NTHMP Grant Semi-Annual Progress Report

NOAA Grant Award Number: NA15NWS4670029

Period of performance (start date to end date of entire grant): September 1, 2015 – August 31, 2017

Award reporting period (date range): March. 1, 2016 – August 31, 2016

Primary award recipient (name, address, telephone, email): James T. Kirby
Center for Applied Coastal Research
University of Delaware
Newark, DE 19716 USA
1-302-831-2438, kirby@udel.edu

Subaward recipient(s): (name, address, telephone, email): Stephan Grilli
Department of Ocean Engineering
University of Rhode Island
Narragansett, RI 02882 USA
1-401-874-6636, grilli@oce.uri.edu

Person submitting report: James T. Kirby

Date of this report: December 2, 2016

Instructions: add rows to the table below as needed to complete reporting on all tasks awarded. Fill in all cells within the table. Make sure that task titles match the current Project Narrative for this grant.

Task #	Task title	Progress made during this reporting period	Challenges and successes	% of total task completed
1	Tsunamigenic Landslide Modeling Benchmark Development, Validation Workshop and Workshop Documentation	Workshop benchmark tests have been organized and a website developed to distribute test data and configurations to participants. The site is presently located at www.udel.edu/kirby/landslide/ The site will be maintained as a public repository for data and model results after the workshop completion.	Organizing data in a useful manner, developing working contacts with workshop participants.	35%
2	Refinement and extension of potential SMF sources and source modeling techniques for tsunami activity in the North Atlantic	Work on West Bahama Banks potential landslides was published. SMF Currituck slide proxies modeled as rigid slumps north of	Four journal papers published on Bahama Bank, Deforming slides in Kitimat and upper east coast, and tide-tsunami	60%

		the Carolinas were revisited and modeled as deforming slides. The Hudson River Canyon SMF and the Currituck slide were remodeled assuming they behave as a dense fluid layer (Fig. 1). The model used was validated with lab. Experiments. As expected, tsunami generation is reduced (see, e.g., Figs. 2). Model parameters/rheology for the deforming slides were selected based on simulating laboratory experiments and field case studies (e.g., Figs., 3). A comparison solid vs deforming slide with respect to coastal hazard off of NJ, NY/Long Island was performed. Both maximum elevation and minimum drawdown are reduced when assuming a deforming slide rather than a rigid slump (Fig. 4).	interactions. Methodology for computing deformable landslides has been developed and used to refine East Coast source descriptions as well as tsunami coastal impact. Two types of deforming slide models (dense fluid and granular flow) were validated against lab experiments and applied to case studies. NGDC tsunami DEM's are now available for the southern portion of Florida, and delayed inundation mapping will be completed during the remainder of this project. Work on deformable slide modeling is strongly synergistic with Grilli and Kirby NSF supported work, covering ongoing model development and improvement, with technology immediately transferred to NTHMP project. This is also synergistic with the organization of the landslide model benchmarking workshop.	
3	Tsunami Hazard Assessment for Un-modeled East Coast Sites	Storm surge maps for US East Coast stated being collected from constituents. Analysis of correspondence between storm surge inundation lines and tsunami inundation lines for mapped areas underway. Work on effect of shelf geometry in controlling location of high tsunami hazard is being	Contacts are being made with individual state agencies to gather information on category 1-5 storm surge inundation maps and evacuation procedures to assist	35%

		completed.	in interpreting tsunami height estimates based on the ray tracing estimates.	

During this reporting period, was any budget reprogramming required for this award? If so…

a. Date reprogramming approved by NWS Tsunami Program Office:
b. Date approved by NOAA Grants Office:

c. Describe where funds were moved and why:

General comments from recipient about progress during this reporting period:

PROBLEMS ENCOUNTERED: DEM's for southern Florida were recently obtained. Inundation mapping for the Florida east coast is underway. Work is slowed somewhat by a change-over in student assigned to the project, with Babak Tehranirad graduating in December 2016.

ANTICIPATED OUTCOMES: Results for the additional mapping efforts described here will be presented in the form of technical reports for each NGDC DEM or similarly sized coastal region, and in the form of draft inundation maps for coastal communities within the DEM regions. Project results are displayed at the project website http://www.udel.edu/kirby/nthmp.html and will be displayed at the NTHMP website http://ws.weather.gov/nthmp/index.html as they are finalized. Draft maps and reports are presently available at an unlinked site http://www.udel.edu/kirby/nthmp_protect.html prior to their review by local state agencies.

Refinement of modeling techniques for simulating landslide (SMF) tsunami generation has led to published papers, and more will be prepared, and enhancements to the public domain model NHWAVE. These have played a central role in the organization and preparation of the landslide tsunami benchmark workshop in January 2017. An overview of ongoing work, in the context of refining sources for East Coast tsunami events, may be found at the end of this document.

PUBLICATIONS AND PRESENTATIONS REFERENCING FY14-15 WORK

Grilli, S.T., Grilli, A.R., Tehranirad, B. and J.T. Kirby 2015a, "Modeling tsunami sources and their propagation in the Atlantic Ocean for coastal tsunami hazard assessment and inundation mapping along the US East Coast". In *Proc. 2015 COPRI Solutions to Coastal Disasters Conf.* (Boston, USA. September 9-11, 2015), ASCE, 12 pps., http://personal.egr.uri.edu/grilli/COPRI15_sgrilli.pdf.

Grilli S.T., O'Reilly C., Harris J.C., Tajalli-Bakhsh T., Tehranirad B., Banihashemi S., Kirby J.T., Baxter C.D.P., Eggeling T., Ma G. and F. Shi, 2015b, "Modeling of SMF tsunami hazard along the upper US East Coast:

Detailed impact around Ocean City, MD". *Natural Hazards*, **76**(2), 705-746, doi: 10.1007/s11069-014-1522-8.

Grilli, S.T., Shelby, M., Kimmoun, O., Dupont, G., Nicolsky, D., Ma, G., Kirby, J. and F. Shi 2016. Modeling coastal tsunami hazard from submarine mass failures: effect of slide rheology, experimental validation, and case studies off the US East coast. *Natural Hazards*, 40 pps., doi: 10.1007/s11069-016-2692-3 (published online Dec. 2016).

Kirby, J. T., Shi, F., Nicolsky, D. and Misra, S., 2016. "The 27 April 1975 Kitimat, British Columbia submarine landslide tsunami: A comparison of modeling approaches," *Landslides*, doi:10.1007/s10346-016-0682-x. (published online Feb. 26, 2016).

Ma G, Kirby JT, Hsu TJ and F Shi (2015). "A two-layer granular landslide model for tsunami wave generation: theory and computation", *Ocean Model*, **93**, 40-55.

Schnyder, J. S. D., Eberli, G. P., Kirby, J. T., Shi, F., Tehranirad, B., Mulder, T., Ducassou, E., Hebbeln, D. and Wintersteller, P., 2016, "Tsunamis caused by submarine slope failures along Western Great Bahama Bank", *Scientific Reports* (Nature Publishing Group) 6, 35925, doi:10.1038/srep35925.

Shelby, M., Grilli, S. T. and Grilli, A. R., 2015, "Dynamic tide-tsunami interaction in the Hudson River estuary", Research Report No. CACR-15-10, Center for Applied Coastal Research, Dept. of Civil and Environmental Engineering, University of Delaware.

Shelby, M., Grilli, S. T. and Grilli, A. R., 2016a, "Tsunami hazard assessment in the Hudson River Estuary based on dynamic tsunami-tide simulations." *Pure and Applied Geophysics*, 39 pps., doi:10.1007/s00024-016-1315-y (published online 5/24/16)

Shelby, M., Grilli, S. T., Ma, G., Kirby, J. T. and Shi, F., 2016b, "Sensitivity of coastal tsunami hazard to the modeling of tsunami generation by Submarine Mass Failures of various rheology". Presented at the *14th Estuarine and Coastal Modeling Conference*, Kingston RI, June 15-17.

Tajalli Bakhsh, T. S., Grilli, S. T. and Grilli, A. R., 2015, "Dynamic tidal effects on tsunami coastal hazard in large estuaries: Case of the Chesapeake Bay/James River, USA", Research Report No. CACR-15-09, Center for Applied Coastal Research, Dept. of Civil and Environmental Engineering, University of Delaware.

Tehranirad B., Harris J.C., Grilli A.R., Grilli S.T., Abadie S., Kirby J.T. and F. Shi 2015a. Far-field tsunami hazard in the north Atlantic basin from large scale flank collapses of the Cumbre Vieja volcano, La Palma. *Pure and Applied Geophysics*, **172**(12), 3,589-3,616 doi:10.1007/s00024-015-1135-5.

Tehranirad, B., 2015, "Effects of bathymetry on tsunami propagation on the US East Coast: Application of ray tracing to tsunamis", presented at *Young Coastal Scientists and Engineers Conference - North America*, Newark, July.

Tehranirad, B., Kirby, J. T., Shi, F., Grilli, S. T. and Grilli, A. R., 2015, "Is continental shelf bathymetry the main control for tsunami inundation patterns on the US East Coast ?", presented at the *Geological Society of America Meeting*, Baltimore, October.

Tehranirad, B., Kirby, J. T., Callahan, J. A. and Shi, F., 2015a, "Tsunami inundation mapping for Atlantic City, NJ NGDC DEM", Research Report No. CACR-15-01, Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware. (DRAFT)

Tehranirad, B., Kirby, J. T., Callahan, J. A. and Shi, F., 2015b, "Tsunami inundation mapping for the northern half of the State of New Jersey", Research Report No. CACR-15-02, Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware. (DRAFT)

Tehranirad, B., Kirby, J. T., Callahan, J. A. and Shi, F., 2015c, "Tsunami inundation mapping for New York City", Research Report No. CACR-15-03, Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware. (DRAFT)

Tehranirad, B., Kirby, J. T., Callahan, J. A. and Shi, F., 2015d, "Tsunami inundation mapping for Montauk, NY NGDC DEM", Research Report No. CACR-15-04, Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware. (DRAFT)

Tehranirad, B., Kirby, J. T., Callahan, J. A. and Shi, F., 2015e, "Tsunami inundation mapping for Nantucket, MA NGDC DEM", Research Report No. CACR-15-05, Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware. (DRAFT)

Tehranirad, B., Kirby, J. T., Callahan, J. A. and Shi, F., 2015f, "Tsunami Inundation Mapping for Virginia Beach, VA NGDC DEM", Research Report No. CACR-15-11, Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware. (DRAFT)

Tehranirad, B., Kirby, J. T., Callahan, J. A. and Shi, F., 2015g, "Tsunami Inundation Mapping for Cape Hatteras, NC NGDC DEM", Research Report No. CACR-15-12, Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware. (DRAFT)

Tehranirad, B., Kirby, J. T., Callahan, J. A. and Shi, F., 2015h, "Tsunami Inundation Mapping for Myrtle Beach, SC NGDC DEM", Research Report No. CACR-15-13, Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware. (DRAFT)

Tehranirad, B., Kirby, J. T., Callahan, J. A. and Shi, F., 2015i, "Tsunami Inundation Mapping for Savannah, GA NGDC DEM", Research Report No. CACR-15-14, Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware. (DRAFT)

Viroulet S., A. Sauret and O. Kimmoun, 2014.Tsunami generated by a granular collapse down a rough inclined plane. *Europhysics Lett.,* **105**(34004) doi:10.1209/0295-5075/105/34004.

REFINEMENT OF SLIDE MODEL CHOICES

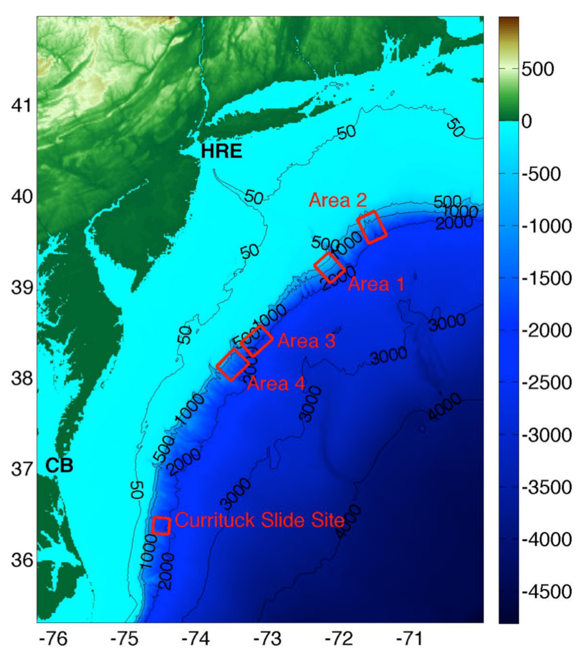

Fig. 1: Location of historical Currituck slide complex and 4 areas where SMF-Currituck proxies are sited
.

As SMF tsunami generation is reduced when the SMF is assumed to behave as a dense fluid rather than a rigid slump, it is important to use a calibrated/validated model in the tsunami source simulations (this also relates to Task 1 on Landslide tsunami model validation workshop). To this effect, a sensitivity analysis of tsunami generation to model parameters was performed, by comparing results to laboratory experiments for granular flows (Viroulet et al., 2014; see Fig. 3) and by simulating the historical Currituck slide (Grilli et al., 2015b; see Fig. 4), when representing the SMF as a dense fluid layer (Kirby et al., 2016) or a granular flow (Ma et al., 2015). Data available for the historical Currituck slide is used to guide the selection of model parameters. See details in Grilli et al. (2016).

In particular, it was found that slide acceleration and spreading, which are important for tsunami generation, are controlled in the model by the selection of the dense fluid viscosity, bottom friction (Manning coefficient n) and mass diffusion parameters. Both the laboratory experiments (Fig. 3) and the observed failure for the Currituck slide (see Grilli et al., 2016) were used to find the best values for these parameters. Once this realistic set of model parameters was identified, the SMF Currituck proxies located in areas 1 to 4 in Fig. 1 will be fully simulated and results will be used to update inundation maps. So far, these simulations have been performed for Area 1 (Fig. 2) and the tsunami elevation for the rigid slump and 3 cases of deforming slides were compared at the 5 m isobath nearshore (Fig. 4).

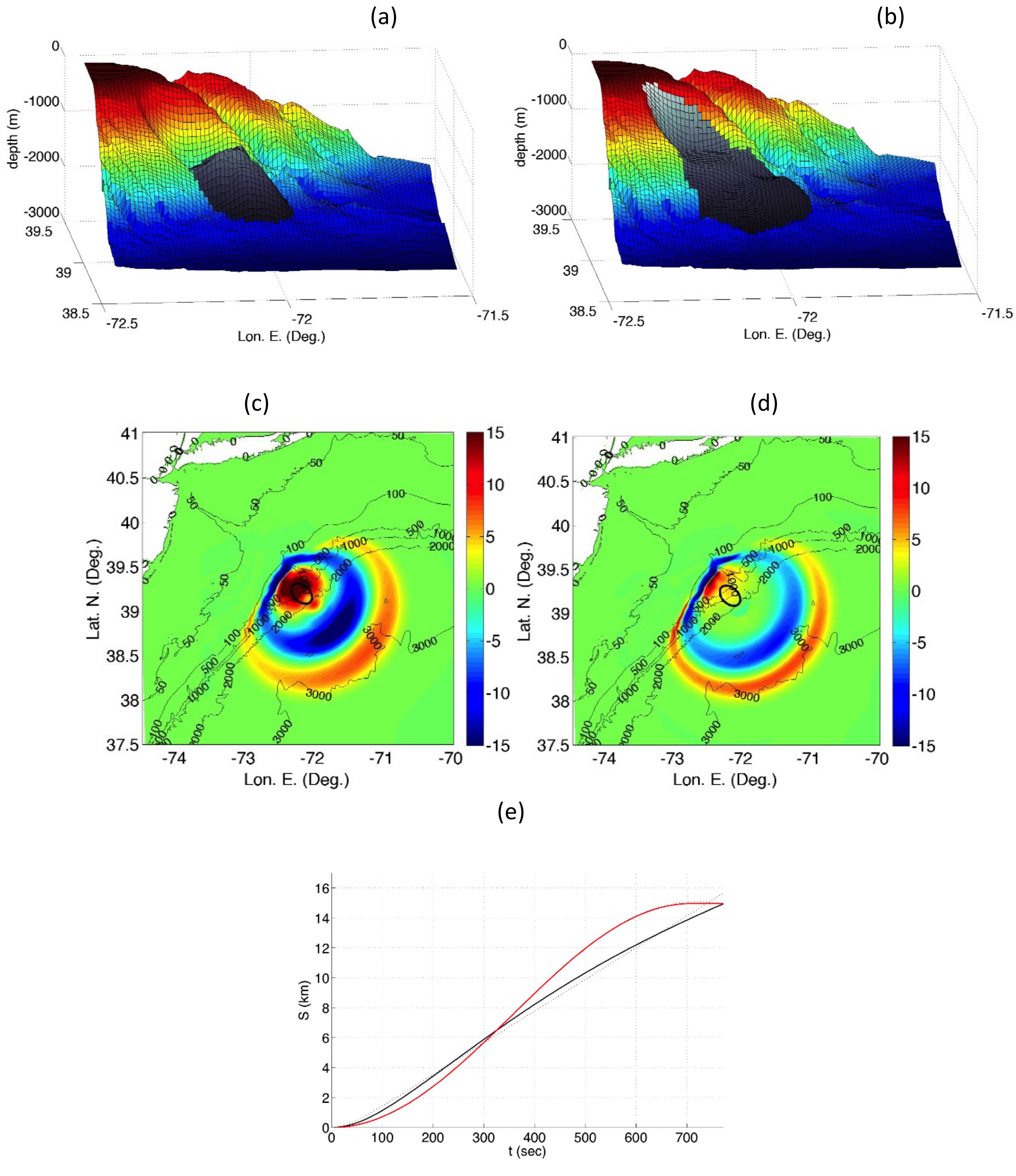

Fig. 2. NHWAVE simulations of landslide tsunamis generated off of the Hudson River canyon (Area 1 in Fig. 1) assuming: (a,c) a rigid slump, modeled as a Currituck SMF proxy (Grilli et al., 2015a,b); (b,d) a deforming slide modeled as a dense fluid layer (Kirby et al., 2016; Grilli et al., 2016), with same initial geometry, location, volume, and runout at the time the slump stops moving (12 min), as the Currituck SMF proxy. Panels (a,b) show in gray the SMF locations after 13.3 min (to the left of the Hudson River canyon), and panels (c,d) show the surface waves generated after 13.3 min (the black ellipses mark the initial footprint of the SMFs). At this time, wave patterns are similar but waves have lower elevations in the deforming slide case;black ellipses mark the

initial footprint of each SMF. (e) solid curves are center of mass motions of (red) slump and (black) slide, with dash curves being curve fits of theoretical laws of motion.

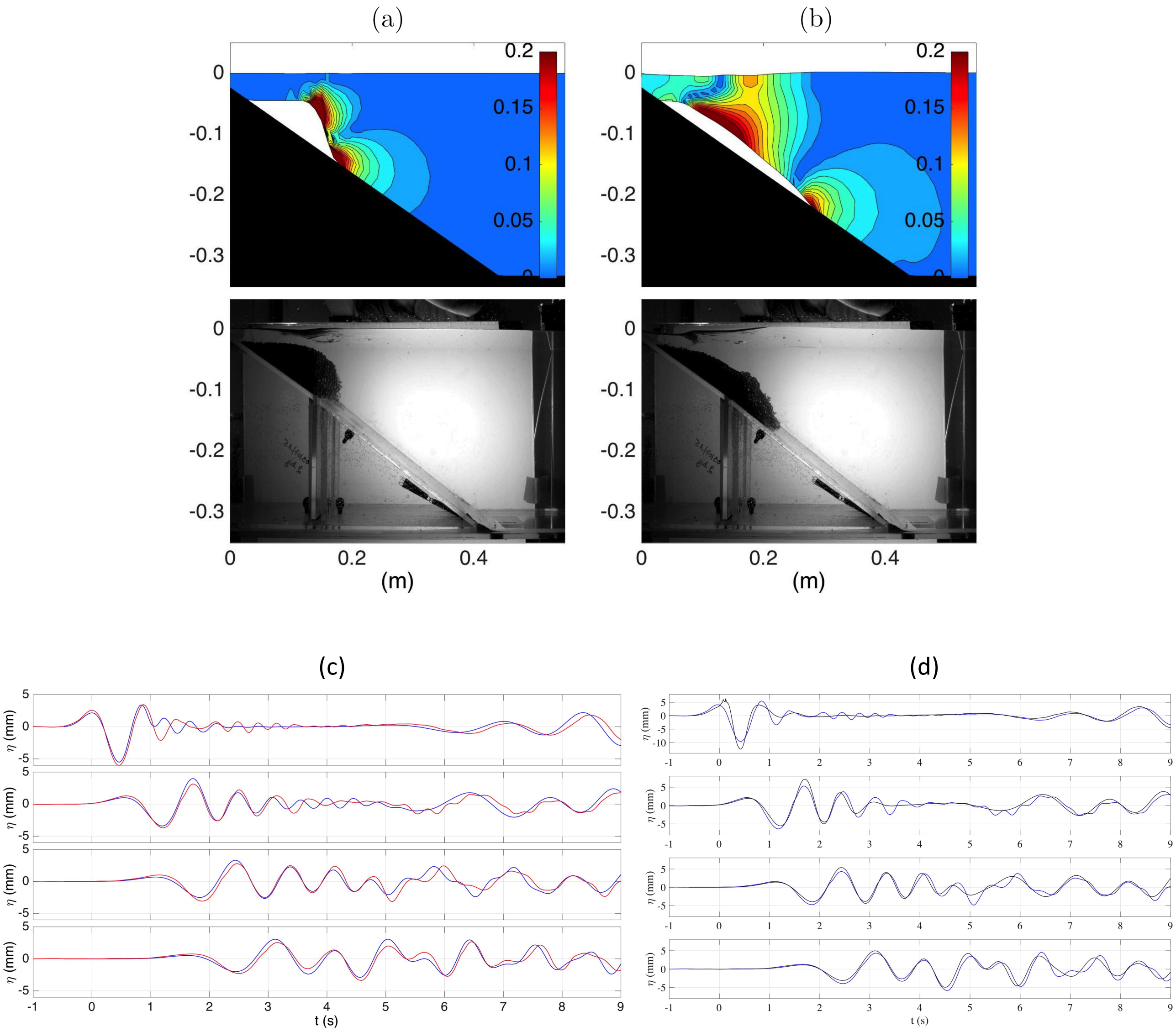

Fig. 3. (a,b) Simulation of Viroulet et al.'s (2014) underwater landslide experiments (slides are made of 4 mm diameter glass beads) on a 35 deg. plane slope using NHWAVE's two layer model that has a depth-integrated layer made of : (c) heavy fluid layer (Kirby et al., 2016) or (d) a ranular flow layer (Ma et al., 2015); 9 sigma layers are used over the vertical in NHWAVE. Plots (a,b) compare the dense fluid simulations (color scale is vertical velocity in m/s) to slide and free surface motions measured with a high speed camera; plots (c,d) compares time series of surface elevations at 4 gages (located at 0.6, 1.6, 2.6, and 3.6 m from initial location slide front, from top to bottom), measured (blue) and simulated (red/black). Note, time zero is when the first elevation wave crest reaches the first gage (0.6 m from the slide front). See Grilli et al. (2016) for details.

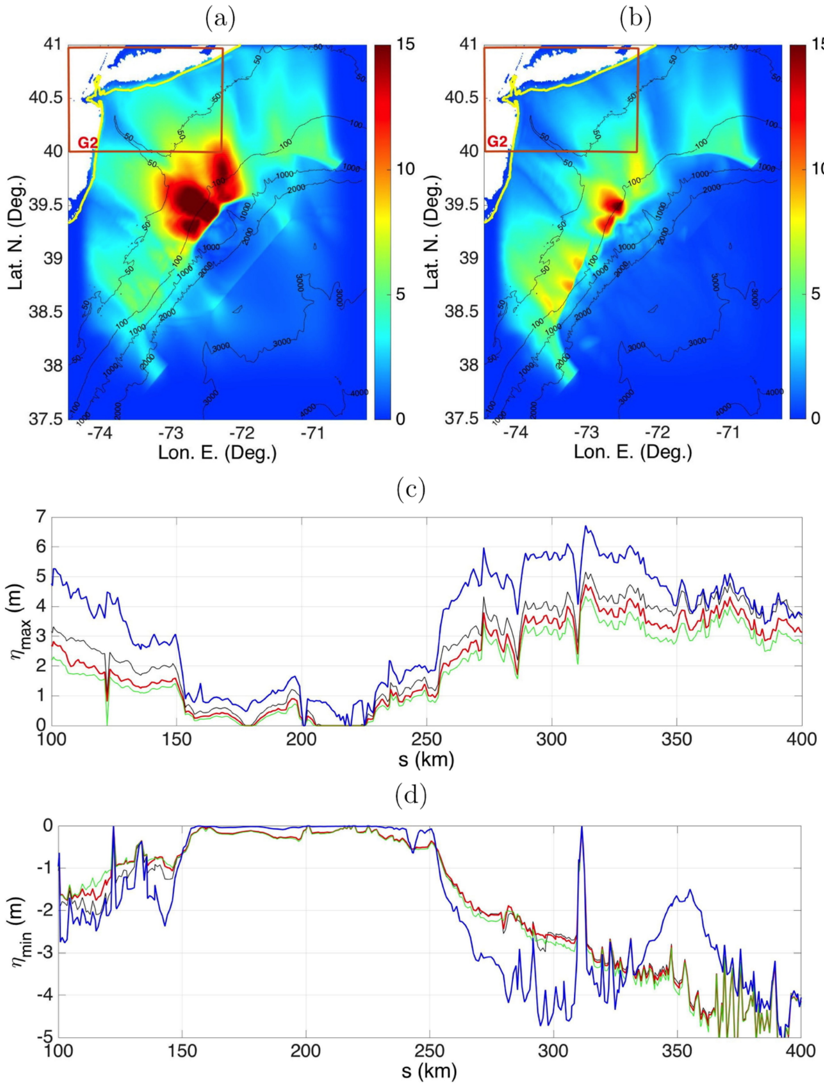

Figure 4: Comparison of tsunami generation and coastal impact for rigid vs deforming SMF located in Area 1 near the Hudson River Canyon (Fig. 1). (a,b) Envelopes of maximum surface elevation (color scale in meters) computed with FUNWAVE-TVD in grids G1 and G2 up to 3 h 8 min (initialized at t=20 min with NHWAVE's results) during propagation of SMF tsunamis generated by: (a) a rigid slump, and (b) a deforming slide (with Manning coefficient n=0.10 in NHWAVE) (bathymetric contours are shown in meters). Based on grid G2 results, envelopes of: (c) maximum and (d) minimum surface elevations computed along the 5 m isobath (yellow line marked in (a) and (b)), for tsunamis generated by a rigid slump (thick blue), and three different deforming slides with n = 0.05 (black), n = 0.10 (thick red), and n = 0.15 (green), for the slide-substrate bottom friction; the curvilinear distance s along the 5 m contour is computed from its southern end; the region of lower maximum surface elevations (210 to 260 km) corresponds to the Hudson River Estuary complex, with the New Jersey shore to the south (left), and Long Island shore to the north (right). Everything else being equal (geometry, location, density,…), both tsunami generation and coastal impact are larger when assuming the SMF is a rigid slump, rather than a deforming slide with different rheology. See details in Grilli et al. (2016)

LANDSLIDE TSUNAMI MODEL BENCHMARKING WORKSHOP

Organization is continuing for the landslide workshop, to be help on January 9-11, 2017 at the Texas A&M Galveston campus. Over thirty participants are registered with 9 invitees to be supported by travel funds from the FY15 East Coast project, and the remaining participants either self-funded or supported by FY16 travel allocations. A website detailing the organization and technical details of the chosen benchmark tests may be found at http://www.udel.edu/kirby/landslide/ The benchmark tests involve three idealized laboratory tests for sliding solid objects, three laboratory tests using deformable granular slides, and one field case based on slide events in Port Valdez, Alaska during the 1964 earthquake and tsunami event. An overview of the test cases may be found at http://www.udel.edu/kirby/landslide/problems.html (Figure 5). Data will be collected from participants for comparison to data starting in mid December, 2016.

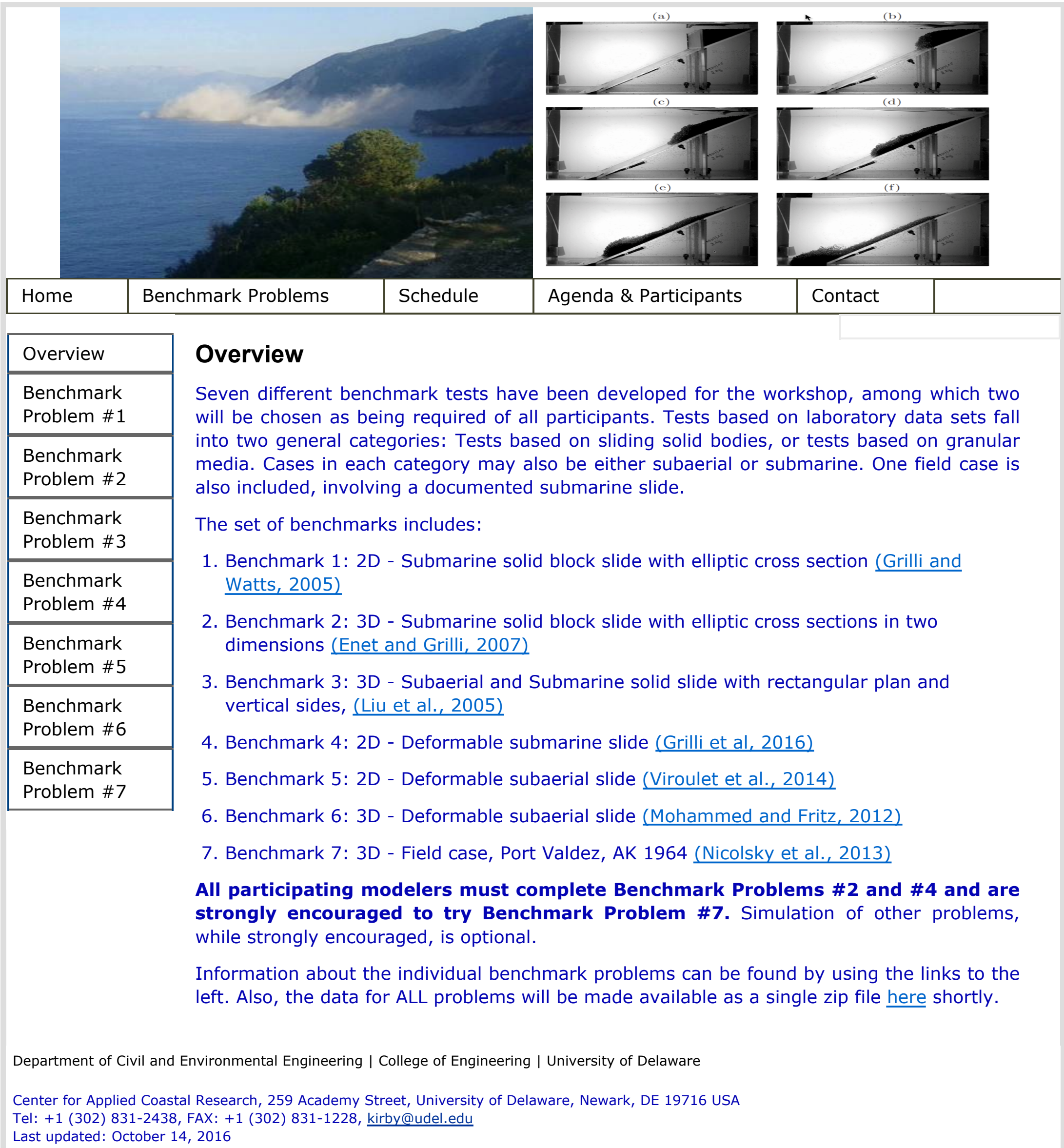

Figure 5. Sample web page for Landslide Tsunami Model Benchmarking Workshop, illustrating selection of benchmark tests developed for distribution to participants.