A NEW MODELING FRAMEWORK FOR PROBABILISTIC LANDSLIDE TSUNAMI HAZARD ANALYSES

Stephan T. Grilli and Annette R. Grilli, University of Rhode Island, grilli@uri.edu, annette_grilli@uri.edu
Wei Cheng and Juan Horrillo, Texas A&M University, chengwei@tamu.edu, horrillj@tamug.edu
Claudia Cecioni and Giorgio Bellotti, Roma Tre University, claudia.cecioni@uniroma3.it, giorgio.bellotti@uniroma3.it

Landslide tsunamis, although even less frequent than coseismic tsunamis, can be particularly damaging for the nearest coast and coastal communities, because: (i) for large slide volumes, shallow submergence, and large vertical displacement, they can be made of steeper, more locally damaging and narrowly focused waves; (ii) they are typically triggered in relatively shallower, sediment rich, nearshore areas (e.g., continental shelf break and slope), hence at a short propagation distance from shore, allowing less time for advance warning when detected; and (iii) they may not even be detected at all before they impact the shore. An additional difficulty in assessing landslide tsunami hazard is the large variety of parameters that significantly influence wave generation (some mentioned earlier), which requires considering a large number of scenarios, and running corresponding simulations, to properly quantify coastal hazard. The latter is best tackled in a probabilistic Monte Carlo simulation (MCS) framework, in which random scenarios are defined on the basis of relevant probability distribution functions (PDFs) for each salient parameter. Such Probabilistic Tsunami Hazard Analyses (PTHA), which are increasingly routinely performed for coseismic tsunamis, are still quite rare for landslide tsunamis (e.g., Grilli et al 2009; Grezio et al 2012; Cecioni et al., 2023) as they face practical difficulties for: (i) properly assessing salient landslide parameters and quantifying their PDFs; (ii) acquiring relevant site-specific data on bottom/sub-bottom sediment properties and triggering mechanisms (e.g., seismicity); and (iii) developing a physically meaningful, but sufficiently efficient, numerical model for tsunami generation and propagation.

Submarine mass failures (SMF) (a.k.a. landslides) that have triggered tsunamis have taken a large variety of rheologic forms, from highly cohesive/nearly solid block short-range motions (e.g., slumps) to highly deforming long runout debris flows. Regarding tsunami generation and hazard, however, earlier work has shown that in most cases, worst case scenario coastal impact can be simulated with a simple rigid-landslide model, considering earlier translational or rotational motion (e.g., Grilli et al., 2005; Schambach et al., 2019); hence, this allows simplifying the SMF rheology. As for geometry, although details will matter in the nearfield, simulations also show that as the distance from the source grows, only the approximate aspect ratios of the SMF will matter to define tsunami wave properties (i.e., length, width, thickness), as well as its initial submergence depth and direction of motion. For these reasons, many past experimental or numerical investigations have considered solid block SMFs of simple geometry, such as semi-ellipsoidal or Gaussian-shaped (e.g., Grilli and Watts, 2005; Enet and Grilli, 2007; Di Risio et al., 2009; Schambach et al., 2019, 2020; Iorio et al., 2021, 2023)

Grilli et al. (2009) proposed an alternative approach of performing a site-specific MCS-PTHA for future tsunamis generated by SMFs (slides and slumps) triggered by earthquakes. Instead of simply randomly selecting SMF parameters within specified PDFs, assuming they would all fail and cause tsunamis, for each selected SMF geometry, orientation, location, and type (based on local sediment properties; Fig. 1b), they performed probabilistic slope stability analyses (along down slope transects; e.g., Fig. 1a), using randomized site-specific seismicity and other triggering mechanisms (e.g., excess pore pressure), for underwater slides and slumps. Although the methodology was well established in this earlier work, there was no relevant and sufficiently efficient model at the time to perform the tens of thousands MCS of landslide tsunamis required to assess coastal hazard in a PTHA framework.

In this work, this earlier MCS-PTHA method is extended and combined with an efficient linear Mild Slope Equation (MSE) model, in the frequency domain (fully dispersive, which is necessary for accurate modeling, since SMF tsunamis are typically made of shorter waves than coseismic tsunamis), forced by a time-dependent source term representing the SMF seafloor motion, implemented in a novel elementary solution (ES) framework (Iorio et al., 2021; Cecioni et al., 2023, 2024). For a selected area (e.g., Fig. 1), the MCS slope stability analyses allow defining a large database of randomly generated SMFs that fail for a given level of seismicity (Fig. 1c,d; associated with an earthquake return period). For each of these, the kinematics and corresponding footprint on the seafloor are defined, with the former obtained based on a balance of forces (e.g., Grilli and Watts, 2005; Fig. 2). The combined footprint of all SMFs is divided into many unit areas/ES sources, to which the MSE model is applied, thus computing a database of ES surface elevation at many nearshore save points. Tsunami elevations are finally computed for each SMF tsunami scenario at the latter by linear superposition of the ES; and statistics of relevant coastal impact metrics (e.g., runup) are computed. Note, tsunami waves are of small steepness and, hence, well represented by a linear model for depth > 20-50 m or so. Save points are defined along such an isobath and runup estimated using semi-empirical equations, based on save point results (Cecioni et al., 2023).

Significant work was devoted to implementing multiple levels of parallelization in the MSE-ES model, on the thousands of ES/sources, on the range of frequencies used in the MSE, and finally on the solution of the resulting algebraic system of equations for each case. Results show a speed-up in performance of several orders of magnitude compared to a repeated simple application of the standard MSE model.

Results for tsunami propagation and coastal impact in the USEC area of Fig. 1, as well as their statistics, will be presented at the conference. Another application to the Messina straight will be presented by Cecioni et al. (2024).

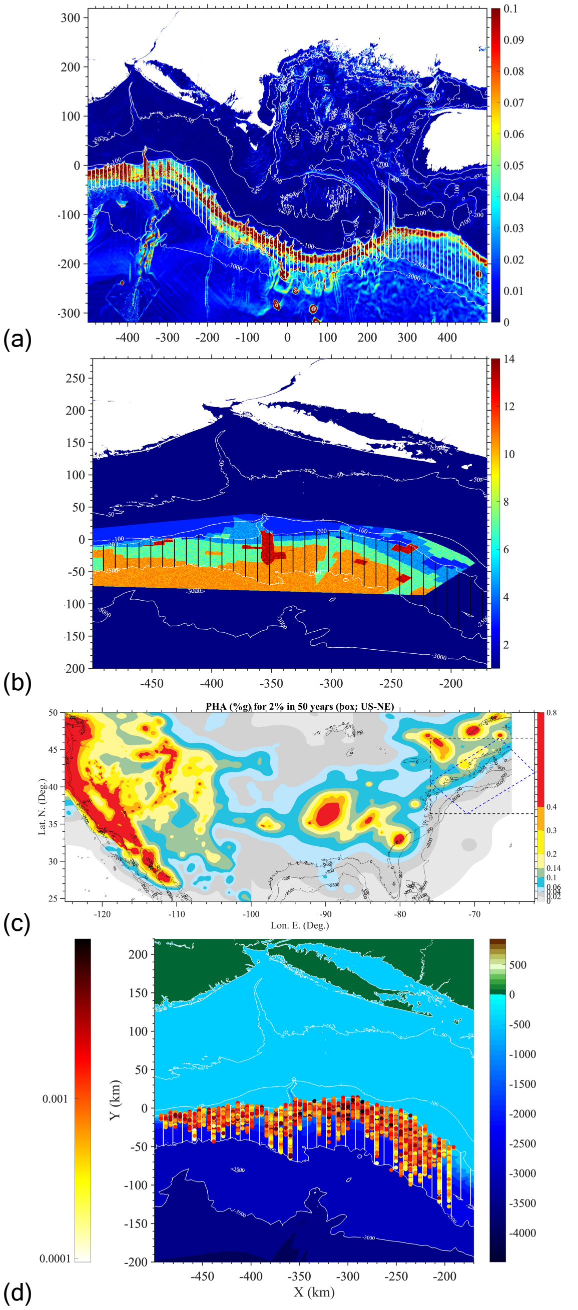

Fig. 1: Upper US East Coast. (a) MCS-PTHA area with selected transects, bathy-contours (in m) and bottom slope (color scale); (b) Map of 14 classes of seafloor sediments; (c) Seismic map of 2% in 50 year probability Peak Horizontal Acceleration (PHA); and (d) Failing SMFs in MCS data base with excess yearly probability (color) of PHA that fails each one.

REFERENCES

Cecioni C., G. Bellotti, V. Iorio and S.T. Grilli (2023). Probabilistic landslide tsunami modeling of the 2018 Palu Bay event. Coastal Engineering, 183, 104332.

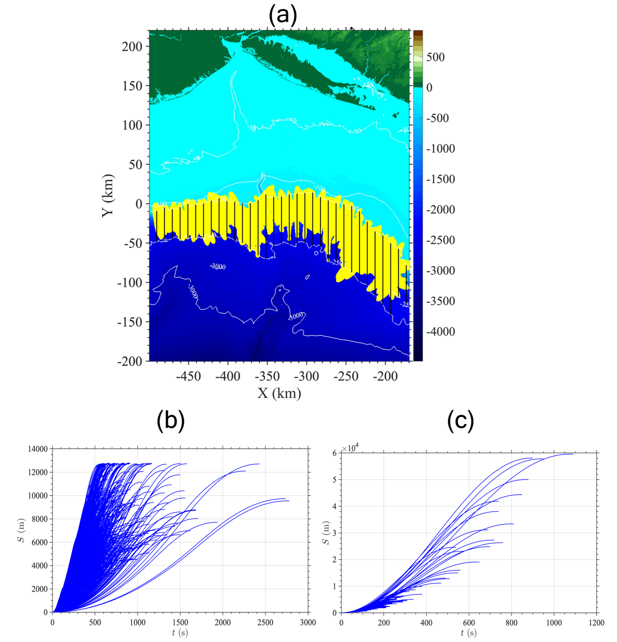

Fig. 2: (a) Seafloor footprint of slide/slumps that fail (Fig. 1d); and (a,b) Slide/slump kinematics used in tsunami modeling.

Cecioni C., G. Bellotti and S.T. Grilli (2024). Probabilistic tsunami hazard analysis from submarine mass failure: a Monte Carlo approach to a case study in Italy. Submitted to the 38th Intl. Conference on Coastal Engineering.

Di Risio, M., De Girolamo, P., Bellotti, G., Panizzo, A., Aristodemo, F., Molfetta, M. G., Petrillo, A. (2009). Landslide-generated tsunamis runup at the coast of a conical island: New physical model experiments. Journal of Geophysical Research, 114, 1(16).

Enet, F., Grilli, S. T. (2007). Experimental study of tsunami generation by three dimensional rigid underwater landslides. Journal of Waterway Port Coastal and Ocean Engineering 133, 442-454.

Grezio, A., Sandri, L., Marzocchi, W., Argnani, A., Gasparini, P., Selva, J. (2012). PTHA for Messina Strait area (Sicily, Italy). Nat. Hazards 64 (1), 329-358.

Grilli, S.T. and Watts, P. (2005). Tsunami generation by submarine mass failure Part I: Modeling, experimental validation, and sensitivity analysis. J. Waterway Port Coastal and Ocean Engng., 131(6), 283-297.

Grilli, S.T., Taylor, O.-D. S., Baxter, D.P. and S. Maretzki 2009. Probabilistic approach for determining submarine landslide tsunami hazard along the upper East Coast of the United States. Marine Geology , 264(1-2), 74-97.

Iorio V., Bellotti, G. Cecioni C., Grilli S.T. (2021). A numerical model for the efficient simulation of multiple landslide-induced tsunamis scenarios. Ocean Modell., 168, 101899.

Schambach L., Grilli S.T., Kirby J.T. and F. Shi (2019). Landslide tsunami hazard along the upper US East Coast: effects of slide rheology, bottom friction, and frequency dispersion. Pure Applied Geophys., 176(7), 3,059-3,098

Schambach L., Grilli S.T., Tappin D.R., Gangemi M.D., and G. Barbaro (2020). New simulations and understanding of the 1908 Messina tsunami for a dual seismic and deep SMF source. Mar. Geology, 421, 106093.