Keynote 2

How Numerical Simulations May Contribute to Tsunami Risk Preparedness: The 26 December 2004 Indian Ocean Event and the Thailand Case Study

M. Ioualalen[1,*], J. Asavanant[2], N.Kaewbanjak[2], S.T. Grilli[3], and J. T. Kirby[4]

[1]*Institut de Recherche pour le Developpement, "Geosciences Azur", Villefranche-sur-mer, France,*
[2]*Mathematics Department, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand*
[3]*Department of Ocean Engineering, University of Rhode Island, Narragansett, RI 02882, USA*
[4]*Center for Applied Coastal Research, University of Delaware, Newark, DE 19716, USA*

[*]*Corresponding author: Mansour.Ioualalen@geoazur.obs-vlfr.fr*

Abstract

The tsunami information, i.e. the sea level elevation, presents useful features that can be used for different case studies. It can be derived from observations, e.g. tide gages records or anomaly of sea level obtained with altimeters, but also through numerical modeling of the tsunami propagation. Once a robust numerical simulation is performed, the wave sequence, compared to available hydrodynamical observations, may help in a better characterization of the tsunami source, e.g., earthquake – or landslide-derived tsunami among the most widespread sources. It may be used for refining a source derived from seismological instrumentations (GPS positioning, seismic stations analysis). As a result, a better identification of source parameters along with a reliable ensemble of numerical simulations of the tsunami propagation and run-up within an area is useful for tsunami risk assessment, e.g., tsunami run-up maps and optimization of the tsunami instrumentation for the purpose of a tsunami warning system. In this context we describe the Thailand case study of the 26th December 2004 Indian Ocean tsunami event.

KEY WORDS: numerical simulation, tsunami, risk assessment, warning system, Thailand case study

Introduction

Any fast deformation of the ocean sea floor may, in some circumstances, generate a long wave tsunami which can propagates at very fast speed over an entire ocean basin like the Pacific ocean without significantly loose of its energy and substantially amplify at coasts or even offshore within the continental shelf: the wave is mainly conservative because its long time scale (or period) inhibits viscous damping and, rather, the energy is redistributed along its propagation. Consequently the tsunami risk is tightly linked to the seismic or gravitary risks that are the most widespread tsunami sources. As a result, a better knowledge of the mode of triggering and propagation of a tsunami may help in a better characterization of the geophysical source. The relationship is however not straightforward because some functions of transfer are not known accurately. In particular: For a co-seismic deformation it is not an easy task to estimate the seafloor deformation resulting from an earthquake localized at a certain depth and the horizontal depth-varying deformation of the water column is also approximated. Most of the time also, the seafloor deformation is characterized through Okada (1985) representation which constrains the medium to be homogeneous. It is also fair to say that a more complex formulation or simulation of these functions of transfer would require much more elaborated and extended observational networks than the existing ones to constrain them, e.g., tide gages for the hydrodynamics, GPS positioning, seismic stations for the earthquake. In other words, the degree of precision, the variety and the extension of the observational networks always adapt itself to our capability to simulate/represent the physical processes through improving numerical/theoretical representations and computational facilities. This relationship between the instrumentation and the modeling is in constant progress. This is indeed an interesting issue because we may always, at a certain degree of accuracy, use the tsunami information to complement the direct observations of any tsunamigenic source for its better characterization. The tsunami information are mainly the sea level observations instrumented with tide gauges (eventually altimeters) and the numerical modeling of the tsunami propagation.

Another key issue of tsunami modeling is the ability of a robust numerical simulation to provide a synoptic picture of a particular event and, in particular, the run-up distribution along a coastline. A robust simulation relies on accurate bathymetric and topographic data set (an accurate computational domain), a best-fit geophysical source and a reliable numerical model simulating the tsunami propagation and run-up. The best-fit solution may be obtained through tsunami modeling by using both available hydrodynamical and geophysical data sets. Then, ideally, the run-up distribution could be obtained in a prognostic mode (or predictive), or at least partially. As a result the simulation would be validated with available run-up observations and, elsewhere, the simulation would predict run-up. Such methodology is interesting because the simulation may predict run-ups where no observations were made, generally because such locations were sparsely populated or difficult to access, or simply because the coast line is too extended to be fully sampled for the cases of large events like the 26th December 2004 Indian Ocean tsunami. Besides the picture may reveal vulnerable areas as well as protected ones. Such tsunami risk assessment may help in future development plans of a particular coastal area in the case of an eventual recurrent geophysical event. This aspect is essential for building a reliable and optimal instrument sampling for a tsunami warning system.

The above statements are not exhaustive and we want to describe here the 26th December 2004 Indian Ocean tsunami and the Thailand case study to illustrate them.

The Tsunami observations in Thailand

We report here the run-up observations that have been made in this area of Thailand by various international field survey teams (Tsuji *et al.*, 2006). All of the six provinces that border Thailand's Andaman coast (Ranong, Phang Nga, Phuket, Krabi, Trang, and Satun) have exposed coastline that was impacted by the tsunami (Figure 1). The largest tsunami run-up (11 to 14 m) were recorded near Khao Lak (Figure 2). The second most impacted area was the island of PhiPhi, which is located in the Krabi province, 50 miles East of the Southern tip of Phuket (Figure 2; 98.8°E, 7.8°N). An up to 6 m waves submerged a highly populated, narrow and low lying sand strip connecting two mountain ranges. Finally, Phuket island, another of Thailand's most popular tourist areas, was the last region to be severely impacted by the tsunami (Figure 2). A 5.5 - 6 m high wave hit the western coast of the island, causing large run-ups (up to 10 m) and major damage.

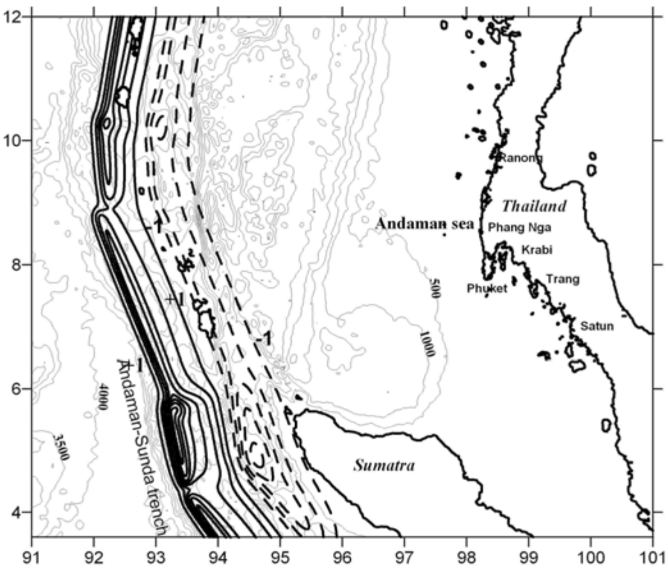

Figure 1: The tsunami source proposed by Grilli *et al.* (2006) and Ioualalen *et al.* (2006) based on Okada's (1985) dislocation model, placed in the computational grid. Red lines represent uplift and blue lines represent subsidence, both at 1 m contour intervals. The background bathymetry is plotted at 500 m contour intervals. The 5 exposed provinces of the Andaman coast of Thailand are identified in blue.

The numerical procedure

Numerical simulations of tsunami coastal impact require three components: (i) a source based on the known geology and seismology of the event; (ii) a tsunami propagation and run-up model; and (iii) the ocean bathymetry and coastal topography. Before proceeding with detailed simulations of nearshore or onshore tsunami impact, the tsunami source must be iteratively refined through comparing the generated tsunami with direct observations of tsunami arrival time and ocean surface elevations, wherever available. For the 12/26/04 event, a number of tide gauge (Hirata *et al.*, 2006) and satellite transect records (Gower, 2005) were available in the Indian Ocean. This source calibration has been performed by Ioualalen *et al*. (2006) and Grilli *et al*. (2006) who have defined a tsunami source made of five separate segments and have iteratively refined each segment's geometrical, geological, and seismological parameter values by comparing tsunami predictions with observations at tide gages and along one satellite transect (Figure 2).

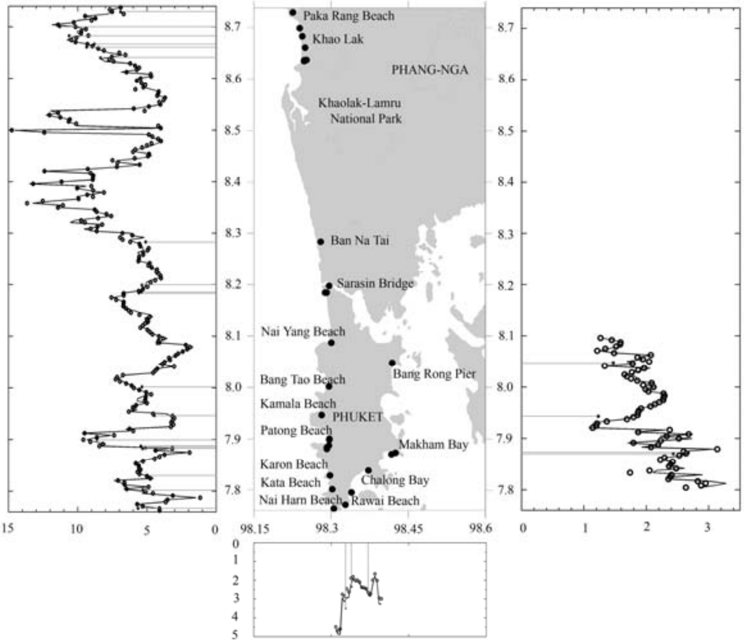

Figure 2: Observed and simulated run-ups along the Andaman coast of Thailand, Phang Nga (Khao Lak) and Phuket island provinces, where most of the damage was recorded. Locales of observations are identified in the middle panel. The observed run-ups are reported as line segments. The simulated run-ups are continuously plotted along the coast. Solid lines indicate run-ups derived from the fully nonlinear Boussinesq simulation while the scattered plot (*) is obtained with the Nonlinear Shallow Water model (no dispersion).

A 0.25 minute Cartesian grid has been used to describe the Andaman coast of Thailand. The grid includes the entire Andaman coast of Thailand, as well as most of the tsunami source (only small parts of the first and fifth segments are not included). ETOPO2 data was used to specify bathymetry in this grid, except in coastal Thailand (from Ranong, 98.59°E - 9.95°N, to Satun, 100.08°E - 6.53°N). In this region, a combination of 2 minute ETOPO2 and other more accurate and resolved bathymetric data, derived from a composite approach using 30 m resolution data from the NASA Space Shuttle Radar Topography Mission for the land area and digitized maritime charts for the ocean area (Royal Thai Navy, Hydrographic Department overlaid onto the 1:20,000 scale administrative boundary GIS; ESRI Thailand, Co. Ltd**.**) Marine charts have up to a 50 m resolution in most Bays (e.g., Patong in Phuket, Khao Lak). As a result a relatively accurate computational grid with 0.25 minute horizontal spacing (about 460x460 m at these latitudes), both on land and sea, and study coastal tsunami impact along the Andaman coast of Thailand, where most of the damage and large run-ups were observed

The numerical model used is based on Funwave numerical model for the tsunami propagation, run-up and inundation and, for the seismic source, on the half-plane solution of an elastic dislocation problem for the vertical co-seismic displacement (Okada, 1985). Funwave is a fully nonlinear

Boussinesq water wave model developed at the University of Delaware (Kirby, 2003). Wei *et al*. (1995) have demonstrated that the retention of nonlinear effects beyond the usual ordering in weakly nonlinear Boussinesq models is crucial to the correct modeling of shoaling solitary wave crests, and thus is important in the modeling of shoreline inundation. The presence of frequency dispersion in the model is important for the case of short wave propagation into relatively deep water, and allows for the mechanism of wave crest splitting during wave propagation over shallow bathymetry. Funwave includes dissipation from breaking waves, and model predictions of shoreline run-up have been well tested in the case of short wave shoaling and breaking. Run-ups have also been tested successfully tested for the cases with solitary waves on a shoal.

Results

Figure 2 shows the continuous distribution of simulated run-ups along the coast, compared to all available (26) observations. We find quite a good agreement between these at all locations and, particularly, that the simulated run-ups reproduce well all abrupt variations seen in observations (e.g., in Khao Lak, near Sarasin bridge, in Patong beach, in the southern coast of Phuket island). More specifically, the observed and simulated run-ups: are in the range, 1.47, 1.69 m (15% over-estimate), to 11.29, 11.87 m (5% over-estimate), respectively; have a 5.62 and 5.56 m mean, respectively (1% under-estimate), with a standard deviation of 2.56 m and 2.79 m, respectively (8% over-estimate. This indicates that the simulation results truly reflect tsunami impact as it occurred in Thailand during the 12/26/04 event. Hence, we posit that such model results provide a synoptic picture of tsunami impact that can meaningfully be used *in lieu of* field data, in locations where post-tsunami field studies have not been conducted.

Conclusions

It should be stressed that the observed run-up were not used to constrain this simulation. Hence, the good agreement of simulated and observed run-ups in Figure 2 provides an independent validation of the approach, indicating that the numerical simulation is highly robust and all of its components (source, computational grid and associated bathymetry, and numerical model) are consistent with each other. Hence, at the selected scales, the model adequately represents physical processes at play during tsunami generation, propagation and, more importantly, run-up, including shoreline motion, dissipation due to wave breaking, and reflection.

In view of the robustness of the simulation, predicted run-ups may reasonably be used to estimate tsunami impact in regions where no observations were made. At the very least, such results could be used to identify areas of significant tsunami impact, where further field surveys should be conducted. Most of the observations so far have indeed been made in locations where heavy casualties were reported, such as Khao Lak, Patong Beach, and Phi Phi Island, which are also areas with important tourist related infrastructures. There were very few observations made outside these areas. Our results, for instance, clearly predict large run-ups north of Ban Na Thai and at Khao Lak Lamu, slightly south of Khao Lak. According to our simulation, this area may have experienced run-ups in excess of 10 m. Up-to-date there are no observations or even eyewitness reports to compare with in those locations. Besides pointing at large potential run-ups, simulation results also identify the less vulnerable regions, e.g., south and east of Phuket Island, where one could more safely rebuild.

It is a worldwide trend that more and more urban areas are developed along coastlines, and is thus of prime importance to identify vulnerable coastal areas that may be considered for development in the future. This could be the case for the coastal section of Thailand located in between Khao Lak and Phuket Island, which is likely to have experienced a 10-15 m run-up during the 12/26/04 event, at a few locations identified in our simulations.

References

Gower, J. 2005. Jason 1 detects the Dec. 26, 2004 tsunami. EOS 86:37-38.

Grilli, S., Ioualalen, M., Asavanant, J., Shi, F., Kirby, J., and Watts, P. 2006. Source Constraints and Model Simulation of the December 26, 2004 Indian Ocean Tsunami. J. Wtrwy, Port, Coast, and Oc. Engrg.**,** ASCE. In press.

Hirata, K., Satake, K., Tanioka, Y., Kuragano, T., Hasegawa, Y., Hayashi, Y. and Hamada, N. 2006. The 2004 Indian Ocean tsunami: Tsunami source model from satellite altimetry. Earth Planets and Space 58:195-201.

Ioualalen, M., Asavanant, J., Kaewbanjak, N., Grilli, S.T., Kirby, J.T., and Watts, P. 2006. Source Constraints and Model Simulation of the December 26, 2004 Indian Ocean Tsunami. J. Geophys. Res., Oceans. In revision.

Kirby, J.T. 2003. Boussinesq models and applications to nearshore wave propagation, surf zone processes and wave-induced currents. In: Advances in Coastal Modeling**,** V.C. Lakhan (ed), Elsevier Oceanography Series 67:1-41

Tsuji, Y., Namegaya, Y., Matsumoto, H., Iwasaki, S., Kanbua, W., Sriwichai, M. and Meesuk, V. 2006. The 2004 Indian tsunami in Thailand: Surveyed run-up heights and tide gauge records. Earth Planets and Space 58:223-232.

Acknowledgements

The authors would like to gratefully acknowledge the following organizations in Thailand: the NECTEC center for the use of their computer cluster, the Chulalongkorn University Tsunami Rehabilitation Research Center through DrS.P. Charusiri and A. Snidvongs for providing us with useful field survey data, and the Marine Dept. through Dr. A. Sanitawong for providing us with digitilized topography and bathymetry data sets). M. Ioualalen acknowledges with thanks IRD for granting him a 4-month visit at Chulalongkorn University, Maths Dpt., and AVIC colleagues and students for having hosted him. He also acknowledges with thanks the French Agence Nationale pour la Recherche, ANR, for supporting this work through the TSUMOD Grant ANR-05-CATT-016-02.