. The numerical model is further used to study convective sedimentation and its

depositional and mixing characteristics. By analyzing model results of more than 40 runs for different inlet sediment concentration (density ratio), settling velocity (particle Reynolds number), and inlet velocity/height (inlet Reynolds number), we identified four distinct flow regimes ranging from divergent plumes, intense convective fingers, weak convective fingers and negligible convective finger (Snyder and Hsu, manuscript in preparation). Our research efforts during FY10 have also been focused on validating this RANS-VOF model for wave-current interactions in a well-controlled condition. Main findings are summarized in the “Results” section.

Since FY10, we have carried out coastal modeling of Gaoping River mouth (Liu et al. 2009) using FVCOM (Chen et al. 2005) through collaboration with James T. Liu at National Yat-Sen University, Taiwan and Fengyan Shi (UD). This international collaboration is in part facilitated by Hsu’s ongoing NSF support to study initial deposition of sediment off small mountainous river. Recently, we have also set up FVCOM for New River Inlet using the most recent bathymetry data (bathymetry data obtained through collaboration with J. McNinch, U.S. Army Corp of Engineers). In the near future, we will carry out numerical modeling of the New River inlet to assist the planning of the field experiments.

RESULTS

In the literatures, there are several laboratory flume studies for regular waves propagating against or follow a turbulent current over a horizontal bottom (Brevik and Aas 1980; Kemp and Simons 1982, 1983; Thomas 1981, 1990; van Rijn 1993; Umeyama 2005). In general, these wave flume studies report an increase of current intensity near the surface when waves propagate against the current. On the other hand, a decrease of current intensity near the surface is observed when waves propagate with the current (For example, see Figures 3 and 4 of Van Rijn et al. 1993). These main features of wave-current interaction shall be captured by any numerical model (including coastal models) attempt to model mixing and sediment transport under wave-current interaction.

Figure 1 presents model results of waves propagate against and with a current over a horizontal bed of water depth of 3.4 meter (wave height 0.4 m; period 6.0 sec; depth-averaged current velocity 0.36 m/s; silt of grain size 60 μm can be resuspended from the bed). In our prior study on wave-mud interaction (Torres-Freyermuth & Hsu 2010), we demonstrate our model capability to resolve both the bottom wave boundary layer and free-surface wave propagation concurrently with a vertically stretched grid system. With a similar stretched grid system ($\Delta z=0.5$ cm near the bed and $\Delta z=2.5$ cm near the free-surface) our numerical model is able to predict the full-depth profile of current velocity under wave-current interactions. When waves propagate against the current, the wave length is noticeably shorter than that of waves propagate with the current (compare black and blue curves in Figure1 (a)). Near the bed ($z=0\sim0.3$ m), enhanced roughness due to wave-current interaction in the bottom boundary layer (Grant and Madsen 1981) can be clearly observed when comparing the wave-averaged current profiles with the logarithmic profiles without waves for both waves propagate against (see (b1)) and with the current (see (c1)). Near the surface ($z=2\sim3$ m), we also observe an enhanced (reduced) current intensity for the case of waves propagate against (following) the current. These features are similar to the wave flume observations discussed previously. More important, the numerical model predicts significantly higher turbulent intensity in the upper water column when wave propagates against the current (compare

(b2) and (c2) in Figure 1). The flow shear caused by wave-current interaction in the upper water column is much stronger when waves propagate against the current.

Such intense shear layer causes large turbulence and mixing in the upper water column that further penetrate downward and approach the bottom boundary layer. In this case, sediment transport is significantly affected by wave-current interaction in the upper water column (see (b3) and (c3)). For waves propagate with the current, the bottom boundary layer and the surface mix layer are essentially separated with a low turbulence regime in the middle of the water column ($z=1\sim 2$ m, see (c2)) and sediment is suspended no higher than $z=1$ m above the bed. On the other hand, for waves propagate against the current, the surface mix layer extends all the way to the bed and sediment is suspended as high as $z=2.7$ m above the bed. Our detailed numerical modeling demonstrates the importance of wave-current interactions on the vertical flow structure, mixing and sediment transport. The effects of upper wave-current mix layer in conjunction with the well-established apparent roughness in the bottom wave-current boundary layer on the resulting sediment resuspension and deposition shall be studied in more details.

Figure 2 further illustrate the model capability to simulate more realistic interaction between river outflow and incoming waves with arbitrary bathymetry. A well-mixed river outflow (current velocity 0.55 m/s) is sent from the left boundary and a periodic wave train (wave height 0.7 m; period 6 sec) is concurrently sent from the right boundary which propagates toward the river (see Figure 2a). Comparing to the condition of current only (compare Figure 2a and 2b, vectors represent wave-averaged velocity), waves significantly modify the river outflow in many aspects. The riverine current intensity is reduced by 40% ~100% except near $x=32.5$ m where current is affected by local wave breaking. Waves also modify the shape of current profiles especially near the upper water column. According to the calculated turbulence intensity (not shown), waves break locally near the crest of the river mouth bar (see $x=32.5$ m in (a)). However, when the river outflow is removed, this wave train is in fact non-breaking (see (c)). Hence, numerical results shown here suggest wave-breaking in panel (a) is induced by the river outflow. Strong wave-current interaction due to tidal current and incoming waves can be expected in the New River inlet and an intra-wave study is necessary.

IMPACT/APPLICATIONS

Our small-scale modeling effort will improve the current understanding on the effect of wave-current interactions on the full-depth vertical flow structure, mixing and sediment transport and provide improved parameterizations for coastal models. Our coastal modeling effort using FVCOM for the proposed field site at New River Inlet provides a modeling alternative based on unstructured finite volume scheme which is complementary to other participants in this DRI utilizing Delft3D, time-domain and frequency domain Boussinesq wave models. We plan to collaborate closely with field experimentalists and other numerical modelers in this DRI. PI Hsu has an ongoing NSF project to study the dynamics of sediment-laden river plume and initial deposition off small mountainous rivers. FVCOM is also used in this NSF project for large-scale coastal modeling of Gaoping river mouth – submarine canyon system. The tidal inlet modeling efforts provide a great opportunity to validate the numerical model for tide-wave dominant, relatively well-mixed environment. Validated numerical model will be further used to model riverine-dominated and stratified small mountainous river system.

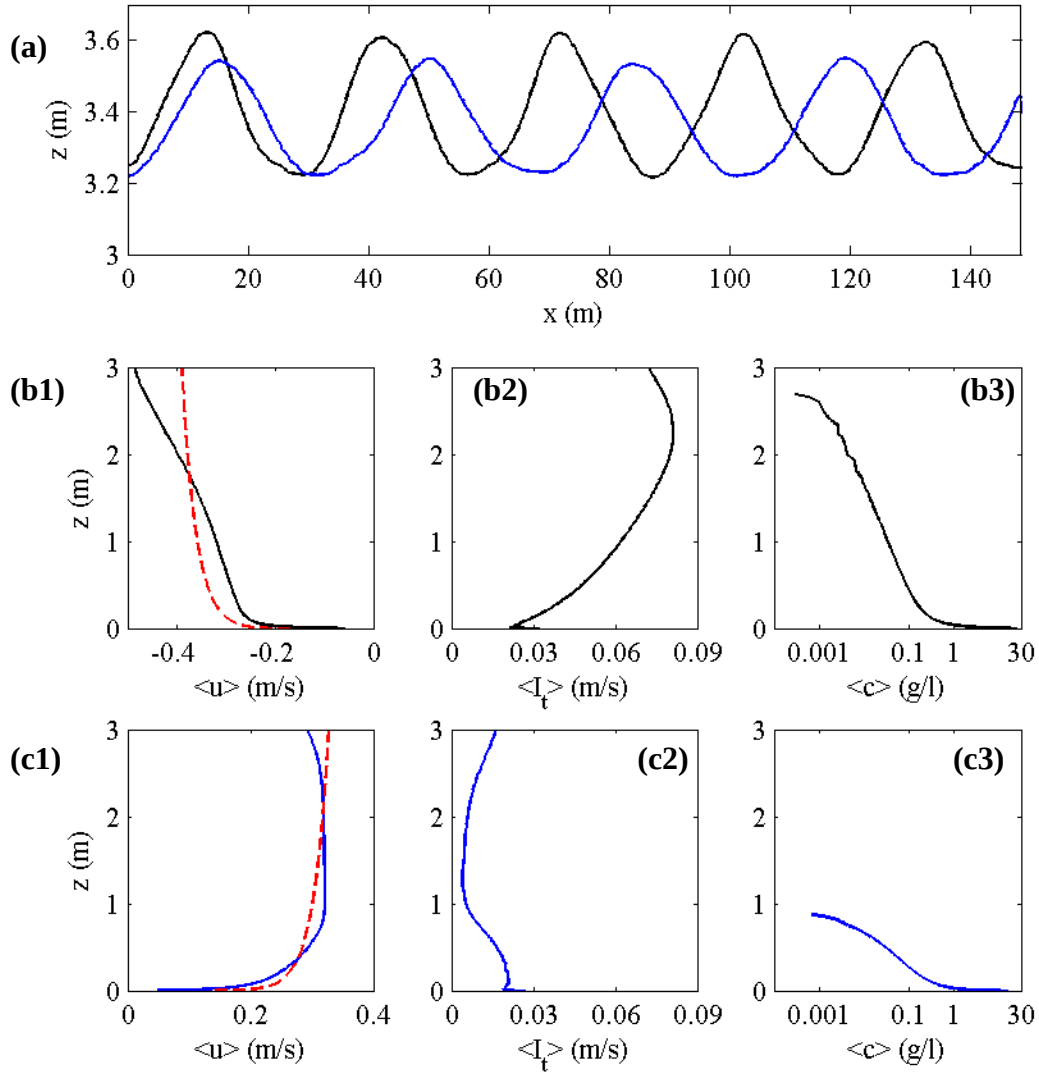


Figure 1: Model results for waves propagate against current (black curves) and waves following the current (blue curves). (a) Free surface elevation in the computational domain at $t=400$ sec. Subplots in the second row show model results for the case of waves against current with (b1) Wave-averaged velocity profile, (b2) wave-averaged turbulent intensity profile and (b3) wave-averaged sediment concentration profile. Subplots in the third row show the model results for the case of waves following the current with (c1) Wave-averaged velocity profile and (c2) wave-averaged turbulent intensity profile and (c3) wave-averaged sediment concentration profile. The red-dashed curves in (b1) and (c1) represent the logarithmic current profiles without the waves.

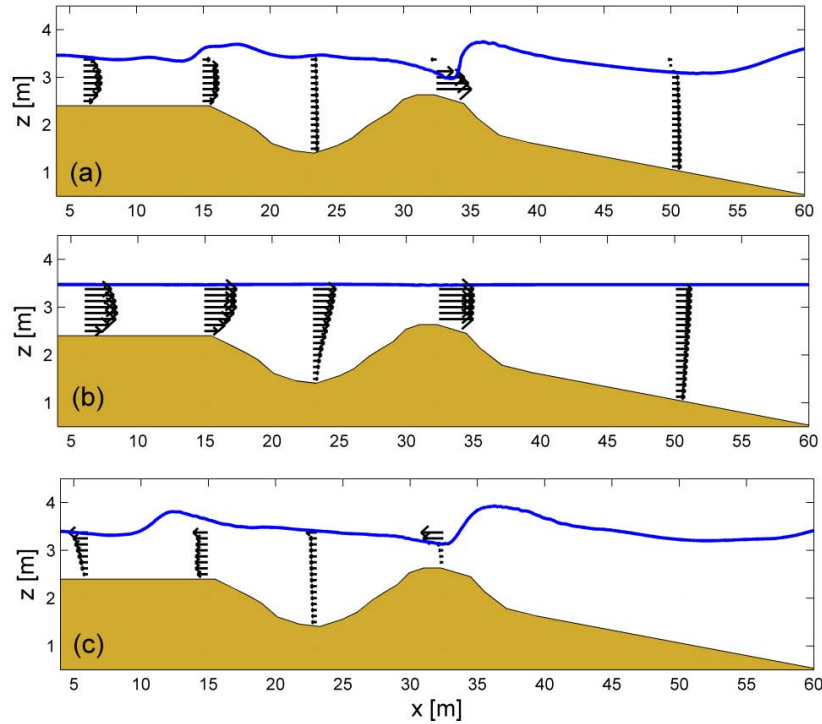


Figure 2: Wave-resolving RANS model results on wave-river flow interactions over a river-mouth bar. Snapshots of flow field (a) wave-river flow interactions; (b) river flow only (from left, velocity 0.55 m/s); (c) Wave only (from right, wave height 0.7 m and period 6 sec). Wave-averaged cross-shore velocity profiles (vectors) are also shown at selected cross-shore location.

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PUBLICATIONS

New start in FY10.