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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 time.

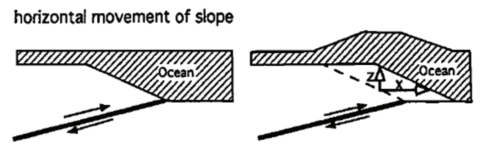
1. Neglecting the Horizontal Advection of Topography

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

1.a. Apparent Vertical Displacement

The vertical displacement of water due to the horizontal movement of the slope, u_h, can be calculated by the following equation:

$$u_h = u_x \frac{\partial H}{\partial x} + u_y \frac{\partial H}{\partial y}$$



in which H is the water depth and u_x and u_y are the horizontal displacements due to faulting (Tanioka & Satake, 1996).

1.b. Horizontal Momentum Transfer

The horizontal displacement of a slope can accelerate water in the horizontal directions, therefore transferring momentum to the ocean water and providing the ocean with kinetic energy, and can be included in the tsunami modelling 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 (Ohmachi et al. 2001; Dutykh and Dias, 2009; Gisler, 2008).

Motivation

The main shock of the 2011 Tohoku earthquake occurred less than a 100 km from Japan's east coast, with an inferred rupture encompassing an area of 200 km wide and 500 km long, thus providing multiple observations within the source dimension. Extremely large horizontal seafloor displacements, as much as 50 m, have been measured near the trench after the 2011 Tohoku tsunami, compared to less than 10 m of maximum vertical displacement (Fujiwara et al., 2011; Sato et al., 2011; Kido et al., 2011). Horizontal slip values of up to 60 m have also been inferred at shallow depth near the trench (Lay et al., 2011).

We propose to use the abundant observations recorded during the 2011 Tohoku-Oki earthquake and tsunami to study the effects of time-varying deformation and the contribution of horizontal seafloor displacement on tsunami generation. First, we will simulate the earthquake using a kinematic rupture model (Ide et al.,2011), in which the fault slip (magnitude and direction) at each point in space and time for the assumed fault geometry. Then, we will use SPECFEM3D (Tromp et al., 2008), a spectral element numerical code, to solve the elasto-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.

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Workflow

- Kinematic Rupture Model slip(x,y,z,t)
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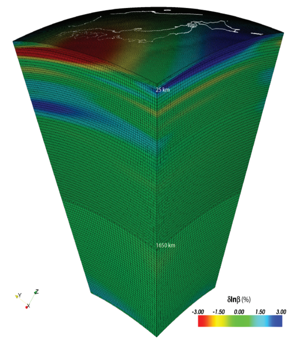
- 3D MESH Velocity model + topogrpahy
- → SPECFEM3D Spectral Element Solver →
- Time-Dependent Deformation → Tsunami Modelling
- Static (residual) Deformation → Significance of Horizontal Displacements
- Validation against real data (seismic, GPS, pressure gauges, etc)



Testing Models with Increased Complexity

1. Homogeneous model w/o Topography
2. Homogeneous model w/ Topography
3. Layered model w/ Topography
4. 3D "realistic" model w/ Topography

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Modelling Requirments

Previous qualitative tests with SPECFEM3D Cartesian show that the choice of mesh discretization and volume size affects static displacements, due to the finitness of the model (Tape et al., 2011). We have done a similar test with SPECFEM3D Globe using a Mw 7.4 dip-slip point source at a depth of 15 km in a 25° by 25° chunk of the earth and a 1D velocity model with a homogeneous crust. We compare two different discretizations, ~19.5 km and ~4.9 km grid spacings (fig. C-D). The bulk of the difference between the two models is observed around the epicenter and along the strike of the fault, with an average of ~33% error in magnitude and ~30 deg in direction.

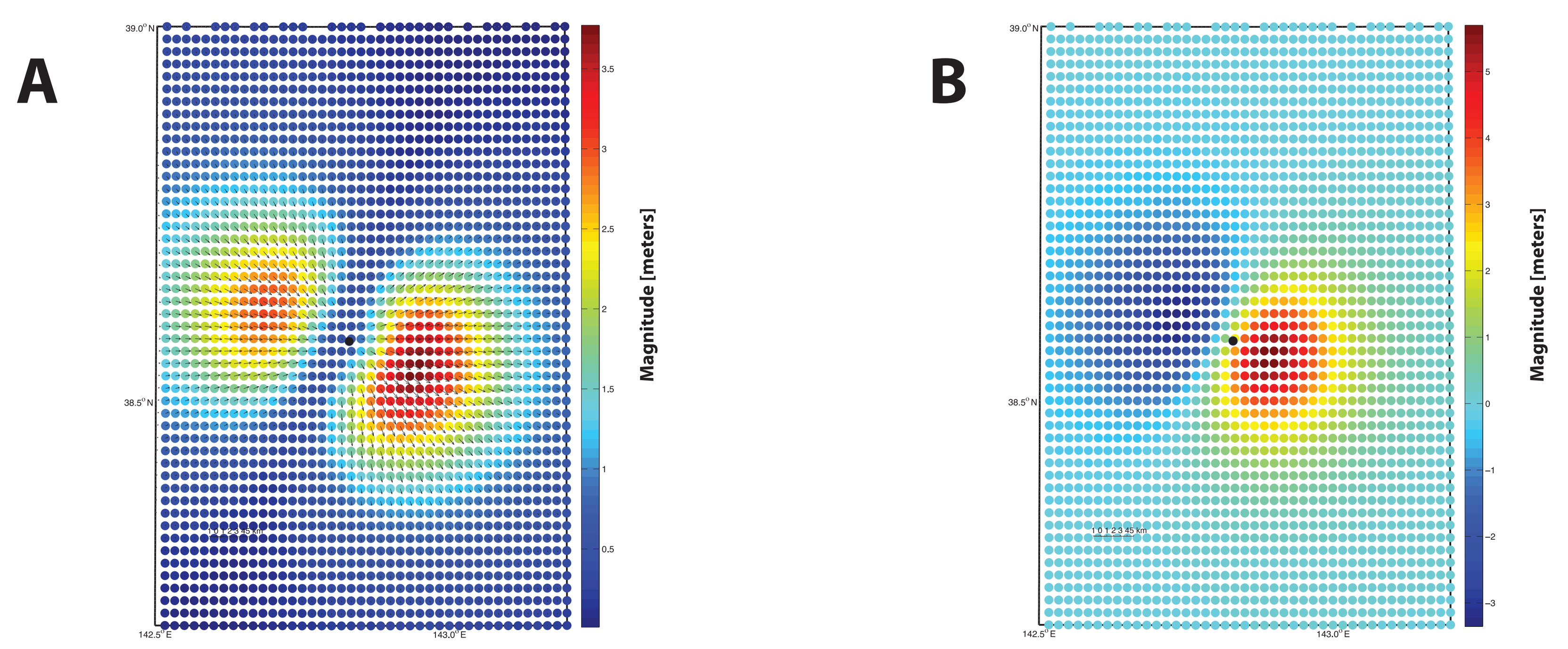

Fig. A: Horizontal residual displacements of the seafloor above the source (colors are absolute magnitude). Fig. B: Vertical residual displacements of the seafloor above the source.

Comparing Different Model Discretizations

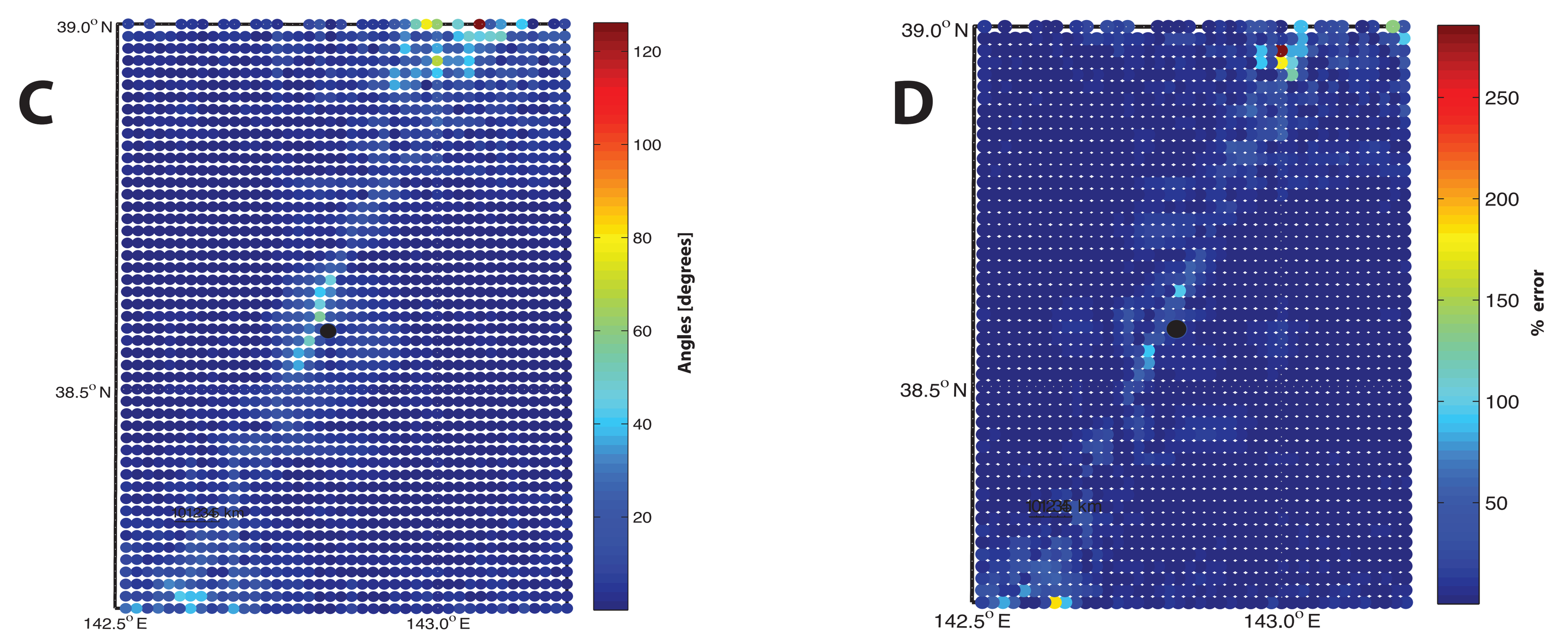

Fig. E-F: Difference between fine and coarse discretizations in SPECFEM3D Globe for the total residual displacements shown in figures A & B. Figures C and D show the angular and magnitude difference, respectively.

Conclusions and Future Work

We expect that for the full rupture, which spans ~100,000 km^2, with larger magnitude sub-events, the effect of mesh discretization on static displacements would be even more important. In addition, in any finite-element method 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 model in order to mitigate artificial returns from the edges of the mesh. ~6.3M cubic km, is required to contain the rupture area alone. Further tests will need to be done in order to optimize the model discretization and validate our results.

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