DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

A 3D Coupled Euler-Lagrangian Numerical Modeling Framework for Poly-dispersed Sediment Transport Simulations

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

Grant Number: N00014-14-1-0586

LONG-TERM GOALS

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

OBJECTIVES

- Develop and validate a finite-volume Euler-Lagrangian solver, CFEDM, for sediment transport applications, including transport of non-spherical grains.
- Evaluate several existing mathematical models for non-spherical particles to simulate sediment transport in terms of their efficiency and resulting transport physics.
- Investigate poly-dispersed sediment transport in energetic wave-current boundary layer, namely, sheet flow and momentary bed failure (plug flow) using the Euler-Lagrangian model and the more efficient Eulerian two-phase model.

INTRODUCTION

Understanding various modes of sediment transport and the resulting transport rate under waves and currents are the key to a better prediction of morphodynamics in the coastal environments. Sediment transport mode is also critial to the parameterization of bottom friction in coastal modeling systems. In the past two decades, major progress has been made to understand mechanisms driving onshore/offshore sediment transport in sandy beaches. Now it is well-recognized that several wave-induced mechanisms (e.g., Drake & Calantoni 2001; Hoefel & Elgar 2003; Conley & Beach 2003; Henderson et al. 2004; Hsu et al. 2006) can cause onshore sediment transport while offshore transport is mainly driven by the undertow currents (e.g., Gallagher et al. 1998). When these mechanisms are incorporated into coastal evolution models (e.g., Ruessink et al. 2007; Chen et al. 2014), the model is able to predict beach erosion and recovery on weekly and seasonal timescales, including the impact of moderate storms. However, model skill remains to be low during major wave events (e.g., hurricane, see Ruessink & Kuriyama (2008)). With the threat of sea-level rise and increased intensity/frequency of storms, researchers must now focus on processes that become dominant during extreme events. Past progresses made in nearshore research have benefited from several community-wide meetings. In the

recent Nearshore Vision Meeting, sediment transport during extreme events and heterogeneous sediments are both identified among the list of focused research areas.

Large-scale models (e.g., Warner et al. 2008) for coastal morphological evolution typically split the total sediment transport into bedload and suspended load components. Invoking dilute flow assumptions, suspended load transport is resolved. However, the concentrated region of sediment transport near the bed cannot be resolved in this type of models and semi-empirical parameterizations of bedload transport rate and pickup flux are used to complete the mathematical description. These parameterizations are often developed from direct extension of simple flow conditions and hence many key assumptions are adopted (e.g., ignoring unsteadiness) when applied to coastal environments. These sediment transport parameterizations also do not explicitly consider mixed grain size transport and non-spherical particle shapes. Therefore, more research is needed in order to include the effect of heterogeneous sediments.

The two-phase flow methodology provides a more comprehensive framework to model these complicated sediment transport processes and to improve the existing parameterizations used by the coastal evolution models. A two-phase model can resolve the concentrated region of transport by including closures of particle stresses and fluid-particle interactions in the governing equations. Several two-phase models for sediment transport have been developed, where the sediment phase is modeled either with an Eulerian scheme (e.g., Hsu et al. 2004) or a Lagrangian scheme (e.g., Drake & Calantoni 2001). These two-phase models can resolve the full profiles of sediment transport without conventional bedload/suspended load assumptions. However, most existing two-phase models are based on Reynolds-averaged approach and often simplified into one-dimensional-vertical (1DV) formulation. 1DV models cannot capture the development of inhomogeneous flow features and imposes severe restriction on problems driven by energetic waves and currents. 1DV model also cannot resolve turbulence-sediment interaction because turbulence is naturally 3D. In many respects, the Lagrangian description of sediment phase, typically called Discrete Element Method (DEM), is also superior to the Eulerian description. Particle stresses in DEM is resolved to the individual grain level and hence it has no restriction on multiple contacts (Drake 1990). Therefore, DEM can simulate the whole dynamics of intergranular interaction more accurately than typical Eulerian models. Moreover, because each sand grain in DEM is unique, it is straightforward to simulate transport of mixed grain sizes, which is the first step toward modeling heterogeneous sediments, such as bed armoring (e.g., Wiberg et al. 1994). In the Euler-Lagrangian model of Calantoni et al. (2004), the predicted sediment transport rate is improved when modeling natural sand grain shape using composite particles.

The primary goal of this study is to develop the next generation simulation tools to study sediment transport. Specifically, we focus on developing a multi-dimensional Eulerian two-phase model with turbulence-resolving capability and multi-dimensional Euler-Lagrangian model capable of simulating non-spherical grain shapes.

APPROACH

For the Euler-Lagrangian model of sediment transport, we implemented the open-source code CFDEM (Kloss et al. 2012), which couples the fluid solver OpenFOAM with the DEM solver LIGGGHTS (revision of LAMMPS (Plimpton 1995) for granular flow applications). CFDEM allows various particle-laden flow applications in industrial and natural systems. The goal in this study is to

revise the code for sediment transport application and to implement new modules for nonspherical sand grains.

With ongoing NSF supports (CMMI-1135026, OCE-1356855), we have successfully developed a multi-dimensional model for sediment transport that solves the complete Eulerian two-phase equations. The model is solved numerically using the open-source CFD library of solvers, OpenFOAM (Rusche 2002). The turbulence-averaged version of ths model has been validated with laboratory data of sheet flow in steady channel flow (Sumer et al. 1996) and oscillatory flow (O'Donoghue and Wright 2004). This numerical model, called twoPhaseEulerSedFoam (version 1.0), was recently disseminated to the research community as an open-source code via Community Surface Dynamics Modeling System (CSDMS) model repository. This model is the backbone for our ongoing development of the 3D turbulene-resolving Eulerian two-phase model for sediment transport. As we will present later, the turbulence-resolving version was just completed and we are currently carrying out model validation (Cheng and Hsu 2014). This Eulerian model, which is much computationally efficient, will be used in conjunction with the Euler-Lagrangian model to study the proposed science issues.

WORK COMPLETED

This project was just started on June 1, 2014. Hence, this section will be focused on presenting the model capability resulted from previous efforts. Figure 1(b), (c) shows the validation of the 2DV Reynolds-averaged two-phase model with measured sediment concentration for medium sand (diameter d_{50}=0.28 mm) in oscillating water tunnel (O'Donoghue & Wright 2004). The model is driven by measured free-stream velocity time series (see Figure 1(a)), which is a sine wave with velocity amplitude 1.5 m/s and period T=5.0 sec. The estimated peak Shields parameter θ is about 2.1 and sheet flow is expected. However, the estimated Sleath parameter S (Sleath 1999; Foster et al. 2006) is only around 0.1 and momentary bed failure/plug flow is not expected. The model is able to reproduce full profiles of sediment concentration at different wave phases. Figure 1(d) show a snapshot of sediment concentration color contour for the lower half of the model domain. The model is able to reproduce a fully-developed flow in the streamwise (x)-direction in the turbulence-averaged sheet flow condition. The sheet flow layer thickness can be visually estimated to be around 1 cm. However, a numerical experiment carried out with only the wave period reduced to T=1.8 sec, which gives a Sleath parameter of S=0.33, shows the occurrence of wave-like bed instabilities throughout the entire wave (see Figure 1(e)). The instabilities have a streamwise length scale of 5~10 cm and through the instability, the sheet flow layer thickness is increased to about 3 cm. The wave-like bed instabilities observed in the model results seem to be consistent with a couple of the field observations under near-breaking waves. For example, Conley & Inman (1992) described their observation of a carpet of tufts (about O(6 cm)) under the crest of near-breaking waves in the surf zone. Although a 2DV Reynolds-averaged model is capable of modeling the onset of instabilities, their subsequent cascade into smaller eddies is parameterized by turbulence closures, e.g., use eddy-viscosity to dissipate turbulence so that the ensemble-averaged flow features are captured. Hence, a turbulene-resolving study on the evolution of wave-like instabilities, its association with momentary bed failure and the resulting transport rate will be investigated in this project.

The development of a 3D turbulence-resolving Eulerian two-phase model based on LES modeling strategy has been completed recently. Here we demonstrate the advantage of the turbulence-reolving capability using a fine sand simulation driven by sinusoidal wave. Figure 2 shows the 3D snapshots of iso-surface of sediment concentration during flow peak and flow reversal. In each panel, the blue iso-

surface represents high sediment concentration of 30%, while the green iso-surface represents dilute concentration of 0.1%. We can see that during flow peak (Figure 2(a)), the distance between these two iso-surfaces is larger, suggesting a large sheet flow layer thickness. There is mild spatial variation due to turbulent eddies. On the other hand, during flow reversal (Figure 2(b)), the averaged distance between these two iso-surfaces becomes much smaller. However, we observe much significant spatial variation. Locally, we have sediment bursts penetrating upward for about 2~3 cm. Simulation results presented here are similar to a few oscillating water tunnel measurements where burst events are only observed during flow reversal for sufficiently fine sand (Dohmen-Janssen et al. 2002).

In the past 4 months, we have rigorously evaluated the capability of CFDEM to simulate sediment transport. Preliminary results and planning will be discussed next.

RESULTS AND PLANNING

We successfully utilized CFDEM to model mixed grain size transport using a 2DV Reynolds-averaged fluid description with a k-ε closure and DEM for sediment phase. Figure 3 shows an example of sediment transport simulation under oscillatory flow. To illustrate the effect of sorting and armoring, we specify 95% of the grain to be of diameter 0.5 mm (see red grain), while the remaining 5% of coarser grains is of diameter 0.8 mm (see blue grain). A total amount of 150,000 grains is used. Because the initial sediment bed is obtained by settling all the particles to the bottom, we can observe that during the first wave, more fine (red) grains are distributed near the surface layer (see Figure 3(a)). However, after the flow is driven by another five waves, a similar snapshot shown at the sixth wave shows that the surface layer is mainly covered by coarser (blue) grains. The observed vertical grading is due to a mechanism called granular convection, or more well-known as the "Brazilian Nut" effect (Rosato et al. 1987).

To further study the effect of particle shape on sediment transport, we adopted the approach used by Calantoni et al (2004), in which non-spherical particles are modeled as composite particles by bonding two spherical particles together. During the summer of 2014, a high school intern joined Hsu's group through a K-12 outreach program organized by the University of Delaware. The student analyzed the shape of many natural sand grains using a microscope and image processing software (see Figure 4) in order to fit the observed shape with the dual-sphere model of Calantoni et al. (2004) and to obtain the Corey shape factor (Corey 1949). Currently, we use another open-source tool YADE (https://yade-dem.org/doc/index.html) to generate the composite particles, which provide more flexibility for year 2 (see next). In each simulation, we will prescribe the diameter of sphere 1 and sphere 2, as well as the distance from the center of the two spheres. We will follow Calantoni et al (2004) to compute the initial values of the center of mass, total mass, moments of inertia of each composite particle and feed this information to LIGGGHTS. For year 2, we will investigate more complicated composite particle scheme (see Guo & Curtis (2015) for a thorough review), which is conceptually similar to dual-sphere model but more computationally intensive. Inter-comparison between simulation results using idealized (spherical) sand grain and non-spherical shaped sand grain will reveal the effect of grain shape on sheet flow and momentary bed failure/plug flow.

IMPACT/APPLICATIONS

Studying an effective modeling approach for natural sand grain shape using composite particle models is the first step to model more complicated problems in the future such as floc aggregates relevant to

cohesive sediment transport and ocean optics. The numerical models developed in this project are all based on open-source codes and hence they will also be disseminated to research community as open-source. See PI Hsu's simulation data/source code page at http://www.coastal.udel.edu/~thsu/simulation_data.htm.

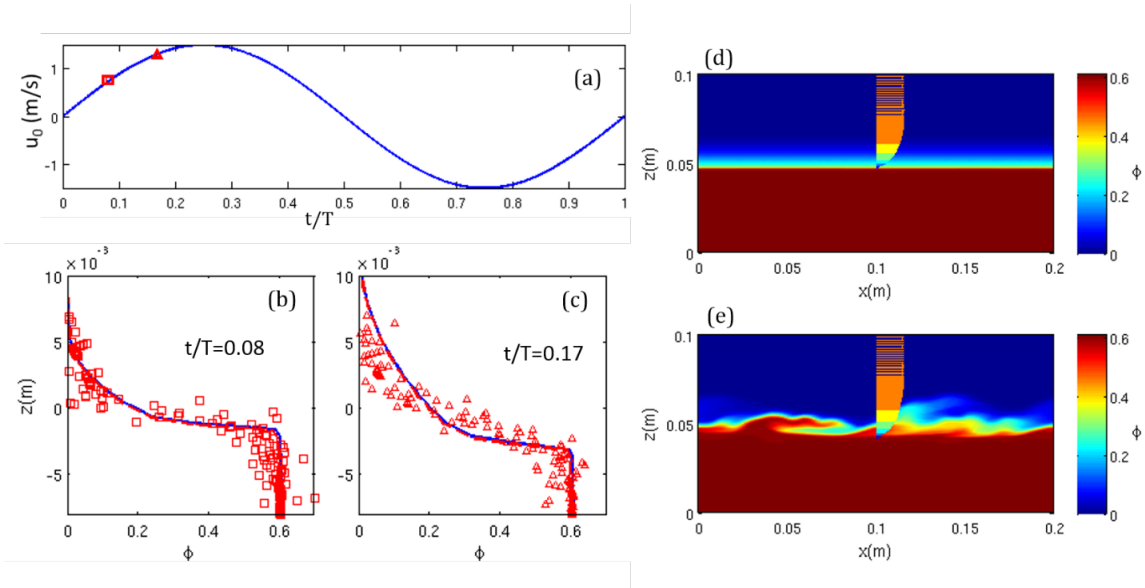

Figure 1: 2DV Reynolds-averaged two-phase model validated with oscillating water tunnel experiment of O'Donoghue & Wright (2004) for sheet flow driven by an oscillatory flow with velocity amplitude 1.5 m/s and period T=5.0 sec. (a) shows the time-series of free-stream velocity and (b) and (c) shows measured (symbols) and modeled (curves) concentration profiles at two instants. (d) shows a snapshot of sediment concentration color contour near flow peak. (e) another simulation carry out with wave period reduced to T=1.8 sec shows wave-like bed instabilities under near flow peak.

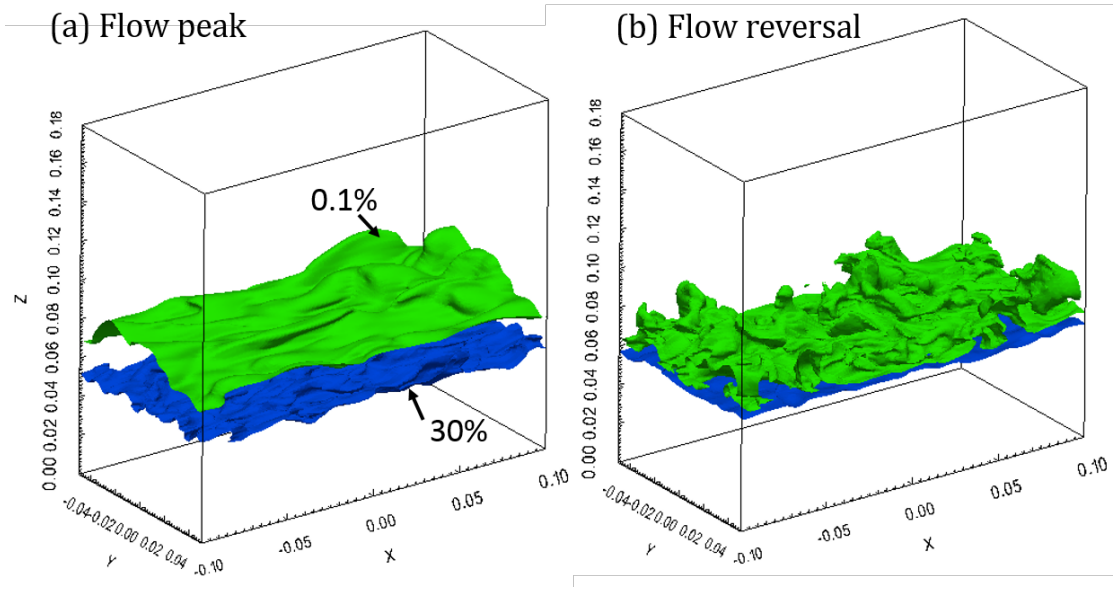

Figure 2: 3D turbulence-resolving simulation of fine sand transport in oscillatory flow with velocity amplitude 1.5 m/s and T=5.0 sec. Snapshots of iso-surface of sediment concentration during (a) flow peak and (b) flow reversal. The green iso-surface represent volumetric concentration of 0.1% and the blue iso-surface represent 30%.

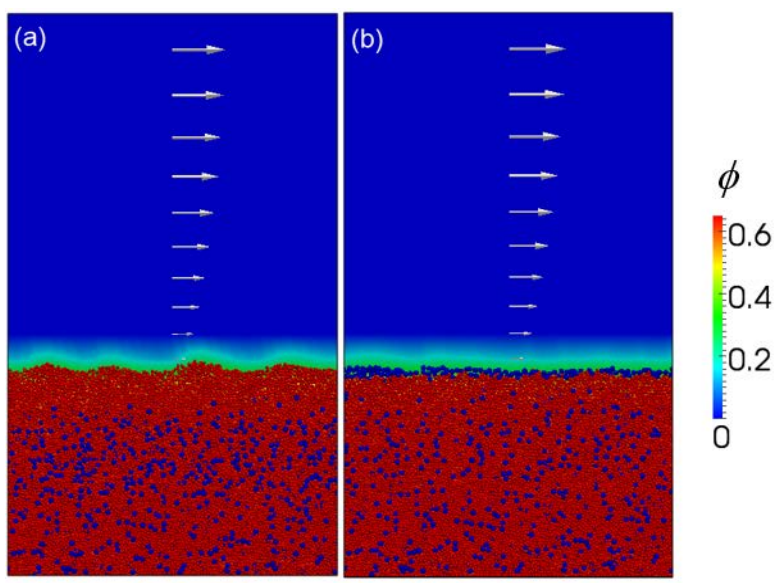

Figure 4: Simulation of sediment transport driven by an oscillatory flow of velocity amplitude 1.5 m/s and period 5 sec using CFDEM. The fluid phase is modeled with a 2DV Reynolds-averaged approach while the particle phase is modeled with 3D DEM. (a) shows a snapshot of the flow domain near flow reversal at the 1st wave. (b) shows a similar plot but at the sixth wave. Majority (95%) of the sand grain is of diameter 0.5 mm (red) while the remaining small amount of coarser grain of diameter 0.8 mm (blue) is also added. The entire domain is 3 times wider and 3 times deeper than that shown.

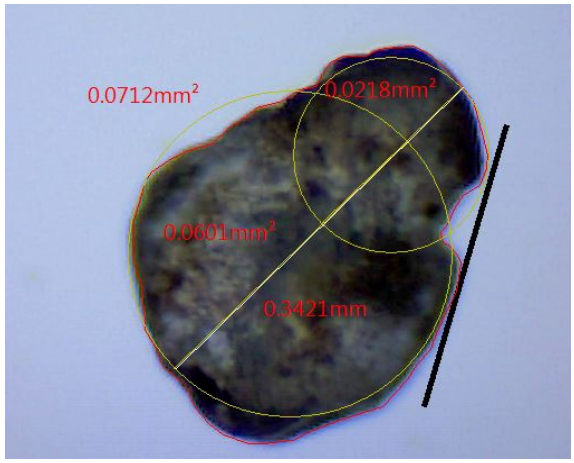

Figure 4: Natural sand grain fitted with a dual-sphere model. In this case, the resulting Corey shape factor is 0.89.

REFERENCES

Calantoni, J., Holland, K. T., Drake, T. G., 2004. Modelling sheet-flow sediment transport in wave-bottom boundary layers using discrete-element modeling. *Phil. Trans. R. Soc. Lond. A*, 362, 1987-2001.

Chen, J.-L., Shi, F., Hsu, T.-J., Kirby, J. T., 2014. NearCoM-TVD — A quasi-3D nearshore circulation and sediment transport model, *Coastal Engineering*, 91, 200-212.

Conley, D. C., Inman, D. L. 1992. Field observations of the fluid-granular boundary layer under near-breaking waves. *J. Geophys. Res*., 97(C6), 9631-9643.

Conley, D. C., and R. A. Beach, 2003. Cross-shore sediment transport partitioning in the nearshore during a storm event, *J. Geophys. Res*., 108(C3), 3065, doi:10.1029/2001JC001230.

Corey, A. T. 1949. Influence of shape on the fall velocity of sand grains. MS thesis, Colorado A&M College, Fort Collins, CO, USA.

Dohmen-Janssen C. M., Kroekenstoel D. F., Hassan W. N., Ribberink J. S. 2002. Phase lags in oscillatory sheet flow: Experiments and bed load modeling. *Coast Eng.*, 46:61–87.

Drake, T. G., 1990. Structural features in granular flows, *Journal of Geophysical Research: Solid Earth,* 95(B6), 8681-8696.

Drake T. G., Calantoni J. 2001. Discrete particle model for sheet flow sediment transport in the nearshore. *J. Geophys. Res.*, 106(C9):19859–68.

Foster, D. L., A. J. Bowen, R. A. Holman, and P. Natoo 2006. Field evidence of pressure gradient induced incipient motion, *J. Geophys. Res.*, 111, C05004, doi:10.1029/2004JC002863.

Gallagher, E.L., Elgar, S., Guza, R.T., 1998. Observations of sand bar evolution on a natural beach. *J. Geophys. Res.*, 103, 3203–3215.

Guo, Y., and Curtis, J. S. 2015. Discrete Element Method Simulations for Complex Granular Flows, *Annual Rev. Fluid Mech.,* in press. DOI: 10.1146/annurev-fluid-010814-014644.

Henderson, S.M., Allen, J.S., Newberger, P.A., 2004. Nearshore sandbar migration by an eddy-diffusive boundary layer model. *J. Geophys. Res.*, 109, C06024. doi:10.1029/2003JC002137.

Hoefel, F., Elgar, S., 2003. Wave-induced sediment transport and sandbar migration. *Science*, 299, 1885–1887.

Hsu, T.-J., J. T. Jenkins, and P. L.-F. Liu, 2004. On two-phase sediment transport: Sheet flow of massive particles, *Proc. R. Soc. London, Ser. A*, 460(2048), doi:10.1098/rspa.2003.1273.

Hsu, T.-J., Elgar, S. and Guza, R. T., 2006. Wave-induced sediment transport and onshore sandbar migration, *Coast. Eng.,* 53, 817-824.

Kloss, C., Goniva, C., Hager, A., Amberger, S., Pirker, S. 2012. Models, algorithms and validation for open-source DEM and CFD-DEM. *Progress in Computational Fluid Dynamics, An Int. J.*, 12(2/3),140 – 152.

O'Donoghue, T., and S. Wright, 2004. Concentrations in oscillatory sheet flow for well sorted and graded sands, *Coastal Eng.*, 50, 117–138, doi:10.1016/j.coastaleng.2003.09.004.

Plimpton, S. 1995. Fast Parallel Algorithms for Short-Range Molecular Dynamics, *J. Comp. Phys*., 117, 1-19.

Rosato, A., K.J. Strandburg, F. Prinz, and R.H. Swendsen. 1987. Why the Brazil nuts are on top: size segregation of particulate matter by shaking, *Physical Review Letters*, 58(10), 1038-1040.

Ruessink, B. G., Y. Kuriyama, A. J. H. M. Reniers, J. A. Roelvink, and D. J. R. Walstra 2007. Modeling cross-shore sandbar behavior on the timescale of weeks, *J. Geophys. Res.*, 112, F03010, doi:10.1029/2006JF000730.

Ruessink, B. G., and Kuriyama, Y. 2008, Numerical predictability experiments of cross-shore sandbar migration, *Geophysical Research Letters*, 35(L01603).

Rusche, H. 2002. Computational fluid dynamics of dispersed two-phase flows at high phase fractions, Ph.D. thesis, Imperial College London (University of London).

Sleath, J. F. A. 1999. Conditions for plug formation in oscillatory flow, *Cont. Shelf Res.,* 19, 1643–1664.

Sumer, B. M., Kozakiewicz, A., Fredsoe, J. & Deigaard, R. 1996 Velocity and concentration profiles in sheet-flow layer of movable bed. *J. Hydraul. Engng* **122**, 549–558.

Thornton, E., Humiston, R., Birkemeier, W., 1996. Bar-trough generation on a natural beach. *J. Geophys. Res.,* 101, 12097–12110.

Warner, J. C., Sherwood, C. R., Signell, R. P., Harris, C. K., Arango, H. G. 2008. Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model. *Comput. Geosci.*, 34(10):1243–60.

Wiberg, P.L., Drake, D.E., Cacchione, D.A., 1994. Sediment resuspension and bed armoring during high bottom stress events on the northern California continental shelf: measurements and predictions. *Continental Shelf Research* ,14(10/11), 1191–1219.

PUBLICATIONS

1. Cheng, Z., and Hsu, T.-J. (2014) A multi-dimensional two-phase Eulerian model for sediment transport — twoPhaseEulerSedFoam (version 1.0). Center for Applied Coastal Research technical report, CACR-14-08, University of Delaware. [PUBLISHED]