Modeling Tsunami Inundation and Assessing Tsunami Hazards for the U. S. East Coast

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BACKGROUND

Tsunami hazard assessment along the eastern US coastline is still in its infancy, in part due to the lack of historical tsunami records and the uncertainty regarding the magnitude and return periods of potential large-scale events (e.g., transoceanic tsunamis caused by a large Lisbon 1755 type earthquake in the Azores-Gibraltar convergence zone, a large earthquake in the Caribbean subduction zone in the Puerto Rico (PR) trench or near Leeward Islands, or a flank collapse of the Cumbre Vieja Volcano (CVV) in the Canary Islands). Moreover, considerable geologic and some historical evidence (e.g., the 1929 Grand Bank landslide tsunami, and the Currituck slide site off North Carolina and Virginia) suggests that the most significant tsunami hazard in this region may arise from Submarine Mass Failures (SMF) triggered on the continental slope by moderate seismic activity (as low as $Mw = 6$ to the maximum expected in the region $Mw = 7.5$); such tsunamigenic landslides can potentially cause concentrated coastal damage affecting specific communities.

In this project, we propose to assess tsunami hazard from the above and other relevant tsunami sources recently studied in the literature (ten Brink et al., 2008; MG special issue, 2009), and model the corresponding tsunami inundation in affected US East coast communities. Based on our experience with a variety of tsunami sources and case studies, we will model tsunami propagation, inundation, and runup using the robust and well-validated Fully Nonlinear Boussinesq Model (FNBM) FUNWAVE (Wei et al., 1995; Kennedy et al., 2000; Chen et al., 2000; Shi et al., 2001). Both Cartesian and curvilinear grids will be used for a variety of nested computational domains, at various grid scales. Whether frequency dispersion matters (e.g., for the SMF and other slide sources) or not (e.g., for the large co-seismic sources), this FNBM framework contains all the relevant physics without need to modify the model or its equations, whether one type of tsunami source or another is used. The same goes for linear versus nonlinear effects in generated tsunami wave trains, as well as for dissipation by bottom friction or bathymetrically induced breaking (which are modeled through adequate semi-empirical terms). Finally, a recent spherical coordinate implementation of FUNWAVE including Coriolis effects (Kirby et al., 2009), together with a very efficient parallel MPI and nested-domain implementation, make FNBM transoceanic simulations possible on a typical multi-core desktop computer or on the cluster computing environment available at the University of Delaware (UD), Center for Applied Coastal Research.

Large co-seismic sources (e.g., PR trench or Lisbon 1755 sources) will be modeled as initial instantaneous ocean surface deformations, based on estimates of event size, magnitude and geological parameters, using Okada's (1985) method. For reference, we recently successfully conducted a case study of the 2004 Indian Ocean tsunami using FUNWAVE, following this methodology (Grilli et al., 2007; Ioualalen et al., 2007; Karlsson et al., 2009). Co-seismic source parameters will be obtained from both our past work (Grilli et al., 2008, 2010) and other recent work reported in the literature (e.g., MG special issue, 2009).

Both historical (e.g., 1929 Grand Bank) and other local SMF sources will be modeled according to the methodology reported in Watts et al. (2003, 2005) and Grilli et al. (2005), and validated for a number of historical case studies (e.g., Day et al., 2005; Tappin et al., 2008). In this method, relevant SMF sources are semi-empirically generated from geomechanical, geological, and geometrical parameters, and specified as initial conditions (wave elevation and velocities) in the FNBM propagation model. Such (experimentally validated) sources were derived, based on a large number of 3D simulations of slide kinematics using a model solving fully nonlinear (inviscid) 3D Euler eqs. with a free surface. Since our earlier modeling and scaling analyses showed that the key parameter in SMF tsunami generation is initial acceleration, and typical SMF deformation rates do no significantly affect key tsunami features (Grilli and Watts, 2005), the methodology assumes rigid (translational or rotational) slides. But this is not a limitation and if known from sediment rheological properties, slide deformation effects can be included in the tsunami source.

Location and parameters for local SMF sources (other than historical) will first be identified by performing a first-order probabilistic analysis of SMF hazard along the east coast. Such work was already conducted by Grilli et al. (2009), for coastal areas from New Jersey to Maine. Results of this analysis were presented in terms of 100 and 500 year runup from seismically induced tsunamigenic SMFs. An extensive Monte Carlo (MC) model was developed and employed, in which distributions of relevant parameters (seismicity, sediment properties, type and location of slide, volume and dimensions of slide, water depth, etc.) were used to perform large numbers of stochastic stability analyses of submerged slopes (along actual transects across the shelf), based on conventional pseudo-static limit equilibrium methods for both translational and rotational failures. The distribution of predicted slope failures along the upper US East Coast was found to match published data quite well (Booth et al., 1985, 1993; Chaytor et al., 2007, 2009). Estimates of tsunami runup associated with SMF hazard were found to be low at most locations except, for the 500-yr tsunami, for two regions off Long Island, NY (up to 3-m) and off the New Jersey coast (up to 4-m). However, detailed deterministic tsunami generation, propagation and inundation modeling is required, in order to accurately estimate the inundation (and runup) hazard at these sites. This will be done in this project. Further, to estimate relevant SMF sources from the Florida border to New Jersey, we will perform a similar MC analysis for this East coast region, and observed slope failure distributions will again be used to ground truth the MC model predictions.

Recent field measurements, slope stability analyses, and 3D-Navier-Stokes multi-fluid (material) modeling work (Abadie, et al., 2009) will be reviewed and used to define and simulate realistic scenarios for a CVV flank collapse source. These will be used to develop a defensible approach for estimating tsunami hazard from this hypothetical event. We will simulate tsunami hazard from the few selected CVV flank collapse scenarios.

We will combine ocean scale simulations of transoceanic tsunami sources, such as Lisbon 1755 like or Puerto Rico Trench co-seismic events, and CVV collapse, with regional scale simulations of these events, along with the regional scale SMF events, in order to establish the relative degree of hazards for East Coast communities. Detailed inundation studies will be conducted for highest-risk East Coast communities, and results of these studies will be used to construct a first-generation of tsunami inundation maps for the chosen communities.

ACCOMPLISHMENTS

The following section summarizes the status of accomplishments for each Objective and related Task funded under this grant award. Summary descriptions are organized according to the overall objectives of the NTHMP that reflects the Sub-Committee structure. A more thorough document describing progress in the University of Rhode Island portion of the project is posted on the project web site. University of Delaware progress will be posted once inundation studies for initial sites are underway.

Objective. Modeling Tsunami Inundation and Assessing Tsunami Hazards for the U. S. East Coast

Mapping and Modeling Sub-Committee:

Task #	Project	Strategic Plan Metric	Subcom.	Accomplishment
1.1	*Literature Review on East Coast tsunami sources*	*Successful execution of NTHMP tsunami mapping, modeling, mitigation, planning and education efforts*	*MMS*	*Draft Literature review completed and posted on web site given above.*

1.2	*Monte Carlo modeling of East Coast SMF sources*	*Prioritize inundation map development*	*MMS*	*Bathymetry and geologic data for east coast continental margin has been collected. MC analysis has been completed. Summary results are given in report posted on web site given above. A presentation of this work will be given at AGU 2011.*

1.3	*Reanalysis of previous Cumbre Vieja simulations.* *Simulation of event using 3-D Multi-fluid VOF model.*	*Successful execution of NTHMP tsunami mapping, modeling, mitigation, planning and education efforts*	*MMS*	*CVV flank collapse scenarios were selected based on slope stability analyses. These were modeled using the 3D-NS THETIS code to define tsunami sources. FUNWAVE simulations using the latter were performed in regional grid (to estimate impact on other Canary Island and provide 2D source) and are being performed in ocean scale basin grids. A paper on this work was presented and published at the ISOPE conference (June, 2011; posted on website). Amore complete and detailed journal paper is about to be submitted.*

1.4	*Establish method for determining sources for inundation models based on MC simulation*	*Successful execution of NTHMP tsunami mapping, modeling, mitigation, planning and education efforts*	*MMS*	*This work is underway, based on both MC results and on results of a new collaboration with the USGS Woods Hole group (who has done extensive field work on underwater landslide for the East Coast).*

1.5	*DEM, GIS databases for East Coast inundation studies*	*Successful execution of NTHMP tsunami mapping, modeling, mitigation, planning and education efforts*	*MMS*	*East Coast tsunami DEM's collected. Local GIS and mapping people are learning NTHMP guidelines, familiarizing themselves with previous efforts on West Coast and other Pacific regions. Inundation mapping for Ocean City, MD and Atlantic City, New Jersey will begin after analysis of MC landslide simulations.*

PROBLEMS ENCOUNTERED

None, except for a slight refocusing of Task 1.4 to also account for recent results of USGS field work. In this respect, both S. Grilli and C. Baxter from URI were invited to participate in a USGS workshop on landside tsunami in Woods Hole, Aug. 18-19, 2011.

RELATED EFFORTS

Office of Naval Research funding has been used to develop a modernized version of the Boussinesq model code FUNWAVE being used to predict tsunami propagation and inundation in the present study. This code greatly improves the treatment of shoreline inundation and thus is particularly useful in the context of the NTHMP project. The code is described in the draft manuscript by Shi et al (2011). Tsunami benchmarking of the code is described in Tehranirad et al (2011). Both manuscripts are posted on the project web site. This effort is also reported in the summary report for the NTHMP-sponsored Model Benchmark Workshop.

ONR funding has also led to the development of a non-hydrostatic wave model NHWAVE which is being benchmarked for landslide and inundation simulation. The basic model is described in Ma et al (2011), posted on the website. A tsunami benchmark document will be reported soon.

NSF funding has been used to develop a nesting methodology for FUNWAVE simulations, using various resolution grids (e.g., basin scale, regional, and local).

ANTICIPATED OUTCOMES

This project is aimed at providing a comprehensive analysis, simulation and first generation mapping effort for at-risk coastal communities on the U. S. East Coast. An extensive review of the literature on potential tsunami sources with possible effects on East Coast states has been conducted. A probabilistic analysis of the potential hazards associated with submarine mass failure (SMF) events on the East Coast continental margin has been conducted. Reanalysis and simulation of Cumbre Vieja volcanic cone failure and a variety of co-seismic events has been conducted in order to assess the relative importance of a range of ocean scale events. Methodology for performing simulations from source to final inundation at prioritized East Coast sites is being established.

This work will lead to an identification of events representing worst case scenarios and an indication of the magnitude and spatial distribution of the coastal impact of such events along the US East Coast. These results will be used to establish priorities for performing detailed inundation studies for chosen East Coast communities. It is anticipated that up to four such sites will be included in the scope of the present project. The detailed local studies will lead to first-generation inundation maps for the chosen sites, which will be based on established NTHMP guidelines for map development.