Dynamic Earthquake and Tsunami Modeling
Offshore Ventura, California

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SCEC Rupture Dynamics Code Validation Workshop

March 23, 2015
March 11, 2011 Tohoku Earthquake and Tsunami

- \( M_w \) 9.0 Earthquake
- Max tsunami runup height over 30 m
- Over 15,700 people killed
- Economic loss in Japan over 300 billion U.S. dollars

Image from Jiji Press/RFP/GePy Images
March 11, 2011 Tohoku Earthquake and Tsunami

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Tsunami Barrier Wall

Image from Jiji Press/RFP/Getty Images
December 26, 2004 Indian Ocean Earthquake and Tsunami

- $M_w$ 9.1 Earthquake
- Max tsunami runup height over 30 m
- Over 225,000 people killed
- Local economies devastated

Image from AFP/Getty Images
Outline

• Motivation for studying the dynamics of thrust faults and tsunamis
• Offshore Alaska earthquake and tsunami scenario
• Model workflow
• Offshore Ventura, California earthquake and tsunami scenario
• Implications for southern California (plus some caveats)
Semidi Sector: 1938 M8.3 EQ with average slip of only ~ 2m
Maximum Tsunami Amplitude of Tsunami Scenario (North East Pacific Ocean, 0-10 meter colorbar)

(Courtesy: Vasily Titov, NOAA/PMEL, the Method of Splitting Tsunami (MOST) model)
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Model Workflow

Meshed Fault Model (via Cubit/Trelis)

Dynamic Earthquake Rupture (via FaultMod)

Final Vertical Free Surface Displacement

Tsunami Propagation and Inundation (via COMCOT)
# Model Parameters

## Elastodynamic Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_0$ (initial shear stress)</td>
<td>49.14 MPa</td>
</tr>
<tr>
<td>$\sigma_0$ (initial normal stress)</td>
<td>78.64 MPa</td>
</tr>
<tr>
<td>$\tau_0$ (initial shear stress in nucleation zone)</td>
<td>65.80 MPa</td>
</tr>
<tr>
<td>Density</td>
<td>2700 kg/m$^3$</td>
</tr>
<tr>
<td>S-wave speed</td>
<td>3162 m/s</td>
</tr>
<tr>
<td>P-wave speed</td>
<td>5477 m/s</td>
</tr>
<tr>
<td>Nucleation Radius</td>
<td>4000 m</td>
</tr>
<tr>
<td>Nucleation Speed</td>
<td>2000 m/s</td>
</tr>
<tr>
<td>Fault element Size</td>
<td>~200 m</td>
</tr>
<tr>
<td>Off-fault element size (~2 km away from fault)</td>
<td>~600 m</td>
</tr>
<tr>
<td>Rupture time step</td>
<td>1.000e-2 s</td>
</tr>
<tr>
<td>$\psi_{ini}$ (initial state variable for friction)</td>
<td>0.1355</td>
</tr>
<tr>
<td>$V_{ini}$ (initial slip speed for friction)</td>
<td>1.000e-12 m/s</td>
</tr>
<tr>
<td>$V_0$ (reference slip speed for friction)</td>
<td>1.000e-6 m/s</td>
</tr>
<tr>
<td>$a$ (constitutive value in rate-weakening zone)</td>
<td>8.000e-3</td>
</tr>
<tr>
<td>$b$ (constitutive value in rate-weakening zone)</td>
<td>1.200e-2</td>
</tr>
<tr>
<td>$a$ (constitutive value in rate-strengthening zone)</td>
<td>1.600e-2</td>
</tr>
<tr>
<td>$L$ (length parameter in rate-state ageing law)</td>
<td>2.330e-2 m</td>
</tr>
<tr>
<td>$\mu_0$ (reference friction coefficient)</td>
<td>0.6000</td>
</tr>
<tr>
<td>$\alpha$ (normal stress dependence of state variable)</td>
<td>0 (no $\sigma$ dependence)</td>
</tr>
</tbody>
</table>

## Hydrodynamic Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrodynamic element size</td>
<td>~30 m – 600 m</td>
</tr>
<tr>
<td>Hydrodynamic time step</td>
<td>1.000e-1 s</td>
</tr>
<tr>
<td>Manning’s coefficient</td>
<td>1.300e-2</td>
</tr>
</tbody>
</table>
Cornell Multi-grid Coupled Tsunami Model (COMCOT, e.g., Liu et al., 1995)

Based on the Shallow Water Equations

\[
\frac{\partial \eta}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = -\frac{\partial h}{\partial t}
\]

Explicit Leap-frog Finite Difference Method
-evaluation of water surface elevation and volume flux are staggered in space and time

\[
\frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left( \frac{P^2}{H} \right) + \frac{\partial}{\partial y} \left( \frac{PQ}{H} \right) + gH \frac{\partial \eta}{\partial x} + F_x = 0
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{PQ}{H} \right) + \frac{\partial}{\partial y} \left( \frac{Q^2}{H} \right) + gH \frac{\partial \eta}{\partial y} + F_y = 0
\]

Bottom friction is modeled via a shear stress relation (Manning’s formula)

A moving boundary scheme is used to model run-up/run-down -the ‘moving shoreline’ is defined as the interface between dry and wet grid cells

\[x, \ y = \text{space coordinates}\]
\[t = \text{time}\]
\[P, \ Q = \text{volume fluxes in } x \text{ and } y \text{ directions}\]
\[\eta = \text{water surface elevation}\]
\[h = \text{water depth}\]
\[H = \eta + h\]
\[F_x, \ F_y = \text{bottom friction in } x \text{ and } y \text{ directions}\]
\[g = \text{acceleration due to gravity}\]
Ventura, California Fault Structure

Figure from Hubbard et al., 2014

Hubbard et al. utilize well data and seismic reflection profiles
Interpreted Fault Geometry

Figure from Hubbard et al., 2014
Fault Geometry and Dip Slip Rate Snapshots

A. Pitas Point surface trace
   - Lower Red Mtn. fault
   - Seafloor
   - RS and RW
   - Dip: 8° at mid depth, 40° at max depth

B. Depth [km]
   - Along-Strike [km]
   - Perp. to Strike [km]
   - Time: 8 s

C. Depth [km]
   - Along-Strike [km]
   - Perp. to Strike [km]
   - Time: 12 s

D. Depth [km]
   - Along-Strike [km]
   - Perp. to Strike [km]
   - Time: 16 s
Vertical Deformation and Total Dip Slip (in meters)

Vertical Surface Deformation and Total Slip

- Along-Strike [km]
- Perp. to Strike [km]
- Depth [km]

- Time = 60 s
- Average slip = 7.6 m
- $M_W = 7.7$
Movie of Tsunami Model
Regional Maximum Tsunami Amplitude

Santa Barbara

Ventura

Oxnard

Santa Cruz Island
Localized Maximum Tsunami Amplitude

Black line indicates coastline

Red line indicates California state reference inundation line

Black circles indicate example locations such as:

SB = Santa Barbara
VH = Ventura Harbor
CIHE = Channel Islands Harbor Entrance
Implications

• It is important to investigate realistic earthquake and corresponding tsunami scenarios for a given region
  – Combining dynamic earthquake and tsunami models is a step in this direction
  – Local tsunamis do not provide as much warning time

• Earthquake sources on the Pitas Point and Red Mountain faults should be included in tsunami hazard assessments offshore California

• Inundation from this model exceeds the state inundation line that incorporates several tsunami scenarios
  – Large northward and eastward tsunami amplitudes from rupture on the Pitas Point and Lower Red Mountain faults

Some of the Caveats

• This parameterization results in a large earthquake!
• A range of earthquake models is needed for this area
  – Different prestress and velocity distributions
  – Different friction distributions
  – Encompass several faults
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