The Effect of Horizontal Advection of Topography and Time Dependent Crustal Deformation on Tsunami Generation

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Introduction

Initial conditions used in tsunami modeling are commonly simplified due to lack of observations, poor understanding of the mechanics of tsunami generation, and limitations on computational power and processing times.

1. Neglecting the Horizontal Advection of Topography

Conventionally, tsunami models neglect the contribution of horizontal advection displacements, in the absence of velocities. However, it has been shown that this can be significant and might explain discrepancies in wave height predictions, under certain conditions, such as the combination of shallow-dipping fault with relatively steep topography (Iwata & Satake, 1996; Song et al., 2008; Dussek et al., 2012).

1.a. Apparent Vertical Displacement

The vertical displacement of water due to the horizontal movement of the slope, \( \Delta h \), can be calculated by the following equation:

\[
\Delta h = H \frac{dF}{dz} + \frac{1}{2} \rho g \frac{d^2F}{dz^2} + \frac{1}{2} \rho g \frac{d^2y}{dz^2}
\]

In which \( H \) is the water depth and \( y \) and \( z \) are the horizontal displacements due to faulting (Iwata & Satake, 1996).

1.b. Horizontal Moment Transfer

The horizontal displacement of a slope can accelerate water in the horizontal directions, therefore transferring momentum to the ocean water and producing with kinetic energy, and can be included in the tsunami model at stage (Song et al., 2008).

2. Time dependence of deformation

The contribution of time-varying deformation of the seafloor is often neglected in tsunami modeling due to the remoteness of the source. However, it has been shown that in the near-field, i.e., within the source dimension, dynamic displacement of the seafloor can have a significant effect on wave height and arrival time (Gomis et al., 2001; Dussek and Dias, 2003; Geller, 2006).

Motivation

The main shock of the 2011 Tohoku tsunami occurred less than a 100 km from Japan coast, with an inferred rupture encompassing an area of nearly 200 km in width and 500 km in length; thus providing multiple observations within the source dimension. Extremely large horizontal seafloor displacements, as much as 30 m, have been measured near the trench after the 2011 Tohoku tsunami, compared to less than 10 m of maximum vertical displacement (Puglisi et al., 2011; Song et al., 2011; Roelefort et al., 2011). Horizontal displacement of up to 50 m have also been inferred at shallow depth near the trench (Jay et al., 2011).

We propose to use the abundant observations recorded during the 2011 Tohoku earthquake and tsunami to study the effects of time-varying deformation and the contribution of horizontal seafloor displacement on tsunami generation. First, we simulate the earthquake using a simplified rupture model (Kikuchi et al., 2011), in which the fault displacement and magnitude at each point in space and time is assumed fault geometry. Then, we will use SPECTRUM (Tramp et al., 2008), a spectral element numerical code, to solve the elastic–dynamic problem including wave propagation and the residual static deformation, to determine the time-dependent seafloor deformation. Finally, we wish to test the effects on wave height and arrival time by using our results as input to a tsunami generation and propagation model.

Testing Models with Increased Complexity

<table>
<thead>
<tr>
<th>Homogenous model w/ Topography</th>
<th>Layered model w/ Topography</th>
<th>3D &quot;realistic&quot; model w/ Topography</th>
</tr>
</thead>
</table>

Workflow

Kinematic Rupture Model

\[ \text{dip}(x,y,z) \]

\[ \text{SPECTRUM} \]

\[ \text{3D MESH Velocity model + topography} \]

Validation against real data (seismic, GPS, pressure gauges, etc.)

Significance of Horizontal Displacements

Time-Dependent Deformation

Tsunami Modeling

References

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Conclusions and Future Work

We expect that for the full rupture, which spans ~100,000 km² with larger magnitude subevents, the effect of mesh discretization on static displacements would be even more important. In addition, any finite-element method for the moment-tensor source is spread across the entire element in which it is located. Thus, where the rupture reaches the surface, we expect discrepancies in the surface displacements if our discretization is coarser than our desired sampling of surface displacements. Given the computational capabilities currently available to us, our discretization is limited. Since the simulation requires a very large mesh to order to mitigate artifacts from the edges of the mesh, ~613 m cubic km, is required to constrain the rupture area alone. Further tests need to be done in order to optimize the model discretization and validate our results.

Modelling Requirements

Previous qualitative tests with SPECTRUM-Cartesian show that the choice of mesh discretization and volume size affects static displacements, due to the thickness of the model (Song et al., 2011). We have done a similar test with SPECTRUM-Eulerian using a Mw 7.4 dip-slip source point at a depth of 15 km in a 25° by 25° source of the earth and a 10 velocity model with a homogeneous crust. We compare two different discretizations, ~15 km and ~4.9 km grid spacing (Fig. C). The results highlight the importance of optimizing the model discretization and validating our results.
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