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

Grant Number: N00014-11-1-0270

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

1. Developing a 3D turbulence-resolving numerical model for fine sediment transport in the oscillatory boundary layer in order to understand how turbulence-sediment interactions can determine the state of muddy seabed (transport modes).
2. Studying the interplay between the rheological stress and turbulence modulation in determining the transition of flow modes and hydrodynamic dissipation.
3. Extending the existing turbulence-resolving numerical study to coarser grain (sand) and poly-dispersed (e.g., size, density and shape) transport based on four-way-coupled Eulerian and Euler-Lagrangian numerical frameworks.

SIGNIFICANCE

Understanding various modes of sediment transport and the resulting transport rate driven by waves and currents are critical to better predictions of hydrodynamic, seabed properties, morphodynamics in the coastal environments. Through an enhanced/reduced bottom friction due to seabed processes, hydrodynamics and seabed dynamics become highly coupled and large-scale numerical models must incorporate appropriate parameterizations on seabed dynamics. For example, in our ongoing numerical modeling work to predict the hydrodynamics through the New River Inlet (NC) using a quasi-3D circulation model NearCoM-TVD, the computed magnitude of ebb tidal current can increase from 1.4 m/s to 2.0 m/s when bottom drag coefficient C_d is decreased from typical value used for surf zone (0.01) to that for estuary (0.003). In other words, it is critical to improve our capability to quantify and characterize seabed dynamics in order to provide reliable prediction of flow intensity in critical areas. In muddy environments, the role of bottom mud state in determining the hydrodynamic dissipation remains unclear. For example, one of the key findings resulted from AMASSEDS (e.g., Nittrouer et al. 1991) indicates significant reduction of bottom drag coefficient as tidal currents propagate over muddy seabed (Beardsley et al. 1995) due to damping of turbulence via sediment-induced density stratification

(Kineke et al. 1994). On the other hand, field and analytical studies on wave propagation over muddy seabed (e.g., Sheremet & Stone 2003; Elgar & Raubenheimer 2008) report significantly increased energy dissipation due to the presence of bottom fluid mud. The observed vast difference on hydrodynamic dissipation appears to be related to a diverse range of muddy seabed state revealed by recent studies through detailed turbulence-resolving simulations (Ozdemir et al. 2010) and field observations (Traykovski 2010; Sahin et al. 2012).

APPROACH

A general modeling framework appropriate for a wide range of grain size (or Stokes number) and sediment concentration must be based on the multiphase flow theory. For fine sediment transport in the muddy environments, the Stokes number of cohesive sediment particles (primary particles or flocs) is typically smaller than 1.0 and the Equilibrium Eulerian Approximation (Balachandar & Eaton 2010) can be adopted. This approximation allows algebraic representation of particle velocity without solving the momentum equations of particle phase and the correspoding coupling terms. This simplified formulation is similar to treating the effect of sediment on carrier flow as straitified flow with additional consideration of settling velocity, and rheology/sediment diffusivity due to inter-particle interactions. To greatly reduce the uncertainties in the turbulence closure for sediment-laden flow, a 3D turbulence-resolving simulation tool is developed in this study. The numerical model extends a 3D pseudo-spectral Navier-Stokes solver with high numerical accuracy (Cortese & Balachandar 1995) to study the role of sediment-induced density stratification in determing the resulting fine sediment transport and bed states in the wave boundary layer (Ozdemir et al. 2010, 2011). Because pseudo-spectral scheme is only suitable for simulation with constant viscosity, recently this code is revised with a sixth-order compact-finite difference scheme in the vertical direction in order to incorporate rheology and shear-induced sediment dispersion. Our goal is to further investigate the interplay between turbulence and rheology in determining the resulting flow regimes and flow dissipation. This new numerical framework also allows us to further develop the code into a complete four-way coupled multiphase formulation without small Stokes number approximation. In fact, since early 2012, we have initiated a new research effort to develop turbulence-resolving numerical model for coarser grain (sand) and poly-dispersed (e.g., size, density and shape) transport in four-way-coupled Eulerian and Euler-Lagrangian numerical frameworks.

WORK COMPLETED AND MAIN RESULTS

3D turbulence-resolving simulation of fine sediment transport

We begin by investigating wave-induced mud transport in the more energetic muddy shelf, such as that in the inner-shelf of Eel River where the Stokes Reynolds number of the wave boundary layer is around Re_{Δ}=1000 (Traykovski et al. 2000). Our simulation results reveal the existence of four flow modes (or possible seabed states Ozdemir et al. 2010) of wave-induced fine sediment transport due to the variation of sediment availability for a fixed settling velocity (~0.5 mm/s) : 1) a well-mixed sediment concentration with no modulation in turbulence in very dilute flow (~1 g/L or smaller), 2) formation of sharp sediment concentration gradient in the water column, i.e., lutocline, at near bed sediment concentration of O(1~10) g/L. The flow above the lutocline is quasi-laminar due to damping of turbulence by sediment-induced stable density stratification but flow below the lutocline remains turbulent, 3) nearly laminar profiles throughout the entire wave boundary layer of both the sediment and fluid phases but followed by burst events due to shear instability during flow reversal. This occurs at near bed concentration of several tens per liter, 4) at O(100) g/l or greater, a complete laminarization throughout the wave cycle. The existence of these flow modes has critical implications to our capability in assessing the muddy seabed states and various applications related to fluid mud transport. For instance, mode I represents a significantly confined, but highly mobile transport close to the seabed. Understanding the transition between mode I and mode II allow us to estimate the amount of offshore fine sediment transport via wave-supported gravity-driven mudflows (e.g., Traykovski et al. 2000). Moreover, mode III and IV represent significantly calm, gooey and less mobile fluid mud. Field observation suggests when modes III and IV occur, large surface wave damping rate is expected. In our recent work (Ozdemir et al. 2011), we also demonstrated the existence of these modes for a range of settling velocity under the same sediment availability and wave intensity (Re_Δ=1000). Our ongoing work focuses on less energetic wave condition, similar to that at Atchafalaya inner-shelf, in the range of Re_Δ=400~800. Our goal is to develop a criteria for the transition between mode II and mode II (or IV), i.e., a saturation condition for wave-induced fluid mud for a range of Reynolds number. Two manuscripts regarding the transitional nature of wave boundary layer at low Re_Δ and the effect of sediment on the resulting flow modes are currently in preparation.

The interplay between turbulence and rheology
To further investigate the interplay between the collapses of turbulence, the rapid settling of sediment associated with laminarization, and the initiation of rheological stress due to the rapid increase of sediment concentration near the bed, we extend the numerical model of Ozdemir et al. (2010, 2011) with capabilities of modeling rheological stress. Because it is difficult to incorporate rheological stress in a pseudo-spectral scheme, this code is recently revised with a sixth-order compact-finite difference scheme in the vertical direction. Simulation is carried out at Re_Δ=600, which represents typical wave condition of typical low energy muddy continental shelves. According to prior studies, such as Spalart & Baldwin (1989) and our own direct numerical simulations (for clear fluid), flow at Re_Δ=600 is not fully turbulent. However, flow instabilities occur during flow reversal that further leads to chaotic motion before the following peak flow.

It should be first mentioned here that because the flow is not fully turbulent for Re_Δ=600, adding sediments further damps flow turbulence via sediment-induced density stratification (Ozdemir et al. 2011) and we found that when computing the simulations for sufficient amount of wave periods, flow started with mode II, i.e., turbulent with a lutocline, eventually laminarizes. This feature is quite different from that observed for Re_Δ=1000 in more turbulent condition. In the present simulation of Re_Δ=600, without incorporating rheology, flow laminarizes after 25 wave periods. Hence, the key issue to be investigated is whether adding rheology may delay or encourage laminarization. To illustrate the turbulent state of the computed flow field, the turbulent coherent structure is identified by λ_{ci}-method (Zhou et al. 1999). To further illustrate the mixing and suspension of sediment near the bed, we use the iso-surface of normalized sediment concentration. These flow visualizations during flow reversal are presented in Figure 1. Comparing to the model results without rheology, we find that the present Newtonian rheological stress with an enhance viscosity tends to attenuate more turbulence and eventually trigger earlier laminarization. Preliminary results reveal that when rheology is incorporated (Figure 1(a1), (a2)), wave boundary layer during flow reversal is less turbulent comparing to that without rheology (Figure 1(b1), (b2)). Similar features are also observed during other flow phases. Laminarization further causes more significant settling, higher sediment concentration accumulated near the bed, and finally results in enhanced hydrodynamic dissipation. Our preliminary finding that rheology encourages laminarization may explain why large attenuation of surface waves over muddy seabed is ubiquitous and the highest dissipation rate is often observed during the waning stage of a storm (A. Sheremet (U. Florida) and P. Traykovski (WHOI), personal communications). Our work of fine sediment transport in the wave boundary layer and the effect of rheology was recently presented in the International Conference on Coastal Engineering 2012 (July 2nd~6th in Santander, Spain). Recently, we were notified by the Coastal Engineering Research Council (CERC) of ASCE that our work was selected as outstanding contribution to the conference.

Four-way-coupled Eulerian and Euler-Lagrangian numerical frameworks
In FY12, we extended our earlier one-dimensional-vertical Reynolds-averaged two-phase sheet flow model (Hsu et al. 2004) into a 2D/3D Eulerian Reynolds-averaged or 3D Large-eddy simulation model for sediment transport. The successful extension to multi-dimensions is benefited from an open-source CFD package, OpenFOAM (www.openfoam.org). This is an efficiently parallelized CFD library based on a 2nd-order finite volume scheme that is flexible to simulate objects with complex geometry, irregular bottom bathymetry, and free-surface waves in the future. This 2D/3D Eulerian two-phase Model is currently undergone comprehensive validation with laboratory data on sheet-flow and bedform dynamics. Figure 2 shows our recent simulation of sheet flow of coarse grain of 0.5 mm in diameter but light density in order to model the new U-tube experiment at NRL lead by Dr. Calantoni. To model sheet flow, it is common to assume that sheet flow is fully developed in the streamwise (x) direction (e.g., Hsu et al. 2004). However, in the present 2D simulation, we can clearly see the generation of flow instabilities that further cause large suspension in the sheet flow condition. Simulation results shown here is consistent with laboratory U-tube observation by Dr. Calantoni's group at NRL. It is clear that the conventional 1DV model for sheet flow is not able to capture such flow instability and consequent generation of large sediment cloud. The key issue to be investigated now is whether such large suspension events cause significant transport rate that is not predicted by typical 1DV models. Recently, the timely development of an open-source CFDEM (http://web678.public1.linz.at/Drupal/), which couples the fluid solver OpenFOAM with the Discrete Element Model (DEM) solver LIGGGHTS (an improved LAMMPS for granular flow applications; http://lammps.sandia.gov/), allows various particle-laden flow applications. The greatest advantage of utilizing a DEM approach to describe the particle phase is that the poly-dispersed nature of sediment transport (e.g., mixed grain sizes, density and shape, etc) can be effectively simulated. The code has been modified to simulate sediment transport in an oscillatory boundary layer setting. We are currently evaluating the scalability of the code and in the near future, we will be able to validate the code with U-tube data on sand transport in the sheet flow condition.

IMPACT/APPLICATIONS

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. Ongoing extension of the turbulence-resolving numerical model for transport of coarser sediments and poly-dispersed transport are directly relevant to RIVET I & II where the seabed is mainly sandy or mixed sand-mud environments.

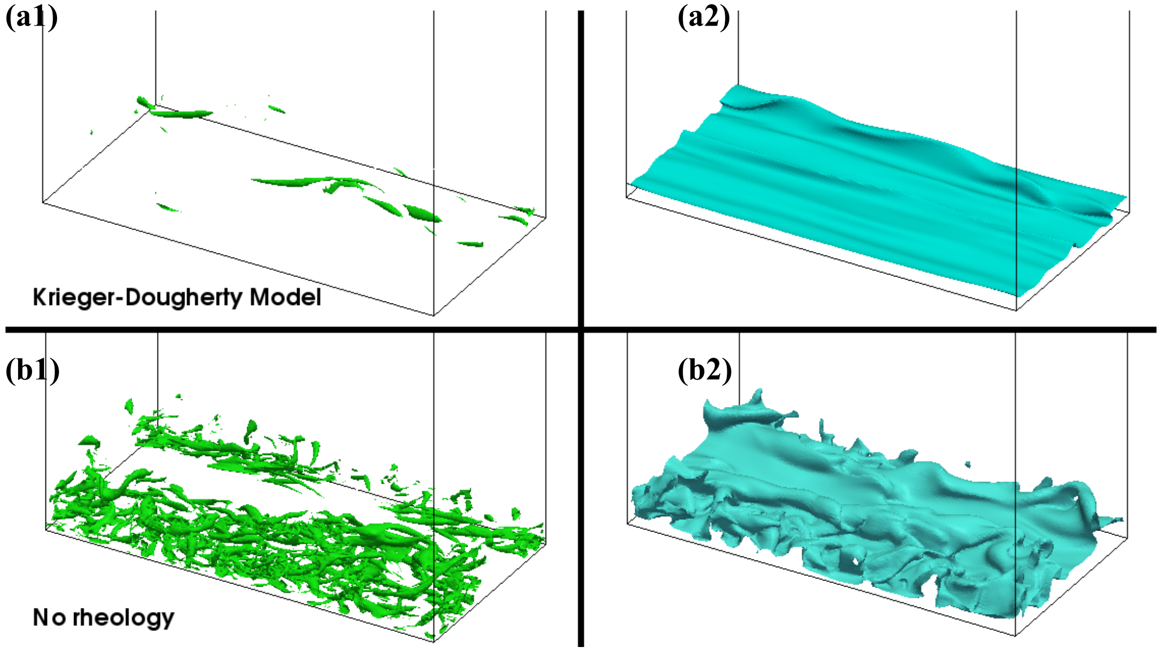
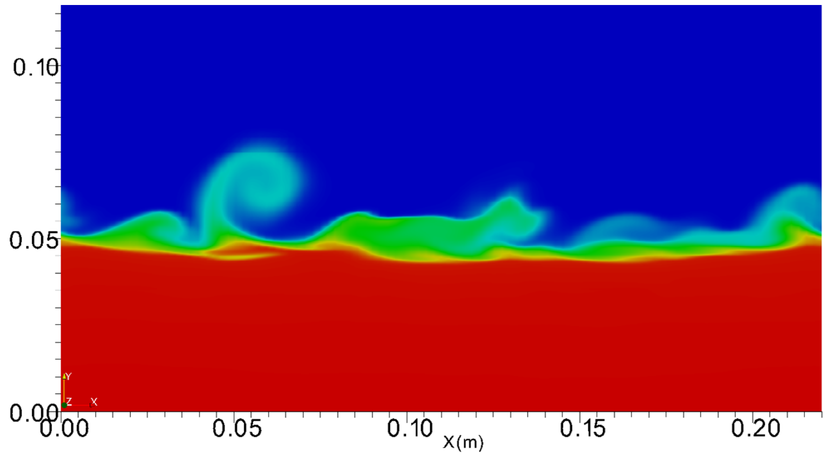


Figure 1: Numerical simulation of fine sediment transport in the oscillatory boundary layer of Re_{Δ}=600 (similar to the wave condition at the Atchafalaya Shelf) using the new numerical model incorporating sixth-order compact finite difference in the vertical (z) direction to include rheological stress. Results presented here are iso-surface of turbulent coherent structure identified by λ_{ci} (Zhou et al. 1999, see left panels) and sediment concentration (right panels) in Regime II where turbulence below the lutocline is energetic. When rheology is not incorporated (see (b1) and (b2)), near bed turbulence is energetic. However, when rheology is incorporated (Krieger-Dougherty equation where viscosity increases as a power law function with sediment concentration), near bed turbulence is much less energetic (see (a1) and (a2)) and eventually (not shown) the entire wave boundary layer is laminarized.

(a)



(b)

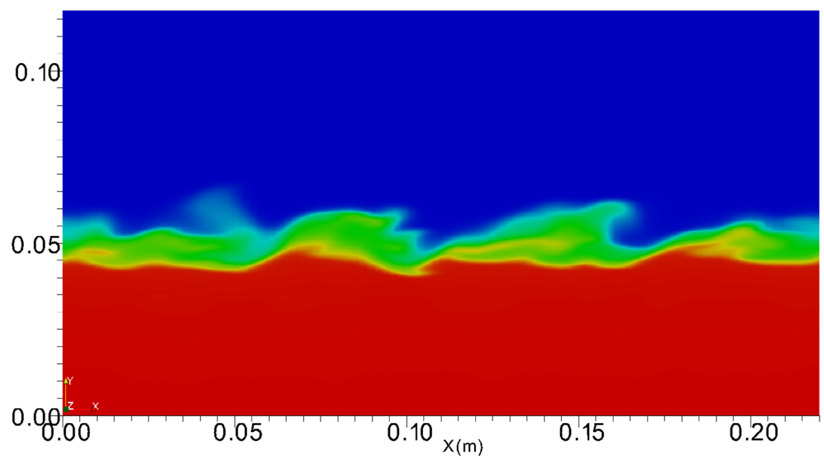


Figure 2: 2D simulation on sheet flow (grain diameter d=0.5 mm, specific gravity s=1.17) transport in an oscillatory flow (U=0.22 m/s, T=2.38 sec) during (a) flow reversal and (b) flow peak. The color represents sediment volumetric concentration. The red color corresponds to sediment volumetric concentration of 0.6 or greater and hence represents the bed. The blue color represents zero sediment concentration. The computational domain is of 0.22 m in x-direction and 0.3 m in the vertical direction (only lower 0.12 m is shown). In this simulation the lower 0.03 m of the bed is never eroded (red color). The minimum grid size in the vertical direction is 0.4 mm and constant grid size of 2 mm is used in the horizontal direction.

REFERENCES

Beardsley, Robert C., Julio Candela, Richard Limeburner, W. Rockwell Geyer, Steven J. Lentz, Belmiro Castro, David Cacchione and Nelson Carneiro, (1995). The M2 tide on the Amazon shelf. *J. Geophys. Res.,* 100(C2), 2283-2319.

Balachandar, S. & Eaton, J. K. 2010 Turbulent dispersed multiphase flow. Annu. Rev. Fluid Mech. 42, 111–133.

Cortese, T. and Balachandar, S. 1995. High performance spectral simulation of turbulent flows in massively parallel machines with distributed memory. *International Journal of Supercomputer Applications,* 9 (3), 187–204.

Elgar, S. and Raubenheimer, B. 2008. Wave dissipation by muddy seafloors, *Geophys. Reas. Lett.* 35, L07611, doi:10.1029/2008GL033245.

Hsu, T.-J., Jenkins, J. T. & Liu, P. L.-F. 2004 On two-phase sediment transport: sheet flow of massive particles. Proc. R.. Soc. Lond. A 460 (2048), 2223–2250.

Kineke, G. C., Sternberg, R. W., Trowbridge, J. H., Geyer, W. R., 1994, Fluid-mud processes on the Amazon continental shelf, Cont. Shelf Res., 16(5/6), 667-696.

Nittrouer, C. A., D. J. DeMaster, A. G. Figueiredo, and J. M. Rine, (1991) AMASSEDS: An interdisciplinary investigation of a complex coastal environment, Oceanography, 3-7.

Ozdemir, C. E., Hsu, T.-J., Balachandar, S., 2010. A numerical investigation of fine particle laden flow in oscillatory channel: the role of particle-induced density stratification, *J. Fluid Mech*., *665, 1-45*.

Ozdemir, C. E., T.-J. Hsu, and S. Balachandar, (2011) A numerical investigation of lutocline dynamics and saturation of fine sediment in the oscillatory boundary layer, *J. Geophys. Res.*, 116, C09012, doi:10.1029/2011JC007185.

Sahin, C., I. Safak, A. Sheremet, and A. J. Mehta (2012), Observations on cohesive bed reworking by waves: Atchafalaya Shelf, Louisiana, *J. Geophys. Res.*, 117, C09025, doi:10.1029/2011JC007821.

Sheremet, A. & G. W. Stone (2003). Observations of nearshore wave dissipation over muddy sea beds, *J. Geophy. Res*., 108 (C11): 3357.

Spalart, P. R. & Baldwin, B. S. 1989 Direct simulation of a turbulent oscillating boundary layer. In Turbulent Shear Flows 6 (ed. J. C. Andre), pp. 417–440, Springer.

Traykovski, P., Geyer, W. R., Irish, J. D. and Lynch, J. F. (2000) “The role of wave-induced fluid mud flows for cross-shelf transport on the Eel River continental shelf,” *Cont. Shelf Res*. 20, pp. 2113-2140.

Traykovski P. (2010) “Observations of mechanisms of dissipation of wave energy over a muddy seabed,” (*Invited*) *Eos Trans. AGU, 91*(26), Ocean Sci. Meet. Suppl., Abstract G021A-02.

Zhou, J., Adrian, R. J., Balachandar, S. & Kendall, T. M. 1999 Mechanisms for generating coherent packets of hairpin vortices in channel flow. J. Fluid Mech. 387, 353–396.

PUBLICATIONS

1. Ozdemir, C. E., Hsu, T.-J., Balachandar, S., (2010). A numerical investigation of fine particle laden flow in oscillatory channel: the role of particle-induced density stratification, *J. Fluid Mech., 665, 1-45.* [PUBLISHED, REFEREED]
2. Son, M., and T.-J. Hsu, (2011). Idealized study on cohesive sediment flux by tidal asymmetry, *Environmental Fluid Mechanics*, 11(2), 183-202, DOI 10.1007/s10652-010-9193-9. [PUBLISHED, REFEREED]

3. Son, M., and Hsu, T.-J., (2011) The effects of flocculation and bed erodibility on modeling cohesive sediment resuspension, *J. Geophys. Res*., 116, C03021, doi:10.1029/2010JC006352. [PUBLISHED, REFEREED]
4. Ozdemir, C. E., T.-J. Hsu, and S. Balachandar, (2011) A numerical investigation of lutocline dynamics and saturation of fine sediment in the oscillatory boundary layer, *J. Geophys. Res.*, 116, C09012, doi:10.1029/2011JC007185. [PUBLISHED, REFEREED]
5. Hsu, T.-J., S.-N. Chen, A. S. Ogston, (2012) On the landward and seaward mechanisms of fine sediment transport across intertidal flats in the shallow water region – A numerical investigation, *Continental Shelf Research*, doi:10.1016/j.csr.2012.02.003. [IN PRESS, REFEREED]
6. Hsu, W. Y., Hwung, H. H., T.-J. Hsu, Torres-Freyermuth, A., Yang, R. Y., An experimental and numerical study on wave-mud interaction, *J. Geophys. Res.* [SUBMITTED]
7. Hsu, T.-J., Yu, X., Ozdemir, C. E., Balachandar, S., (2012) A 3D numerical investigation of fine sediment transport in an oscillatory channel, Proceedings of 33rd International Conference on Coastal Engineering, Santander, Spain, 2012. [IN PRESS]