Numerical simulation of the 2011 Tohoku tsunami: Comparison with field observations and sensitivity to model parameters

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ABSTRACT

The March 11, 2011 M9 Tohoku-Oki Earthquake, which is believed to be the largest event recorded in Japanese history, created a major tsunami that caused numerous deaths and enormous destruction on the nearby Honshu coast. Various tsunami sources were developed for this event, based on inverting seismic or GPS data, often using very simple underlying fault models (e.g., Okada, 1985). Tsunami simulations with such sources can predict deep water and far-field observations quite well, but coastal impact is not as well predicted, being over- or under-estimated at many locations. In this work, we developed a new tsunami source, similarly based on inverting onshore and offshore geodetic (GPS) data, but using 3D Finite Element Models (FEM) that simulate elastic dislocations along the plate boundary interface separating the stiff subducting Pacific Plate, and relatively weak forearc and volcanic arc of the overriding Eurasian plate. Due in part to the simulated weak forearc materials, such sources produce significant shallow slip along the updip portion of the rupture near the trench (several tens of meters).

We assess the accuracy of the new approach by comparing numerical simulations to observations of the tsunami far- and near-field coastal impact using: (i) one of the standard seismic inversion sources, which we found provided the best prediction of tsunami near-field impact in our model (UCSB; Shao et al., 2011); and (ii) the new FEM source. Specifically, we compare numerical results to DART buoy, GPS tide gage, and inundation/runup measurements. Numerical simulations are performed using the fully nonlinear and dispersive Boussinesq wave model FUNWAVE-TVD, which is parallelized and available in Cartesian or spherical coordinates. We use a series of nested model grids, with varying resolution (down to 250 m nearshore) and size, and assess effects on results of the latter and of model physics (such as when including dispersion or not). We also assess effects of triggering the various tsunami sources in the propagation model: (i) either at once as a hot start, or with the spatio-temporal sequence derived from seismic inversion; and (ii) as a specified surface elevation or as a more realistic time and space-varying bottom boundary condition (in the latter case, we compute the initial tsunami generation up to 300 s using the non-hydrostatic model NHWAVE).

Although additional refinements are expected in the near future, results based on the current FEM sources better explain near field observations at DART and GPS buoys near Japan, and measured tsunami inundation, while they simulate observations at distant DART buoys as well or better than the UCSB source.

KEYWORDS: Tsunami source modeling; Tsunami propagation modeling; Boussinesq model; Wave dispersion effects.

INTRODUCTION

On March 11th, 2011, at 2:46 pm JST, a magnitude $M_w = 9.0$ earthquake struck near the northeastern coast of Japan (37$^\circ$49’ N, 143$^\circ$03’ E; Fig. 1), with substantial slip at fairly shallow depths (about 10–20 km), causing large seafloor motions that triggered very high tsunami waves, perhaps the largest in Japan’s recorded history. The main earthquake shocks lasted for 3–4 minutes and, owing to the proximity of the epicenter to shore, the first significant waves reached Japan only 10 minutes after the event started, thus allowing for very little warning time. The tsunami caused extensive destruction along the coast of the Tohoku region, between 35$^\circ$–43$^\circ$ N. Post-tsunami surveys reported maximum of runups and inundation depths values in the 20–40 m range, mostly between 37.7$^\circ$–40.2$^\circ$ N where the Miyagi and Iwate Prefectures are located (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011; Mori et al., 2011a). The largest runups occurred in the north, along the Sanriku/Ria coast (north of 37$^\circ$ N), which has a very complex topography that amplifies tsunami impact. By contrast, areas located directly south, which mostly consist of plains, were less impacted. As a result of the tsunami, nearly 16,000 people lost their lives and 4,000 were reported missing; many were injured and millions more were affected by the lack of water and food, electricity, and transportation (IOC/UNESCO, 2011).

Within one hour of the event, when the tsunami reached the nearest DART buoys (Fig. 1; Deep-water Assessment and Reporting of Tsunami network; Gonzalez et al., 1998), propagation models of the anticipated far-field impact caused sufficient concern to trigger evacuations and warnings in many distant areas across the Pacific Ocean. Large impact