A Numerical Modeling Framework for Cohesive Sediment Transport Driven by Waves and Tidal Currents

Tian-Jian Hsu
Civil and Environmental Engineering
Center for Applied Coastal Research
University of Delaware
Newark, DE 19716
Email: thsu@udel.edu; Tel: 302-831-4172

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LONG-TERM GOALS

To develop a robust multi-phase, multi-class numerical modeling framework for both cohesive and non-cohesive sediment transport in the fluvial, estuarine and coastal environments.

OBJECTIVES

This study specifically focuses on numerical modeling of critical processes at small-scale (O(cm-100m)). Specific objectives are

1. To develop turbulence-resolving numerical model of fine sediment transport in the oscillatory boundary layer in order to understand how turbulence-sediment interactions can determine fluid mud transport and the state of muddy seabed.
2. To develop a two-dimensional-vertical (2DV) numerical model based on Reynolds-averaged Navier-Stokes (RANS) equations and volume of fluid method for free-surface tracking to study mechanisms causing landward and seaward fine sediment transport in inter-tidal zones.
3. To understand the competing effects between mud dissipation and shoaling in determining the resulting nonlinear wave propagation using a 2DV-RANS model for wave-mud interactions.

APPROACH

Cohesive sediment transport involves a variety of physical mechanisms including boundary layer processes (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 a wide range of concentration needs to be based on multiphase flow theory. In this study, a fine sediment transprt 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 three numerical models developed for 1DV (one-dimensional-vertical), 2DV and 3D for different applications investigated in this study. In the Reynolds-averaged 1DV modeling, the dynamics of wave-supported gravity-driven mudflows has been studied (Hsu et al.

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2007; 2008). This model is recently utilized by other researchers to model field observed wave-current driven fluid mud transport (Safak et al. 2010). Efforts are also devoted to improve existing flocculation formulation with more robust parameterizations on fractal dimension and floc yield strength (Son & Hsu et al. 2008, 2009). New flocculation formulation is then adopted in the 1DV model to study the effect of flocculation and bed erodibility on cohesive sediment transport in a meso-tidal environment (Son & Hsu 2011a,b). In the Reynolds-averaged 2DV modeling, we further utilize a volume of fluid (VOF) code for free-surface tracking (Lin & Liu 1998) and investigate wave propagation over muddy seabed (Torres-Freyermuth & Hsu 2010). Recently, this 2DV-VOF code is also extended to simulate cross-shore fine sediment transport in intertidal flats. To greatly reduce the uncertainties in the turbulence closure for sediment-laden flow, a 3D highly accurate turbulence-resolving Navier-Stokes solver is extended to study the role of sediment-induced density stratification in determing the resulting fine sediment transport and bed state in the wave boundary layer (Ozdemir et al. 2010, 2011). Our modeling work reported here are directly related to past and ongoing ONR research programs, such as MURI wave-mud interaction and Tidal flat DRI.

WORK COMPLETED

3D two-way coupled turbulence-resolving simulation

A 3D numerical simulation tool for fine sediment transport in oscillatory boundary layer has recently been developed where all the scales of carrier flow turbulence are resolved without the uncertainties in turbulence closure (Ozdemir et al. 2010). For a fixed Stokes Reynolds number of $Re_\Delta=1000$ (representing the most energetic shelf where mud can be observed) and settling velocity, we vary the available amount of sediment in the oscillatory boundary layer and observe four different flow regimes ranging from well-mixed sediment in the wave boundary layer, formulation of lutocline and laminarization (see Figure 1 for more details). By keeping the sediment availability unchanged, in FY11 we further demonstrate the existence of these flow regimes for a range of sediment settling velocities. All these simulation results allow us to construct a 2D regime map for the state of muddy seabed for a range of sediment availability and nondimensional settling velocity at $Re_\Delta=1000$. Main findings are published recently (Ozdemir et al. 2011). Recently, we have also started simulations at lower $Re_\Delta=400\sim800$. These lower Reynolds number cases are similar to recent field observation at Atchafalaya inner shelf (Traykovski, Sheremet, personal communication). The simulation code utilized so far is based on a pseudo-spectral scheme (Cortese & Balachandar 1995). We recently revise this code with a sixth-order compact finite-difference scheme in the vertical direction (bed-normal direction). This revision allow us to implement more complicated rheological stress closure (e.g., concentration dependent viscosity and yield stress) for mud and hinder settling at higher mud concentration.

2DV RANS-VOF modeling of fine sediment transport across tidal flats

Conventional coastal modeling systems have difficulties in resolving the tidal front at the wetting and drying seabed and some numerical approximations, such as specifying a minimum artificial flow depth, are often adopted. However, it is not clear how such artificial numerical treatment can affect the accuracy of the results when tidal water's edge is of interest. Hence, a new numerical modeling approach for this problem is necessary. The 2DV RANS-VOF numerical model previously used for wave-mud interaction is revised for tidal flow. The model is used to simulate fine sediment transport across an idealized tidal flat and to investigate mechanisms causing the net landward and seaward sediment transport. Similar idealized domain and flow condition are simulated with ROMS to evaluate the capability of typical coastal modeling system in resolving shallow water processes at tidal flats and net sediment transport.

2DV RANS-VOF modeling of wave-mud interaction

Previously we have used the 2DV RANS-VOF model to identify the competing effects between the direct dissipation and the shoaling effect in causing the nonlinear wave energy transfer. Our goal is to clarify the seemly discrepancies between recent field observation (Elgar & Raubenheimer 2008) and classic wave-mud interaction theory (Dalrymple & Liu 1976). A manuscript on this topic is currently in preparation through collaboration with Dr. Alec Torres-Freyermuth who used to be the postdoc researcher in PI Hsu's group (now Assistant Professor at Universidad Nacional Autónoma de México). Recently, PI Hsu also hosted a visit scholar, Mr. Wen-Yang Hsu of National Cheng-Kung University, who was awarded a prestigious 9-month scholarship from National Science Council of Taiwan. As part of his PHD study, Mr. Wen-Yang Hsu carried out detailed laboratory experiment on wave-mud interaction where both wave dissipation and mud rheological were concurrently measured. This is the ideal dataset to validate and calibrate the 2DV RANS-VOF model.

RESULTS

The highlights of our study on cohesive sediment transport for FY11 is summarized here:

The state of muddy seabed in wave-dominant environment

Ozdemir et al. (2010) used a high accuracy pseudo-spectral scheme and resolved all the scales of turbulence and turbulence-sediment interaction at Re_{Δ}=1000. We identified four distinct flow regimes as sediment concentration in the wave boundary layer (or bulk Richardson number) increased from *O*(0.1g/L) to *O*(100 g/L) (see Figure 1). Regime I describes a condition of very dilute sediment concentration where the effect of sediment-induced density stratification is negligible and sediment is nearly passive to carrier flow. Sediment concentration profile is more or less well-mixed in the wave boundary layer. Regime II describes moderate interaction between sediment and carrier flow as sediment concentration near the bed approaches O(10) g/L. Sediment-induced stable density stratification attenuates carrier flow turbulence near the top of the wave boundary layer. Hence, the associated turbulent mixing of sediment is significantly suppressed causing the formation of a lutocline, which separates the lower turbulent layer from the upper quasi-laminar layer (e.g., Traykovski et al. 2000). In Regime III, the near bed sediment concentration is O(50) g/L. Due to the increasing effect of stable sediment concentration gradient that directly suppresses turbulent production in the wave boundary layer, mean flow velocity laminarizes. Turbulent suspension of sediment in the wave boundary layer is shut down during a major portion of the wave period. However, flow destabilizes during flow reversal and episodic sediment burst and high turbulence occur via flow instability. Such sediment bursts events during flow reversal are reported in limited field observation (Foster et al. 2006; Traykovski 2010). In Regime IV, where near bed sediment concentration is greater than O(100) g/l, sediment-induced stable density stratification is severe enough that it further suppresses the instability observed in Regime III and the flow remains laminar at all times. Similar laminarization phenomena appear to have been observed in the laboratory experiments of Lamb et al. (2004). The existence of these flow regimes has critical implications to our ability to assess the state of a muddy seabed and to further understand various applications related to fluid mud transport discussed previously. For example, the transition between Regime II and Regime III (and IV), i.e., laminarization of the mud layer, is known to coincide with the timing where large wave dissipation rate is measured (Traykovski, Sheremet, personal communication).

By keeping the sediment availability unchanged, we further demonstrate the existence of these flow regimes for a range of sediment settling velocities. Simulation results suggest that when settling velocity is larger, the location of the lutocline becomes lower (closer to the bed) and the flow eventually laminarizes when there is further increase in the settling velocity. Hence, the dynamics of lutocline is clearly related to the transition between these flow regimes. The 2D regime map of the flow regimes adopted from our ongoing work is shown in Figure 2 for Re_{Δ}=1000. A complete phase diagram for wave boundary layer must also depend on Re_{Δ}. In Ozdemir et al. (2010), rheological stress is not incorporated in the simulation and hence the effects of rheology on hydrodynamic dissipation in conjunction with turbulence collapse were not investigated. Hence, our ongoing work focuses on simulations of lower Re_{Δ} and including rheology in the new version of the code with sixth-order compact-finite difference scheme.

Mechanisms causing landward and seaward sediment transport in a tidal flat

The 2DV-RAN-VOF model is demonstrated to be able to reproduce the classic theory of tidal flat hydrodynamics of Friedrichs and Aubrey (1996) and predict the turbid tidal water's edge qualitatively similar to prior field observations. To model large-scale coastal and estuarine processes, the Regional Ocean Modeling System (ROMS) is also utilized to simulate the same idealized tidal flat. We demonstrate that when a small critical depth (h_{crit} =2 cm) in the wetting and drying scheme is adopted, ROMS is able to predict the main features of hydrodynamics and sediment transport processes similar to that predicted by the RANS-VOF model. When driving the models with a symmetric tidal forcing, both models predict landward transport on the lower and upper flat and seaward transport in the subtidal region. When the shallow tidal water's edge is well-resolved, both models predict an asymmetry of tidal velocity magnitude between the flood and the ebb that may encourage landward sediment transport on the flat. Further model simulation suggests the predicted landward transport of sediment on the flat is mainly due to the settling-lag effect while the asymmetry of tidal velocity magnitude may add another minor but non-negligible amount. When the bed erosion is limited by the availability of soft mud, the predicted transport becomes landward directed in both the subtidal region and on the flat. These results suggest that the tidal flow generally encourages landward transport while significant seaward transport may be caused by other mechanisms, such as delivery though the channels (Ogston, Fagherazzi, person communication).

IMPACT/APPLICATIONS

The present research efforts produce a numerical modeling framework for cohesive sediment transport for various applications in tide- or wave-dominated environment. The models allow us to predict the state of muddy seabed which can be further linked with hydrodynamics. Our model development efforts 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).

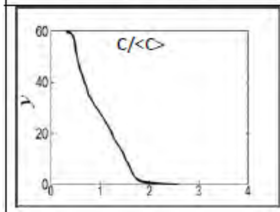
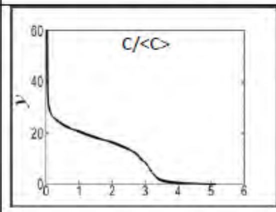
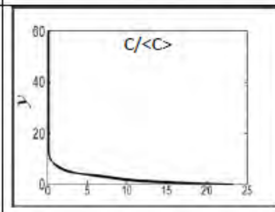
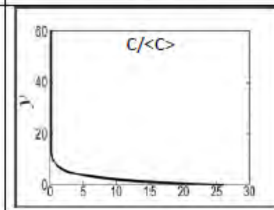
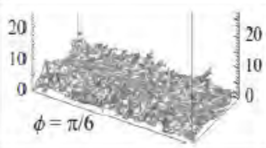
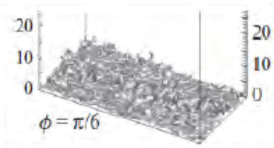
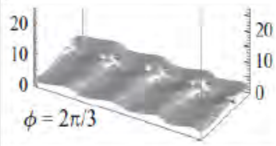
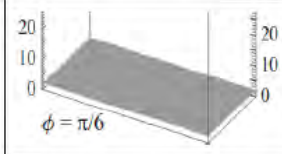
Regime 1	Regime 2	Regime 3	Regime 4
C=O(0.1)g/L	C=O(10)g/L	C=O(50)g/L	C=O(100)g/L
			
			
Sediment is well-mixed and passive to flow turbulence	Formation of lutocline where turbulence is damped ; flow remains turbulent below the lutocline	Collapse of turbulence except flow reversal; mean flow approaching laminar solution	Complete collapse of turbulence; laminar solution

Figure 1: A summary of the four flow regimes revealed by Ozdemir et al. (2010). These regimes occur at different sediment availability (from left to right, each column represents flow regimes due to low to high sediment concentration) under the same wave condition (Stokes Reynolds number = 1000) and settling velocity (0.5 mm/s). The 1st row shows representative sediment concentration near the bed. The 2nd row shows average concentration profiles (C/<C>). The 3rd row shows a snapshot of an instantaneous sediment concentration iso-surface. Transition from Regime I to Regime II signifies the formation of a lutocline from well-mixed condition due to higher sediment availability. Transition from Regime II to Regime III signifies the onset of laminarization. In Regime III, although averaged concentration profile is close to a laminar solution, sediment bursts are clearly seen shortly after flow reversal (ϕ=2π/3).

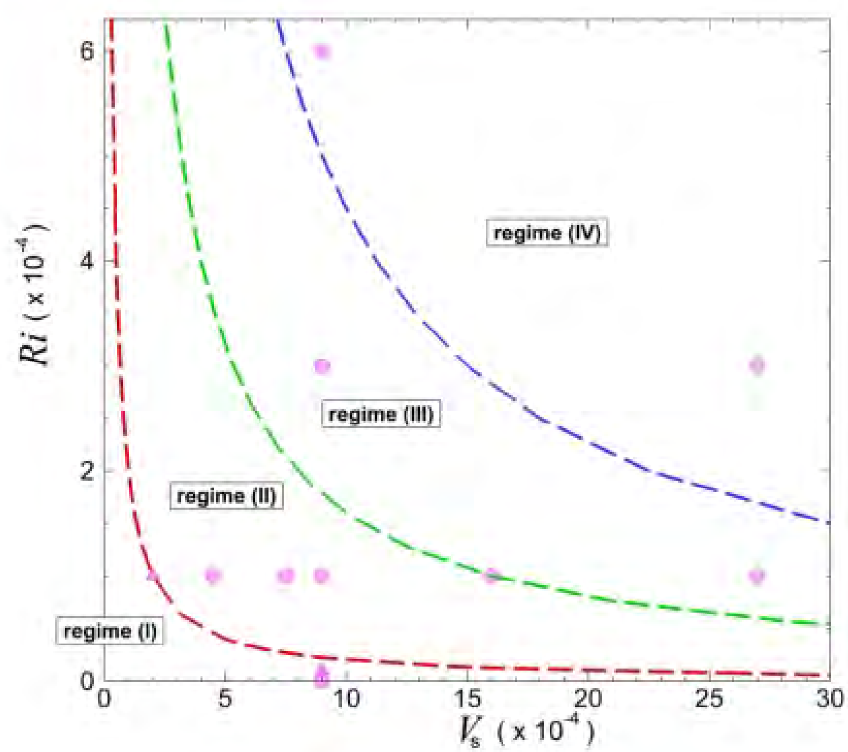


Figure 2: A two-parameter map for the occurrence of the four flow regimes (see Figure 1 for discussion on these regimes) that depend on nondimensional settling velocity, V_s, and bulk Richardson number, Ri (sediment availability) for Re_Δ=1000 based on 3D simulation results (all black-dots). The border between Regimes I and II is obtained via simulation results based on Reynolds-averaged model of Hsu et al. (2009), which is computationally more efficient than the 3D simulation model (triangles).

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