

High Resolution Numerical Modeling of Cohesive Sediment Transport

Tian-Jian Hsu
Civil and Environmental Engineering
Center for Applied Coastal Research
University of Delaware
Newark, DE 19716

S. Balachandar
Mechanical and Aerospace Engineering
University of Florida
Gainesville, FL 32611

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LONG-TERM GOALS

To understand the effects of spatial and temporal variability of sediment fluxes on the morphodynamic stability of intertidal flats.

OBJECTIVES

This study specifically focuses on numerical modeling of critical processes at small-scale ($O(\text{cm-100m})$) based on “first principles”. It is proposed

- (1) to extend existing numerical models for cohesive sediment transport and related bottom boundary layer processes at tidal flats and wave-dominated shelves; and
- (2) to develop an appropriate module of floc dynamics for cohesive sediment transport; and
- (3) to develop appropriate parameterizations of the near bed sediment transport and bottom friction for large-scale hydrodynamic models.

APPROACH

Cohesive sediment transport involve a variety of physical mechanisms including boundary layer dynamics (tidal and wave), gravity-driven flow, turbulence modulation, flocculation, non-Newtonian rheological behavior and consolidation (e.g., Mehta 1989; Winterwerp and van Kerstern 2004). A general modeling framework appropriate for wide range concentration needs to be based on multiphase flow theory. In this study, a fine sediment transport modeling framework based on Equilibrium Eulerian Approximation (Ferry & Balachandar 2001) to the multiphase equations has been developed and extended to model various cohesive sediment transport processes. This fine sediment modeling framework is the basis of the three numerical models developed for 1DV (1-Dimensional Vertical), 2DV and 3D for different applications. In the turbulence-averaged 1DV modeling, the dynamics of wave-supported gravity-driven mudflows has been studied (Hsu et al. 2007; 2008). This code is

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recently extended with flocculation capability to study the effect of flocculation in cohesive sediment transport in meso-tidal environment. In the Reynolds-averaged 2DV formulation, wave-mud interaction (Torres-Freyermuth & Hsu, submitted) and sedimentation at salinity stratified river mouth are simulated. To resolve detailed turbulence-sediment interactions and to improve the closures in the Reynolds-averaged approach, highly resolved 3D simulation of fine sediment transport in oscillatory flow is carried out using a pseudo-spectral numerical scheme (Ozdemir et al., submitted).

WORK COMPLETED

Wave-mud interaction: As a part of this framework, a well-validated 2DV depth/phase-resolving wave model (COBRAS, Lin & Liu, 1998) based on the Reynolds-averaged Navier-Stokes (RANS) equations is modified for the study of wave-mud interaction. The numerical model is able to simulate continuously and consistently the nonlinear water wave propagation, the fluid-mud generation and transport, the wave-boundary layer processes, turbulence modulation owing to the presence of the fluid-mud, and the rheological effects on attenuating the waves with a single set of balance equations and closures. The numerical model is used to study the roles of direct dissipation and nonlinear wave-wave interaction in determining wave attenuation over muddy seabed (Torres-Freyermuth and Hsu, submitted) and to further study the effects of sloping seabed and strong mud dissipation in driving the nonlinear wave energy transfer and the fate of infragravity waves (e.g., Elgar & Raubenheimer 2008). Recently, this code is extended with salinity calculation capability and is ready to study river plume dynamics and initial sediment deposition relevant to Tidal Flat DRI and upcoming Inlet and River Mouth DRI.

Floc dynamics and its effect on cohesive sediment transport in tide-dominated environment: The present cohesive sediment transport framework requires appropriate constitutive equation for floc breakup and aggregation processes (e.g., Winterwerp 1998). Existing flocculation models are able to predict flocs in equilibrium condition. However the predicted temporal evolution of floc size is unsatisfactory (see Figure 1b and Son and Hsu 2008). Based on field/laboratory observations, the fractal dimension is not a constant and shall change dynamically with the flow condition (e.g., Dyer and Manning 1999; Khelifa and Hill 2006). In addition, existing flocculation models commonly assume constant floc yield strength in modeling floc break-up process. However, laboratory evidences suggest floc yield strength depends on total solid area at the plane of rapture (Tambo and Hozumi 1979; Sonntag and Russel 1987). In the past three years, we develop a flocculation model following the framework of Winterwerp (1998) but extend it with variable fractal dimension (Son and Hsu 2008) and variable yield strength (Son and Hsu 2009). When both of these components are incorporated, the flocculation model is able to predict the temporal evolution of floc size observed in laboratory mixing tank or Couette experiment (see Figure 1a). This new flocculation formulation is incorporated into the 1DV version of the cohesive sediment transport model to study cohesive sediment transport in tide-dominated environment. The new 1DV code is now ready and available for carrying out model-data comparisons for new data measured in Tidal Flat DRI.

Turbulence-resolving simulation of wave-driven fine sediment transport: A highly accurate pseudo-spectral flow solver is employed to solve the governing equations of the fine sediment transport modeling framework (Cortese & Balachandar 1995; Cantero et al. 2008; Ozdemir et al., submitted). As a preliminary validation, Direct Numerical Simulation (DNS) is carried out to resolve all scales of flow turbulence without sub-grid closure. Clear fluid simulation results for intermittently turbulent condition (i.e., Stokes Reynolds number $Re_\delta = 1000$, equivalent to half channel depth

Reynolds number $Re = 30000$) agree excellently with earlier DNS results reported by Spalart and Baldwin (1988). Fine sediment with dilute and concentrated concentrations (phrased in terms of various values of Richardson number in the nondimensionalized momentum equations) are then added in a series of numerical simulations to study fine sediment transport dynamics, especially the role of sediment-induced stable density stratification under oscillatory flow.

RESULTS

In this report, we briefly discuss some of the highlights in our overall study on cohesive sediment transport. More detailed discussions and other applications are summarized in several manuscripts that are currently under review (see Publication section) or in preparation.

1. Effect of flocculation on cohesive sediment transport in tide-dominated environment:

To investigate roles of floc dynamics in determining the sediment dynamics in a tide-dominated environment, the 1DV numerical model for fine sediment transport (Hsu et al. 2009) is revised to incorporate four different modules for flocculation, i.e., no floc dynamics, floc dynamics with assumptions of constant fractal dimension and yield strength (Winterwerp 1998), floc dynamics for variable fractal dimension only (Son and Hsu 2008), and floc dynamics for considering both fractal dimension and yield strength variables (Son and Hsu 2009). Model results are compared with measured sediment concentration and velocity time series at the Ems/Dollard estuary (van der Ham et al. 2001). Numerical model predicts very sharp concentration gradient near the bed and nearly zero sediment concentration during slack tide when floc dynamics is neglected or incorporated incompletely (dashed curve in Figure 2). This feature is inconsistent with the observation. When considering variable fractal dimension and variable yield strength in the flocculation model, numerical model predicts much smaller floc settling velocity during slack tide and hence is able to predict measured concentration reasonably well (solid curves Figure 2). Moreover, incorporating variable critical shear stress of mud bed, which is parameterized as a function of total eroded sediment mass, is also shown to be effective in modeling cohesive sediment transport, especially for near bed time series of concentration (not shown here). Without incorporating variable critical bed shear stress, the temporal variation of near bed concentration becomes too large, which is not consistent with measured data. Essentially, flocculation controls the settling velocity and bed erodibility (parameterized by critical shear stress here) controls the bottom supply of cohesive sediment. Both processes need to be incorporated properly in order to predict cohesive sediment transport with satisfactory results.

2. The role of sediment-induced stable density stratification in cohesive sediment transport in wave boundary layer:

Fine sediment transport in oscillatory boundary layer with a range of sediment concentrations is studied with a 3D turbulence-resolving numerical model. We specify settling velocity of 0.5 mm/s, which is typical for fine terrestrial sediment in the coastal ocean. The oscillatory flow condition is of $Re_\delta = 1000$, which is equivalent to wave of 10 sec period and 0.56 m/s velocity amplitude. At this Reynolds number, computing resource also allow us to resolve all the scale of carrier flow turbulence (small-scale turbulence generated around particles is neglected). Here, we discuss numerical results for three different values of bulk Richardson number (Ri). We can consider $Ri = 0$ as the case of very dilute concentration (mass concentration $\ll 1$ g/l) in which sediment has no impact to carrier flow. The case of $Ri = 0.006$ is of near bed mass concentration of $O(10)$ g/l, which is typical for mobile fluid mud and the case of $Ri = 0.018$ is of near bed mass concentration of more than $O(100)$ g/l, i.e., very concentrated fluid mud. Snapshots of sediment concentration iso-surface at the phase of (A) maximum free-stream

velocity, and (B) flow reversal for these three cases are shown in Figure 3. For very dilute condition where sediment is passive, we see suspension events occur at all wave phases. In fact, turbulence and suspension are stronger under wave crest. However, for the case of $Ri=0.006$, strong sediment bursts only occur during flow reversal and under wave crest, we see more calm and layered concentration. Preliminary analysis suggests absence of suspension events under wave crest is due to stable sediment density stratification that attenuates carrier flow turbulence and mixing. On the other hand, burst events observed during flow reversal are caused by mechanism similar to shear instability in stratified condition (e.g., Miles 1961). Finally, for the case of $Ri=0.018$, sediment-induced stable density stratification become very significant causing complete relaminarization of wave boundary layer. Hence, fine sediment transport dynamics is strongly related to the two-way coupled interaction between carrier turbulent flow and sediment. Many interesting intermittent burst features and transitional flow (e.g., relaminarization) cannot be predicted by models based on Reynolds-averaged approach.

IMPACT/APPLICATIONS

The present research efforts focus on developing a numerical modeling framework for cohesive sediment transport for various applications in tide- or wave-dominated environment. Existing applications include wave-supported gravity-driven mudflows, wave-induced fluid mud process, tidal-driven cohesive sediment transport and flocculation and sediment-laden river plume dynamics and initial deposition. Our model development efforts shall contribute the modeling capability in the ongoing ONR related research effort on Tidal Flat DRI, Wave-mud Interaction, Community Sediment Transport Modeling System (NOPP-CSTMS), Inlet and River Mouth DRI and Preliminary Investigations on the Fate of Terrestrial Sediments in the Coastal Ocean Discharged from Taiwanese Small Mountainous Rivers (via NICOP).

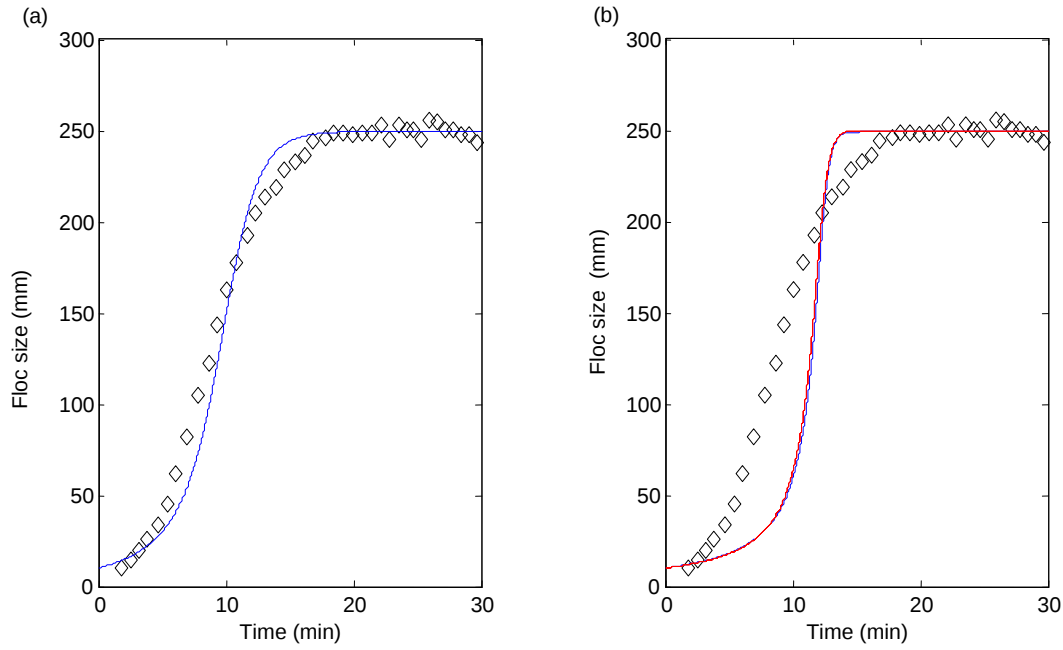


Figure 1: Predicted temporal evolution of floc size comparing with that observed in mixing tank experiment Spicer et al. (1998). (a) predicted floc size by a flocculation model (called FMA here, solid-blue curve) that incorporates variable fractal dimension and variable yield strength (Son and Hsu 2009) agrees very well with measure data (symbol). However, (b) flocculation models that consider constant fractal dimension and variable yield strength (Son and Hsu 2008; FMB, blue curve) and constant yield strength and constant fractal dimension (Winterwerp 1998; FMC, red curve) both predict much slow (rapid) increase of floc size in the beginning (final) stage of the flocculation process.

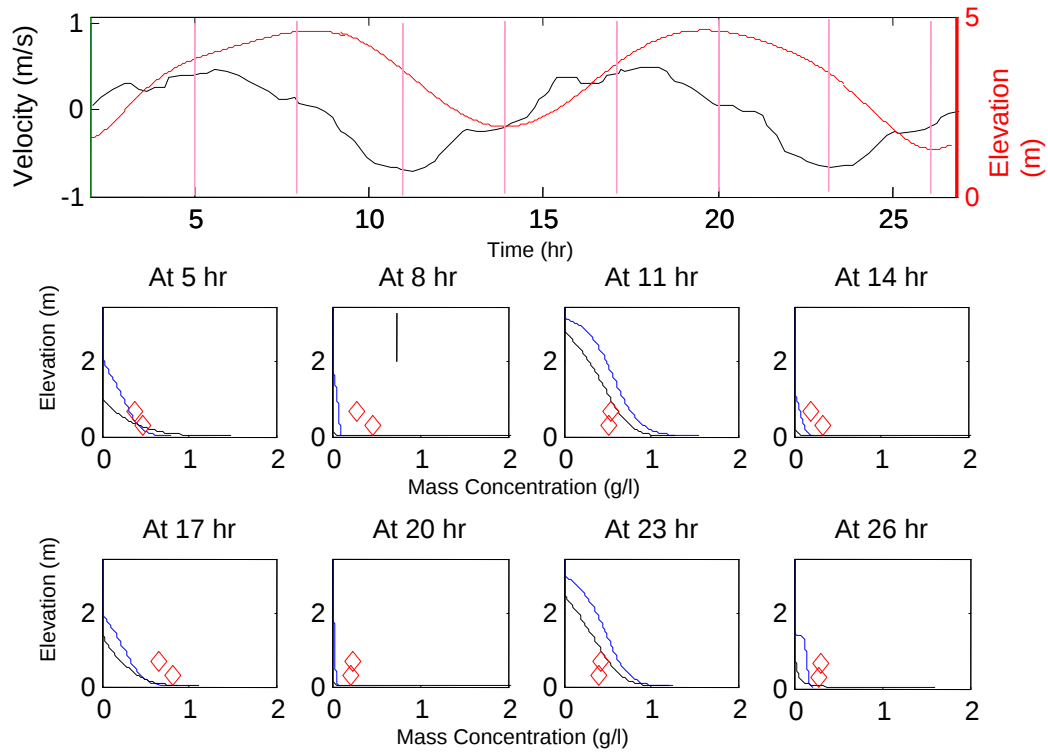


Figure 2: 1DV Sediment transport model predictions with measured sediment concentration time series (at 0.3 and 0.7m above the bed) at EMS/Dollard estuary (van der Ham et al. 2001). The upper panel shows measured tidal elevation (red-dashed curve) and tidal velocity (black curve) which are used to drive the model. The lower eight small subplots are measured concentration (symbol) and predicted sediment concentration profiles using floc dynamics formulation of Son and Hsu (2009) (FMA, solid-blue curve) and without considering floc dynamics (dash-black curve).

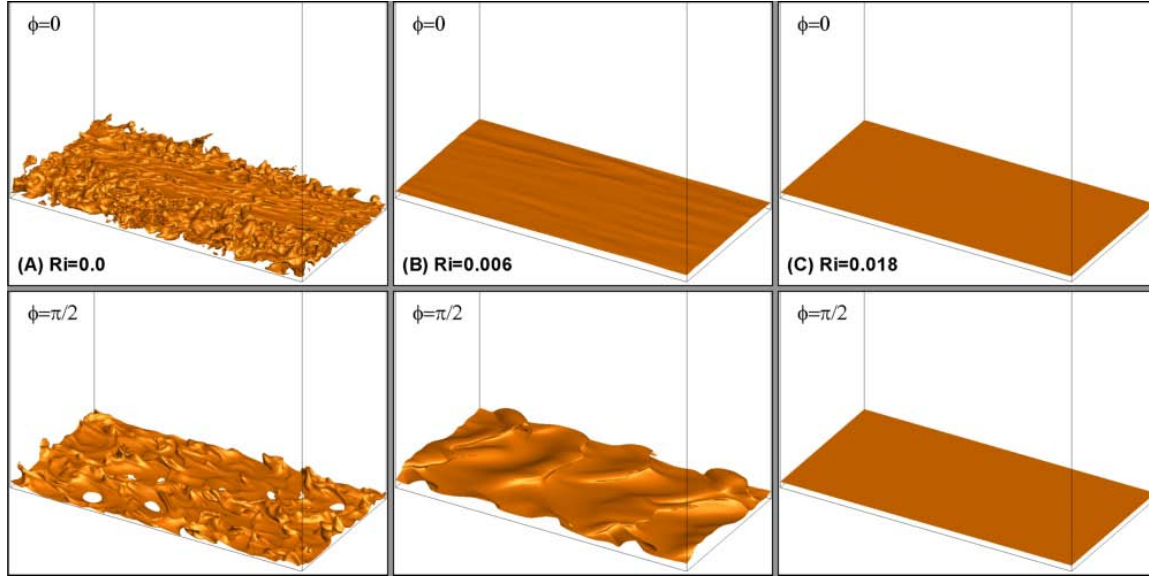


Figure 3: Iso-surface of sediment concentration at the phase of maximum free-stream velocity $\Phi=0$ (upper panel) and flow reversal $\Phi=\pi/2$ (lower panel) for (A) $Ri=0.0$ which represents very dilute condition (e.g., sediment concentration $\ll O(1)$ g/l) and sediment can be considered passive. (B) $Ri=0.006$ which represents intermediate concentration (near bed sediment concentration $\sim O(10)$ g/l). In this case, more intense sediment burst events occur during flow reversal, not under wave crest. (C) $Ri=0.018$ which represents more concentrated condition (near bed sediment concentration $> O(100)$ g/l). The concentration is too high and re-laminarization occurs over the entire wave phases. The wave condition is of $Re_\delta=1000$, which represents wave velocity amplitude of 0.56 m/s and period 10 sec. The sediment settling velocity is set to be 0.5 mm/s.

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