

A Fluid Mud Transport Model in Multi-dimensions

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LONG-TERM GOALS

The long term goal is to develop a robust multi-phase, multi-class numerical modeling framework for both cohesive and non-cohesive sediment transport in the fluvial and coastal environments.

OBJECTIVES

The objectives of the present study focus on extending a fluid mud model for boundary-layer-driven and gravity-driven transport (Hsu et al. 2007) with several new capabilities. Specifically, the objectives are to:

- Carry out model development and model-data comparisons with laboratory/field observed fluid mud processes, specifically in conjunction with new MURI initiative for understanding wave-mud interaction.
- Extend the existing fluid mud model with a flocculation module and a bed module to enable direct modeling on consolidation/fluidization. Extend the model to multi-dimensional for various coastal and estuarine applications.
- In conjunction to NOPP-Community Sediment Transport Model initiative, the fluid model is utilized to provide parameterizations for wave-boundary-layer-scale transport processes.

APPROACH

It is important to understand the fate of terrestrial sediment into the coastal ocean, because it determines for example the seabed properties and the turbidity of the water column. Several recent initiatives, such as *NOPP Community Sediment Transport Model*, *MURI- Understanding Wave-Mud Interaction* and *Tidal Flats DRI* have put forward new outstanding science and technical questions for coastal sediment. The success of these new studies inevitably depends on our level of understandings on the crucial small-scale mechanisms that can be either resolved or parameterized via detailed measurement and modeling. These new initiatives also have a similar goal to establish improved understanding on coastal hydrodynamics and sediment transport processes in heterogeneous environment with more emphasis on cohesive sediment transport.

The dynamics of fluid-mud transport involve a variety of physical mechanisms, including for example, the boundary layer and gravity-driven transport, turbulence modulation, flocculation, non-Newtonian

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rheological behavior and consolidation (Dyer 1989; Mehta 1989). Hence, a general modeling framework for fluid mud needs to be based on multiphase flow theory. In this study, a fine sediment transport modeling framework based on Fast Equilibrium Eulerian Approximation (Ferry and Balachandar 2001) to the multiphase equations has been developed and extended to model various cohesive sediment transport processes. The cohesive sediment modeling framework is the basis of the three numerical models developed for 1DV, 2DV and full 3D for different applications. In the 1DV modeling, the dynamics of wave-supported gravity-driven mudflows is studied (Hsu et al. 2007; 2008). In the 2DV formulation, wave-mud interaction 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, Direct Numerical Simulation (DNS) of fluid mud transport under oscillatory flow is carried out in a full 3D simulator based on pseudo-spectrum scheme.

WORK COMPLETED

Wave-supported gravity-driven mudflows: Typical coastal models, such as the ongoing NOPP-Community Sediment Transport Model (NOPP-CSTM, Warner et al. 2008) are not designed to resolve the thin wave boundary layer near the seabed. Hence, processes that occur within the wave boundary layer need to be parameterized as sub-module to provide quantities such as bottom drag coefficient and sediment transport rate. The 1DV fluid mud model is utilized to study fluid mud transport in the wave-current boundary layer. The characteristics of wave-supported gravity-driven mudflows are diagnosed by varying the bed erodibility, floc properties (fractal dimension), rheological stresses, and floc dynamics in the numerical simulations. Model results for moderate concentration suggest that using an appropriately specified fractal dimension, the dynamics of wave-supported gravity-driven mudflow can be predicted without explicitly incorporating rheological stress. However, incorporating rheological stress makes the results less sensitive to prescribed fractal dimension. For high concentration condition, it is necessary to incorporate rheological stress in order to match observed intensity of downslope gravity-driven current. Model results are further analyzed to evaluate and calibrate simple parameterizations. Analysis suggests that when neglecting rheological stress, the drag coefficient decreases with increasing wave intensity, and seems to follow a power law. However, when rheological stress is incorporated, the resulting drag coefficient is more or less constant (around 0.0013) for different wave intensities. Model results further suggest the bulk Richardson numbers has a magnitude smaller than 0.25 and is essentially determined by the amount of available soft mud (i.e., the erodibility), suggesting a supply-limited condition for unconsolidated mud. In order to predict more quantitatively the dynamics of wave-supported gravity-driven mudflows, more detailed information on floc properties, rheological stress and erodibility are necessary. Findings of this study are summarized in a manuscript submitted for publication.

Flocculation: The present cohesive sediment transport framework requires realistic constitutive equation for floc breakup and aggregation processes (e.g., Winterwerp 1998). Based on field/laboratory observations, the fractal dimension is not a constant and shall change dynamically with the carrier turbulent flow (e.g., Dyer and Manning 1999). Recently, Khelifa and Hill (2006) proposed a model for settling velocity that utilizes a variable fractal dimension depending on the floc size itself (e.g., fractal dimension becomes 3.0 when floc size reduces to that of primary particle). Here, we further derive the balance equations for floc dynamics based on the variable fractal dimension and come up a new model for floc dynamics that can be coupled with numerical model for fluid mud transport. The new formulation is shown to predict the equilibrium floc size under different turbulent shear rates measured in the laboratory (Son and Hsu 2008). Currently, we are testing and accuracy and

robustness of such flocculation formulations in a numerical model for cohesive sediment transport in tidal-dominated condition.

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 has been modified for the study of wave-mud interaction. The resulting governing equations and closures reduce to the RANS equations when the sediment concentration approaches zero. Hence, 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. Since FY08, postdoc researcher Alec Torres-Freyermuth has worked closely with Hsu and Traykovski as well as other teams participated in the Achafalaya field experiment to utilize this 2DV model to study wave-mud interaction. The code has been further improved upon the implementation of a new wave forcing boundary condition (Torres-Freyermuth et al. 2007), the optimization of the mesh and obstacle generation, and the CPU time reduction that allow computing more realistic and longer simulations.

RESULTS

With the aim of gaining insight on the processes related to wave-mud interaction, the 2DV model is employed using three different wave types. Cohesive sediment of floc size $22\ \mu\text{m}$ and specific gravity 1.34 is specified in all tests shown here. High resolution in the vertical water column is adopted and hence wave boundary layer structure and pycnocline are resolved by the numerical model. Monochromatic progressive waves, standing waves, and wave groups propagating over a planar bottom are considered. The monochromatic progressive wave cases are studied as a part of the pre-validation stage of the model. On the other hand, the standing-wave and wave group cases are further studied in order to test different hypothesis. The former concerns the scaling between the wave bottom boundary layer and the fluid mud layer thickness reported in the field (e.g. Traykovski et al. 2007), while the later is used to obtain more insight on the role of nonlinear wave interaction in the damping of the higher (e.g. Sheremet & Stone, 2003) and the lower frequencies waves (e.g. Elgar & Raubenheimer, 2008) in the incident wave spectrum.

For the monochromatic wave tests, a cnoidal wave train of 0.72 m wave height and 6 s period is sent into a 2.5 m water depth numerical flume. The amount of suspended sediment is controlled by varying the sediment availability (erodibility) for each of the two cases, resulting in different fluid-mud characteristics (e.g. thickness, viscosity, etc.) and damping rates under the same forcing. Subsequently, the numerically obtained time- and depth-dependent fluid-mud layer characteristics are integrated to provide the input bulk parameters (mud layer thickness δ and bulk viscosity ν_m) required in simplified two-layer wave propagation model (Kranenburg, 2008). Good agreement between the 2DV model results and the two-layer model results is observed in terms of the wave height at four different cross-shore positions (Figure 1b). These results provide confidence in terms of the model consistency and capability for providing reliable information on the magnitude of wave dissipation rates and the model application on the study of more complicated wave conditions (e.g. wave groups, irregular waves).

A standing wave test is selected to study bottom wave boundary layer dynamics. A small amplitude monochromatic long-wave is propagated into the numerical wave flume and is completely reflected by a vertical wall located at the downstream end of the flume generating a standing wave pattern (Figure 2a). Fluid-mud is preferentially suspended near the nodes (horizontal velocity amplitude maximum)

and in fact the fluid-mud thickness modulates in the cross-shore direction depending on the horizontal velocity amplitude (Figure 2b). The wave boundary layer thickness (blue curve in Figure 2b) coincides with the luctocline location defined as the largest vertical gradient in the sediment concentration profile (red curves in Figure 2b). Moreover, the velocity profiles with fluid-mud (blue curves) when compared with the clear fluid condition (black-dashed curve) shows a significant wave boundary layer enhancement. In terms of the wave amplitude, comparison between the clear fluid and the fluid-mud results shows evidence of wave energy transfer from principle harmonic to higher harmonics due to wave-wave interaction triggered by the presence of fluid-mud (Figure 2c). The reader is referred to unexpected local amplitude maximum near the node when the fluid-mud is present.

Finally, a wave group with its corresponding sub- and super-harmonics is sent to propagate into the numerical wave flume. A sponge layer is placed at the downstream end of the flume in order to absorb the incoming wave energy. Free-surface elevation time series measured downstream of the flume shows a wave decay as compared with another simulation without the fluid mud (Figure 3a). The energy attenuation occurs almost among all frequencies (except around $f=0.1$ & 0.35 Hz) in the energy spectrum (Figure 3b). The frequency dependence of the dissipation rate is obtained by comparing the numerical simulation from the clear fluid with the one with fluid-mud. Differences between nondissipative (blue) and dissipative (red) model predictions are attributed to mud-induced dissipation and mud-induced wave energy transfer. The higher dissipation rates for this case correspond to the sub- and super-harmonic frequencies (Figure 3c) consistent with previous observations pointing out the importance of nonlinear energy transfer as a mechanism of wave attenuation (e.g. Elgar & Raubenheimer 2008). Moreover, the energy increase at discrete frequencies (e.g. $f=0.1$ Hz in Figure 3b) for the fluid-mud simulation is another indication of the excitation of wave-wave interaction by the presence of mud.

IMPACT/APPLICATIONS

The present research efforts focus on developing a numerical modeling framework for cohesive sediment transport. Currently, the PIs are also actively participating in other related initiatives and are partners of the ongoing NOPP-CSTM and CSDMS. Hsu has actively participated in the ongoing NICOP - Preliminary Investigations on the Fate of Terrestrial Sediments in the Coastal Ocean Discharged from Taiwanese Small Mountainous Rivers, supported by ONRG and ONR (Coastal Geosciences). The 2DV model discussed here was recently extended to calculate salinity transport to simulate sedimentation processes at river mouth.

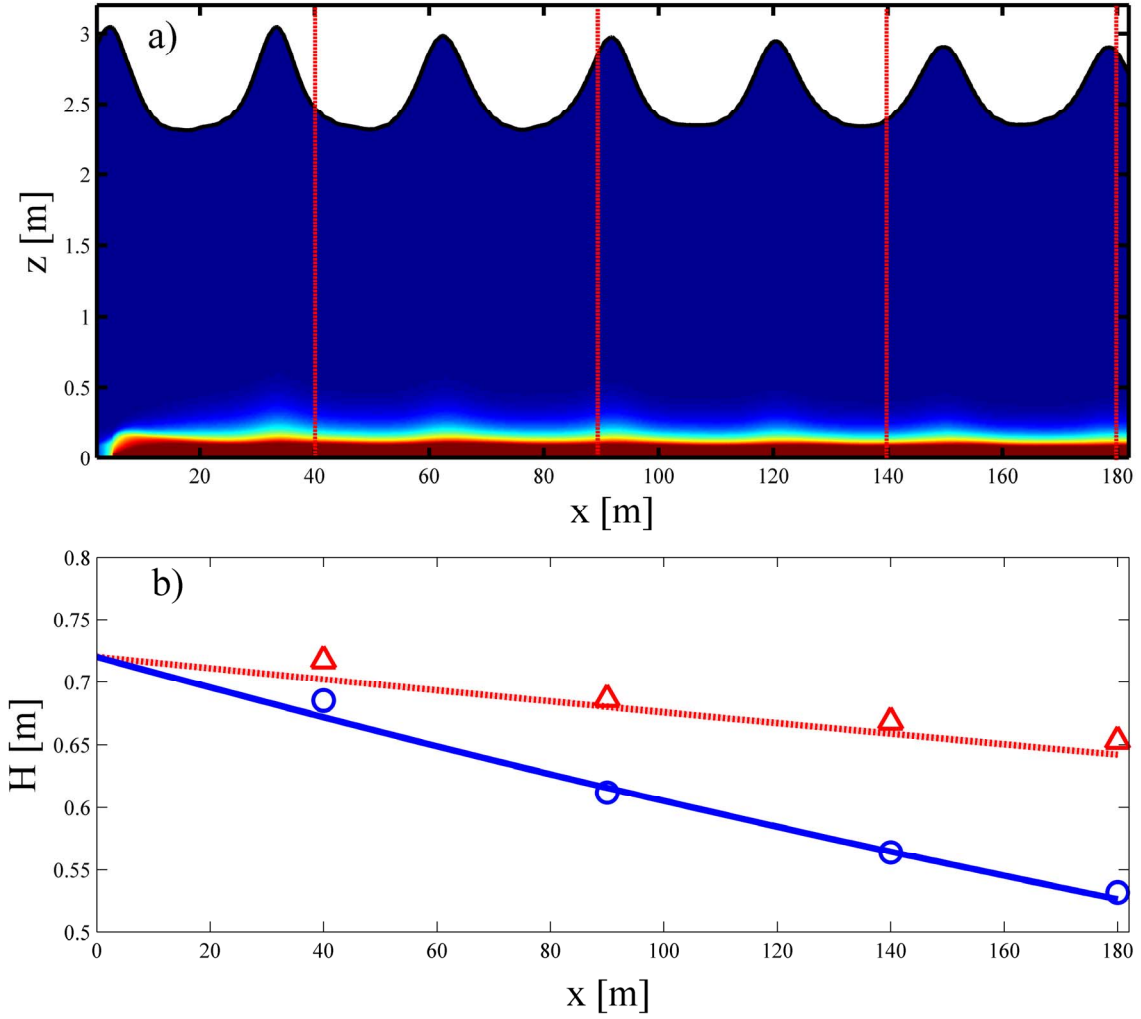


Figure 1: (a) Snapshot of the model results for free-surface elevation and mud concentration in the numerical wave flume. The vertical red-dashed lines correspond to the discrete cross-shore positions where wave gauge data was collected. (b) Comparison of wave gauge data (symbols) and the two-layer model predictions (lines) for wave height as a function of cross-shore position. The triangles (circles) and red-dashed (blue-solid) line represent 2DV model results and two-layer model results respectively for the low (high) erodibility condition with bulk mud layer characteristic required by the two-layer model specified as $\delta=6\text{cm}$, $\nu_m=7.5\times10^{-4}\text{m}^2/\text{s}$, and $\rho_m=1300\text{Kg}/\text{m}^3$ ($\delta=12\text{cm}$, $\nu_m=3.8\times10^{-3}\text{m}^2/\text{s}$, and $\rho_m=1300\text{Kg}/\text{m}^3$). These bulk mud layer parameters are obtained directly by integrating 2DV model results.

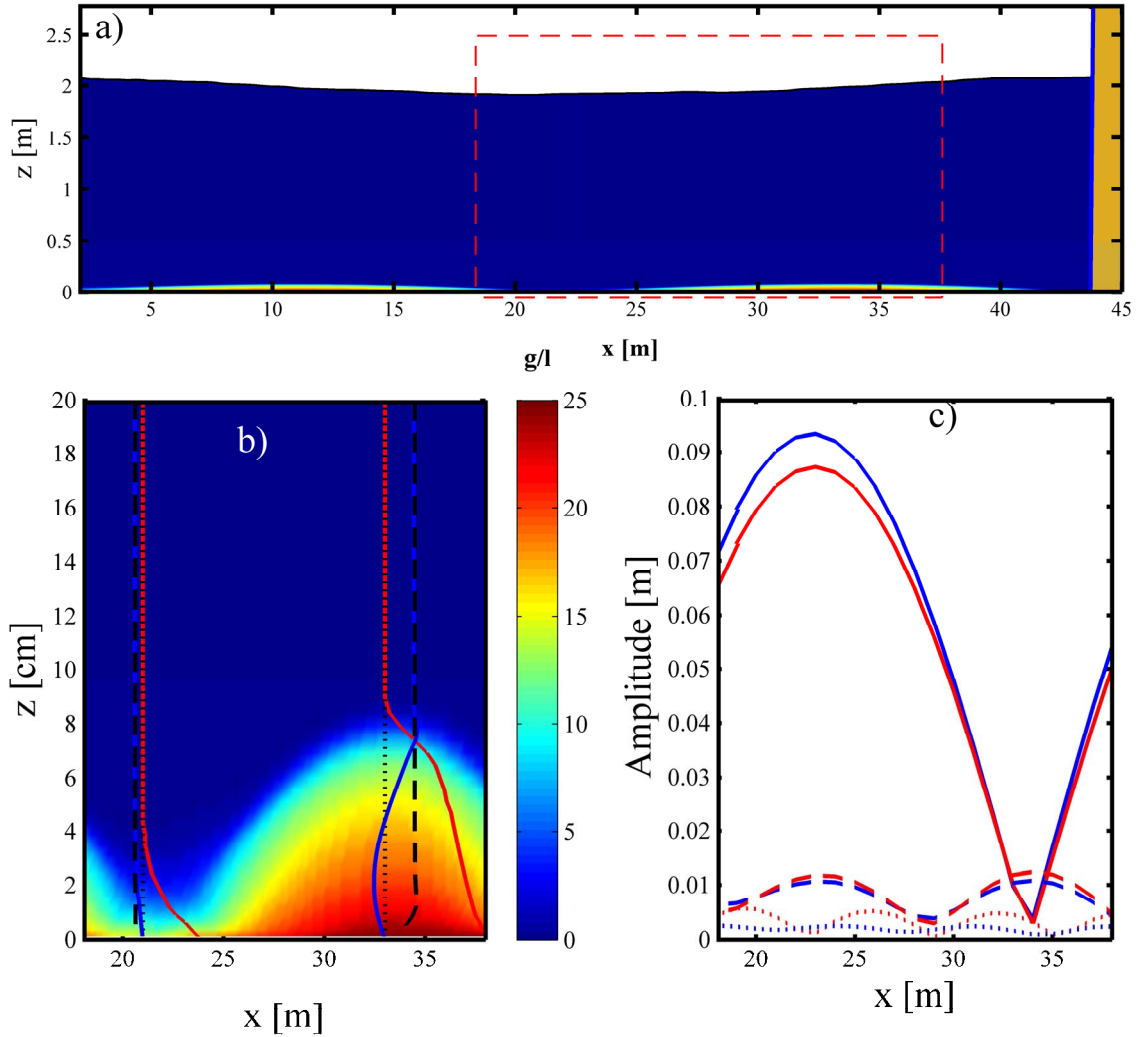


Figure 2: (a) Snapshot of the model results for free-surface elevation and mud concentration in the numerical wave flume for the standing wave case. The dashed square box represents the area discussed in (b) and (c). (b) Snapshot of fluid-mud concentration near the bed with the corresponding velocity (blue curve) and concentration (red curve) profiles under the antinode ($x=21$ m) and the node ($x=34$ m). The dotted curves represent zero mud concentration which is a reference case of clear fluid simulated for the sake of comparing the effect of mud with black-dashed curves represent the corresponding velocity profiles. The wave boundary layer thickness scales with the fluid-mud layer, and is enhanced when comparing to the clear fluid condition. (c) Comparison of the cross-shore variation of wave amplitude for the clear fluid (blue) and the fluid-mud (red) tests. The first harmonic (solid curves) is attenuated due to the presence of the mud at all cross-shore positions. On the other hand, the second- (dashed curves) and third- harmonics (dotted curves) are enhanced near the node ($x=34$ m) when fluid mud presents. Hence the total wave amplitude (sum of all curves) near the node ($x=34$ m) is unexpectedly enhanced.

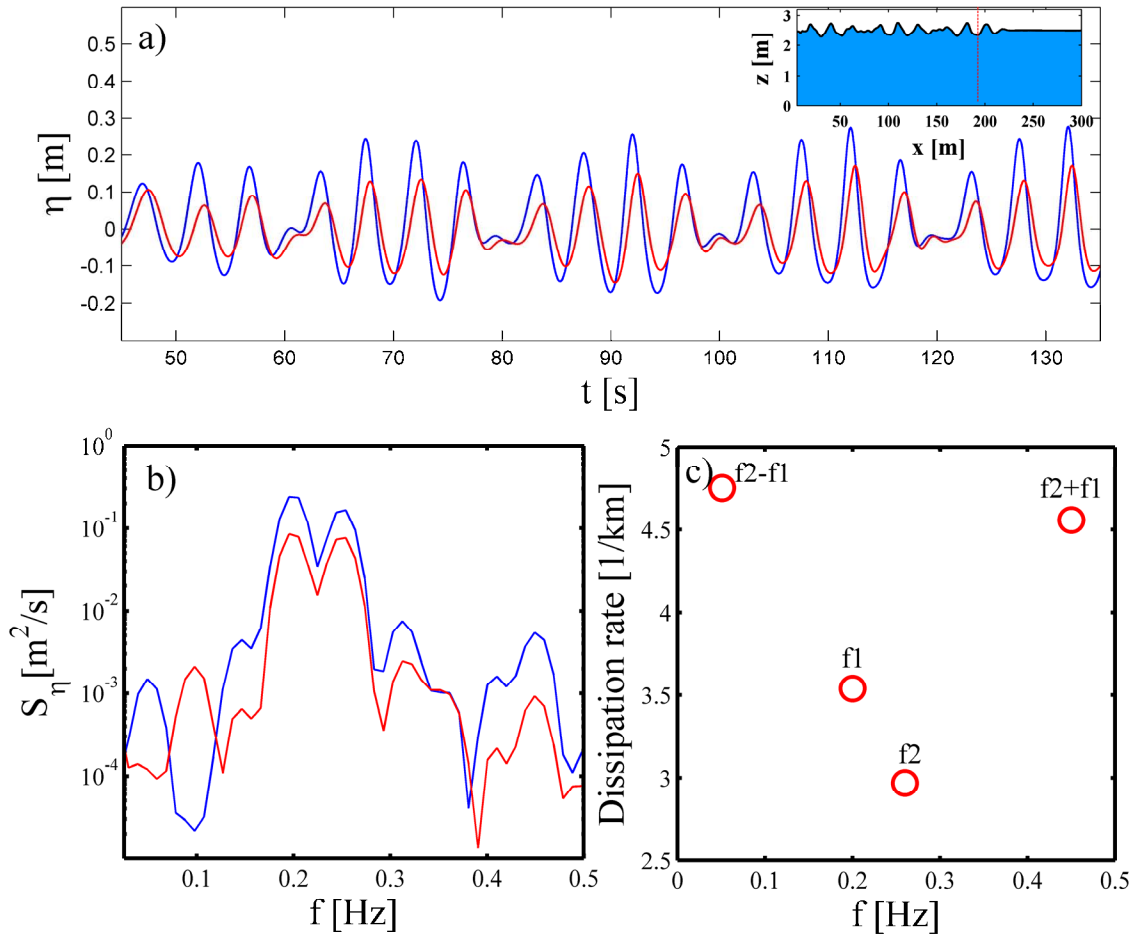


Figure 3: (a) Free-surface elevation time series measured at the downstream of the flume ($x=185$ m) for the clear fluid (blue curve) and the fluid-mud (red curve) tests. (b) Free-surface energy density spectra for these two simulations. Differences between the non-dissipative (blue curve) and dissipative (red curve) cases are attributed to fluid-mud induced dissipation and mud induced wave energy transfer. (c) Dissipation rate at discrete frequencies obtained as the difference in the energy flux from the two simulations. The dissipation rates are higher for the sub-harmonic (f_2-f_1) and super-harmonic (f_2+f_1) frequencies.

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