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

- To enhance and validate a finite-volume Euler-Lagrangian solver, CFDEM, for sediment transport applications, including transport of non-spherical grains.
- To investigate poly-dispersed sediment transport in wave-current boundary layer during extreme wave condition, particularly, sheet flow with momentary bed failure using CFDEM and the more efficient Eulerian two-phase model.
- To implement composite particle method in CFDEM for modeling natural sand grain shape and evaluate the effect of grain shape on the resulting sediment transport.

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 and scour/burial of objects in the coastal/marine environments. In the past two decades, major progress has been made to understand mechanisms driving onshore/offshore sediment transport in sandy beaches. When these mechanisms are incorporated into coastal evolution models, the model is able to predict beach erosion and recovery on weekly and seasonal timescales, including the impact of moderate storms. However, model skill is low during major wave events (e.g., hurricane, 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.

Observations of sediment transport and morphological evolution under long waves (Young et al. 2010; Sumer et al. 2011) indicate that during the drawdown stage of wave impact, substantial upward-directed pore-pressure gradient is measured and as a result, the shear strength of sediment bed is greatly reduced and transport is enhanced. More recently, experiment of Sumer et al. (2013) further

revealed that a series of rollers from a plunging breaker can also trigger upward-directed pore-pressure gradient and the concurrent large bed stress and turbulence can then drive large suspended sediment plume. Field studies in the surf zone further suggest that large horizontal pressure gradients induced by the passage of steep near-breaking or breaking waves can destabilize the sand bed and drive momentary bed failure or plug flow (Madsen 1974; Conley & Inman 1992; Foster et al. 2006), which lead to transport rate many times greater than the conventional sheet flow prediction. Mechanisms associated with enhanced transport by upward-directed pore pressure gradient and momentary bed failure are currently missing in the existing sediment transport parameterizations. Existing parameterizations also do not explicitly consider polydispersed grain sizes and non-spherical particle shapes.

The multiphase modeling methodology provides a comprehensive framework for these complicated sediment transport processes and can be used as a tool to improve the existing parameterizations adopted by the coastal evolution models. A multiphase 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 the conventional bedload/suspended load assumptions. The Lagrangian description of sediment phase, typically called the Discrete Element Method (DEM), is superior to the Eulerian description in several aspects. Particle stresses in DEM is resolved to the individual grain level and hence it has no restriction on multiple contacts (Drake 1990). Therefore, coupled fluid-DEM can be an effective tool to study structural change of the sediment skeleton due to combined shear and vertical pore pressure gradient (Tonkin et al. 2003) and subsequent large transport. 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 (e.g., Wiberg et al. 1994). In the fluid-DEM of Calantoni et al. (2004), the predicted sediment transport rate is improved when grain shape effect is included using composite particles.

The primary goal of this study is to develop the next generation simulation tools to study sediment transport in order to provide improve sediment transport parameterizations particularly for extreme wave scenarios. Specifically, we focus on developing a multi-dimensional Eulerian two-phase model with turbulence-resolving capability and a coupled fluid-DEM capable of simulating heterogeneity of sediment properties, including 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 (extension 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.

Leveage a prior NSF support (see Related Projects), 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 toolbox, 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 & Wright 2004). This numerical model, called sedFoam, was recently disseminated to the research community as an open-source model 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 well as an improved version of the Euler-Lagrangian model CFDEM.

WORK COMPLETED

The investigation of momentary bed failure in sheet flow condition using the multi-dimensional Eulerian two-phase model has been completed. Model results reveal that large transport rate driven by momentary bed failure is associated with the generation of mobile layer instabilities and the threhold for onset of momentary bed failure can be significantly reduced as the Shields paraemter increases. As mentioned before, the model is publicably available as open-source code. To disseminate the model, PI Hsu's group held a 2-hour clinic session in the 2015 CSDMS annual meeting in Boulder, Colorado. A manuscript has been submitted for publication (Cheng et al. 2015).

The development of a 3D turbulence-resolving Eulerian two-phase model based on LES modeling strategy has been completed in 2014. We then focused on careful model validation with sheet flow data of O'Donoghue & Wright (2004) for fine (d_{50}=0.13 mm) and medium (d_{50}=0.28 mm) sand. Generally, we found that LES model is better in predicting transport of fine sand, particularly in terms of the sediment concentration during the deceleration phase when compared with Reynolds-averaged model results. Although LES is more computational demanding, our finding is enouraging as LES is indeed better capturing the transitional nature of turbulent flow due to turbulence-sediment interaction in unsteady flow.

Substantial progress has been made to revise CFDEM for sediment transport applications, including a model for non-spherical grain shape. The existing solver in CFDEM tends to be unstable when sediment concentration is large and hence by default, the time-dependent term of fluid concentration in the continuity equation is ignored. For sediment transport applications, this approximation is a substantial limitation as the fluid mass conservation in concentrated region of transport and sediment bed is violated (e.g., computed pore pressure has large error). Benefited from our prior experience in developing the Eulerian two-phase model, sedFoam, we revised the solver to directly compute the mixture continuity equation and hence the new version of the model satisfies mass conservation and numerically stable. Through collaboration with Dr. Calantoni (NRL), a composite grain module was included in the solver to model non-spherical grain shape. The model is then validated with several U-tube datasets, including Asano (1995) for coarse plastic grain and O'Donoghue & Wright (2004) for coarse sand. Using the validated cases as baseline, we focus on studying the effects of mixed grain size and non-spherical grain shape (see Results).

RESULTS

Newly improved Euler-Lagrangian model for sediment transport is first validated with measured data of sheet flow sediment transport in oscillatory flow (O'Donoghue & Wright 2004) for coarse sand. In the physical experiment, the grain size distribution is sufficiently narrow (d_{10}=0.36 mm, d_{50}=0.51 mm, d_{90}=0.67 mm) and prior Eulerian modeling studies simply assume uniform sphere of grain diameter 0.51 mm (i.e., use d_{50}). Here, this approximation is evaluated by carrying out Case 0 with uniform sphere of 0.51 mm and Case A1 with realistic grain size distribution. To further understand the effect of grain size distribution, we carry out Case A2 with wider distribution especially emphasizing the

coarse fraction (d_{10}=0.32 mm, d_{50}=0.51 mm, d_{90}=0.8 mm). For both Case 0 and Case A1, modeled concentration profiles agree with measured data reasonably well (see Figure 1c,d). According to the model computed time-series of nondimensional transport rate, Case A1 with realistic grain size distribution has slightly smaller transport rate comparing to that of completely uniform spheres (see Figure 1b). The reduction is more significant under the more energetic positive wave phase. The observed difference is due to the well-known armoring effect and it has important implication to the prediction of onshore transport rate in the nearshore. The computed wave-averaged transport rate is onshore directed (positive) for Case A1, but it is 9% smaller than that of Case 0. In Case A2, armoring effect is more pronounced. The resulting wave-averaged onshore transport rate is 15% smaller than that of Case 0. Figure 2a shows in the initial distribution of particles for Case A2. It is clear that different size of particles are more or less randomly distributed in the bed. However, after the action of 5 waves we can clearly observe that many coarser grains are located in the surface layer and effective armor the finer grains below. In Case A3, in which the grain size distribution is made even larger (d_{10}=0.27 mm, d_{50}=0.51 mm, d_{90}=0.92 mm), the net transport rate over one wave is reduced by 50% comparing with that of uniform grain size (not shown). Model results shown here clearly demonstrate the importance of grain size distribution and the armoring effect can reduce onshore transport under skewed waves in the nearshore.

To study the effect of grain shape, we present another 2 simulations (see Case B2 and B3 in Figure 3) for the coarse sand experiment under Stokes 2nd-order wave motion (O'Donoghue & Wright 2004) and comparing with Case 0 (uniform sphere). Each of the additional simulation has the same equivalent volume of Case 0 but are of different Corey shape factor (CSF, Corey 1949). It is worth mentioning that following Calantoni et al. (2004), Case B2 is of CSF=0.84, which is similar to natural sand grain. By examining the computed time-dependent sediment transport rate, it is evident that grain shape effect play a role in sediment transport rate. When the Corey shape factor is lower, more contact points among particles are modeled (Calantoni et al. 2004) which results in more frictional contact and less transport rate. From Figure 3b, it appears that the reduction of transport rate is more significant under the more energetic positive phase. By computing the wave-averaged transport rate, Case B2 with CSF=0.84 has a 7% lower transport rate than that of Case 0. Case B3 with CSF=0.8 has a 15% reduction of transport rate. Overall, our numerical investigation suggests that consider grain shape effect may reduce net onshore transport rate under skewed wave. However, the reduction is only about 10%. More comprehensive investigation, especially for smaller grain diameter, will be carry out in the near future.

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 have been (and will be) disseminated to research community as open-source.

RELATED PROJECTS

The earlier stage of the model development effort was supported by National Science Foundation (CMMI-1135026) NEESR: Tsunami Induced Coherent Structures and their Impact on Coastal Infrastructure (with D. Foster, UNH; P. Lynett, USC).

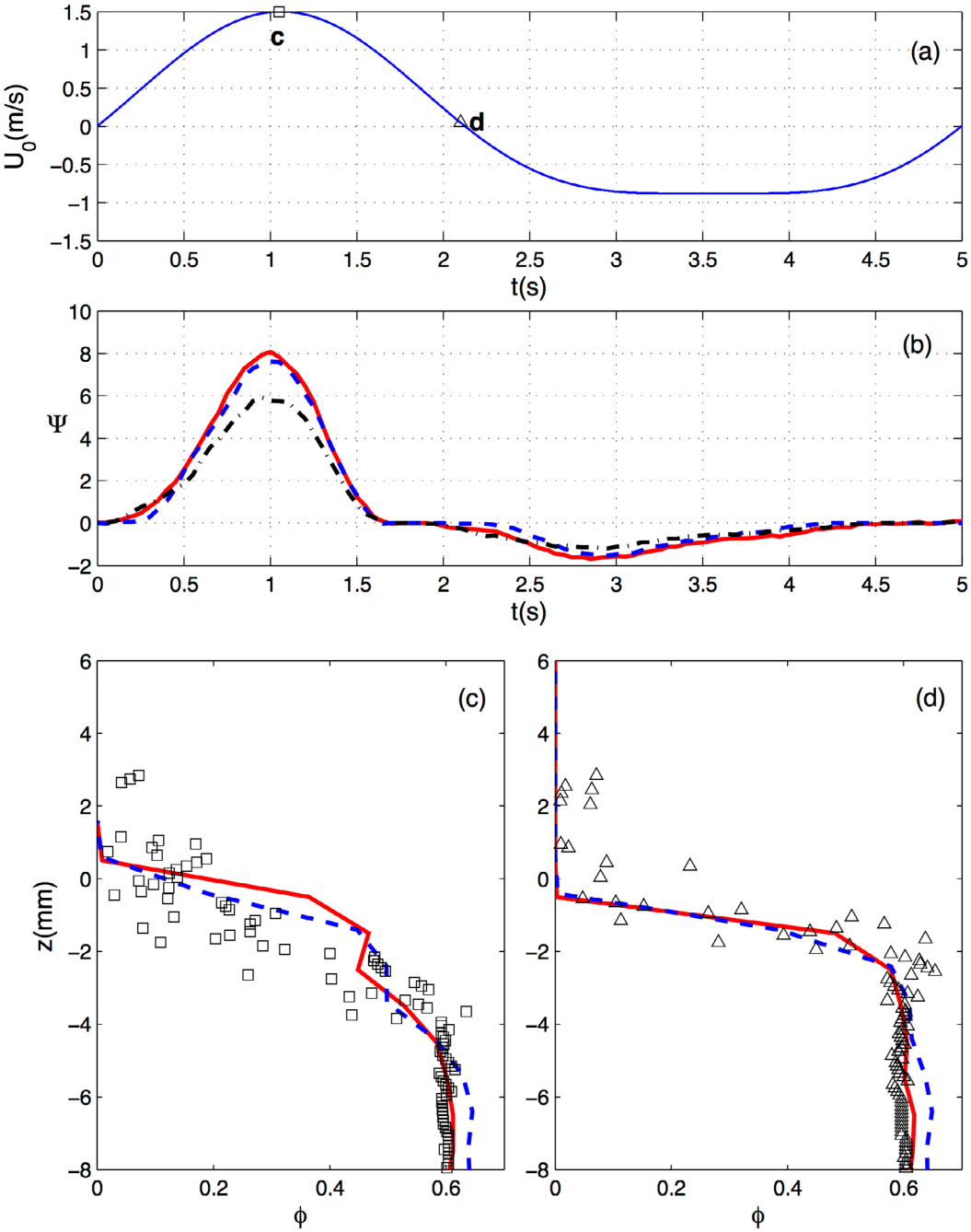

Figure 1: Model validation with O'Donoghue & Wright (2004) for coarse sand driven by Stokes 2nd-order wave motion. (a) Time series of free-stream velocity (b) modeled time series of nondimensional sediment transport rate. (c) and (d) snapshots of sediment concentration profile at flow peak and flow reversal. Case 0 of uniform spheres is represented by red-solid line while Case A1 of narrow size distributon following the physical experiment is represented by blue-dashed line. The black-dash-dotted line in (b) represents the nondimensional transport rate of Case A2 with wider size distribution.

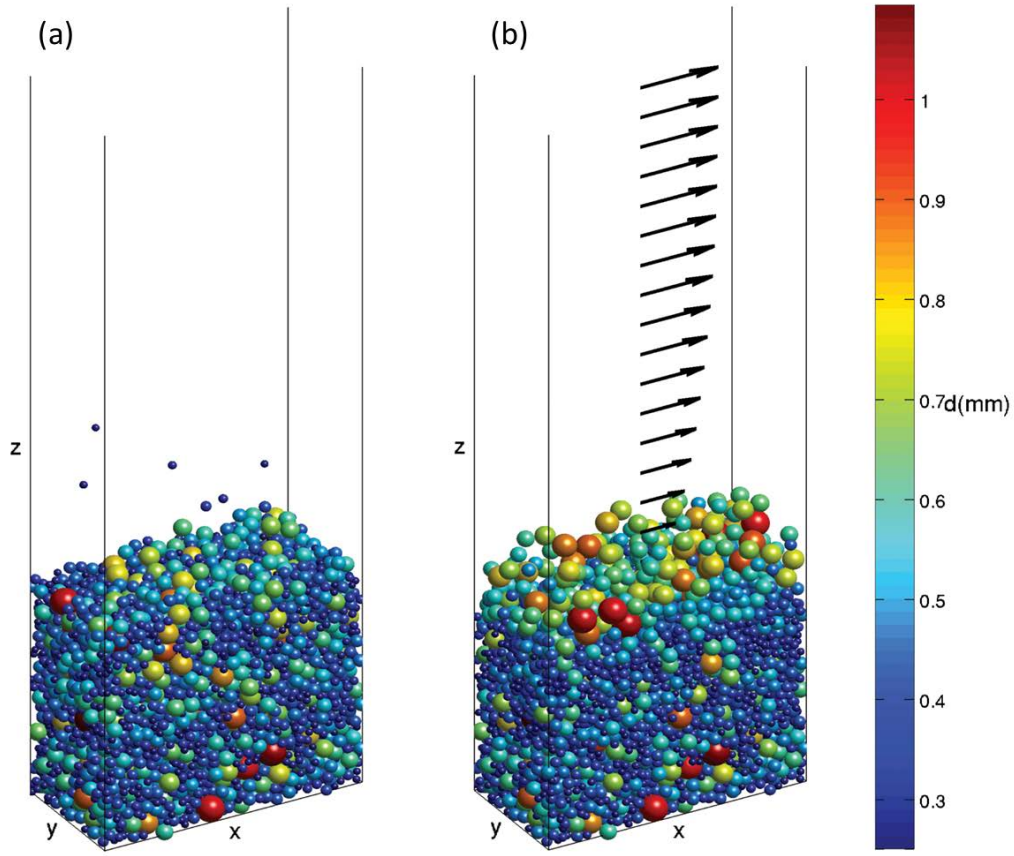

Figure 2: Model results for Case A2 (wide grain size distribution; d_{10}=0.32 mm, d_{50}=0.51 mm, d_{90}=0.8 mm) demonstrate the armoring effect. (a) A snapshot of initial bed. Particles of different size are more or less randomly distributed in the bed without notable vertical grading. (b) A snapshot under flow peak after the action of five waves. The surface layer is mainly covered by coarser particles (d>0.6 mm).

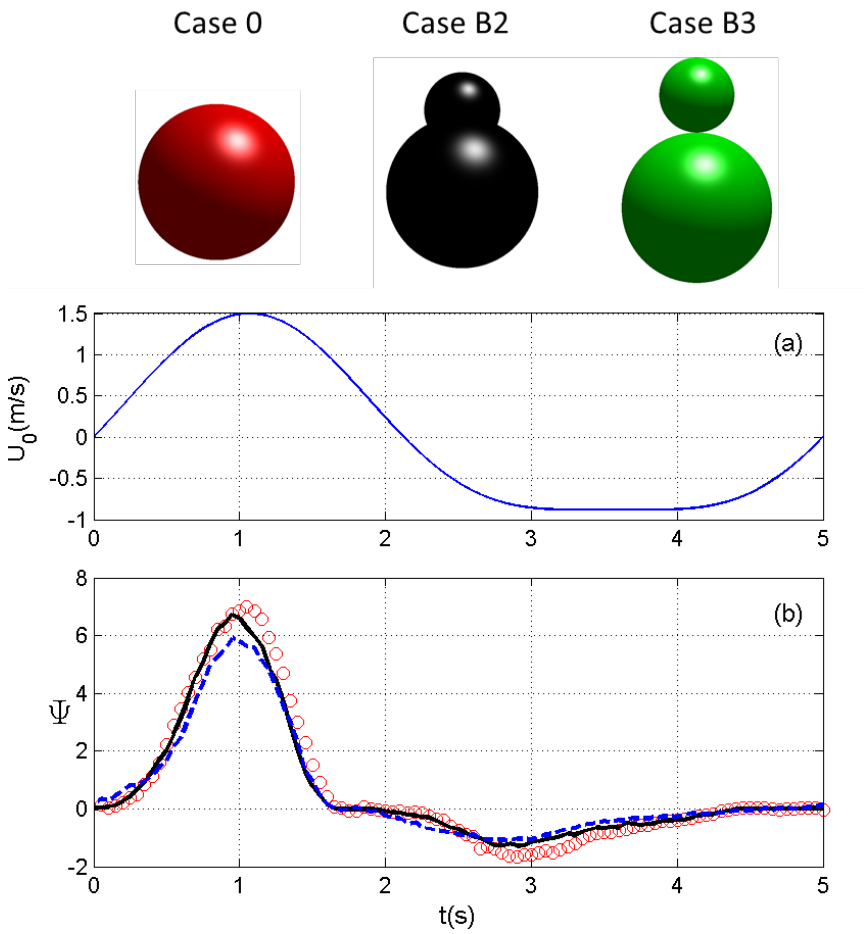

Figure 3: Simulation of three different grain shape (see top panel, each shape has the same grain volume) subject to Stokes 2nd-order wave motion. (a) Time series of free-stream velocity. (b) Time series of nondimensional sediment transport rate for Case 0 (circle symbol), Case B2 (black-solid line, CSF=0.84) and Case B3 (blue-dashed line, CSF=0.8).

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.

Cheng, Z., Hsu, T.-J., Calantoni, J. C., (2015) SedFoam: A multi-dimensional Eulerian two-phase model for sediment transport and its application to momentary bed failure, submitted.

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.

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

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.

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.

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.

Madsen, O. S., 1974. Stability of a sand bed under breaking waves, *Proc. 14th Int. Conf. Coastal Engineering*, Am. Soc. of Civ. Eng., Reston, Va., pp 776-794.

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.

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.

Sumer, B. M., M. B. Sen, I. Karagali, B. Ceren, J. Fredsøe, M. Sottile, L. Zilioli, and D. R. Fuhrman 2011, Flow and sediment transport induced by a plunging solitary wave, *J. Geophys. Res.,* 116, C01008, doi:10.1029/2010JC006435

Sumer, B. M., H. A. A. Guner, N. M. Hansen, D. R. Fuhrman, and J. Fredsøe 2013, Laboratory observations of flow and sediment transport induced by plunging regular waves, *J. Geophys. Res. Oceans*, 118, 6161–6182, doi:10.1002/2013JC009324.

Tonkin, S., Yeh, H, Kato, F., Sato, S., 2003. Tsunami scour around a cylinder, *J. Fluid Mech.,* vol. 496, pp. 165–192.

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.

Young, Y. L., H. Xiao, and T. Maddux (2010), Hydro- and morphodynamic modeling of breaking solitary waves over a fine sand beach. Part I: Experimental study, *Mar. Geol.,* 269, 107–118.

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. Open-source model can be downloaded from CSDMS code repository maintained by GitHub http://csdms.colorado.edu/wiki/Model:TwoPhaseEulerSedFoam

[PUBLISHED]

2. Cheng, Z., Yu, X., Hsu, T.-J. Ozdemir, C. E., Balachandar, S., (2015) On the transport modes of fine sediment in the wave boundary layer due to resuspension/deposition – A turbulence-resolving numerical investigation, J. Geophys. Res. Oceans, 120, 1918-1936, DOI:10.1002/2014JC010623. [PUBLISHED, REFEREED]
3. Cheng, Z., Yu, X., Hsu, T.-J., Balachandar, S., (2015) A numerical investigation of fine sediment resuspension in the wave boundary layer—Uncertainties in particle inertia and hindered settling, Computers and Geosciences, 83, 176-192. [PUBLISHED, REFEREED]
4. Cheng, Z., Hsu, T.-J., Calantoni, J. C., (2015) SedFoam: A multi-dimensional Eulerian two-phase model for sediment transport and its application to momentary bed failure, *Coastal Eng.*. [SUBMITTED]