Dynamic Earthquake and Tsunami Modeling
Offshore Ventura, California

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Outline

• Workflow Process
• Background on the Fault Geometry and the Numerical Methods
• A few models for an offshore earthquake and tsunami – Ventura, California
• Implications and future directions
We model each physical system by dividing them up into a number of elements.

Earthquake simulation based on momentum conservation, elasticity, friction, and material properties.

Tsunami simulation based on momentum and mass conservation, seafloor deformation, and topography/bathymetry.
Ventura-Pitas Point faults

Hubbard et al., 2014

- This is one fault geometry that we utilized
- There are other fault realizations of this region
Method

• Earthquake rupture model
  – Finite Element Method of Barall (2009)
  – Rate- and State-dependent Friction
    • Friction dependent on slip rate and age of contact between slipping asperities

• Tsunami model
  – **Final** vertical free surface (seafloor) deformation from earthquake model is used as a boundary condition for hydrodynamic code
  – Solves shallow water wave equations (Liu et al., 1995)
Planar and Curved Fault Geometries

- Initially, we analyzed the effects from either a planar fault geometry or a curved fault geometry.
- Constant prestress with an average stress drop of approximately 3 MPa.
Planar and Curved Fault Geometries

- Nucleation (red stars) is forced by increased shear stress
- A rate-strengthening friction condition is imposed in the upper 5 km
Vertical Deformation and Total Dip Slip

- The curved fault geometry results in relatively large slip updip due to dynamic changes in normal stress during the rupture process.
- A steeper dip angle near the surface (for the curved fault) generates more vertical seafloor displacement for a given amount of slip.
Regional Maximum Tsunami Amplitude

- Greater tsunami amplitude for the curved fault geometry
- Note that these plots do not show inundation
Fault Geometry and Dip Slip Rate Snapshots

a) Pitas Point surface trace

Depth [km]

Seafloor

RS

RW

Dip ≈ 40° at surface

8° at mid depth

40° at max depth

Along-Strike [km]

60 0

Perp. to Strike [km]

43 km

43 km

b) 0 m/s 1 2 3 4 5 6

Depth [km]

Along-Strike [km]

60 0

Perp. to Strike [km]

60

8 s

c) 0 m/s 1 2 3 4 5 6

d) 0 m/s 1 2 3 4 5 6

Depth [km]

Along-Strike [km] 60 0

Perp. to Strike [km] 60

12 s

16 s
Vertical Deformation and Total Dip Slip

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

- Average stress drop is approximately 6 MPa
- time = 60 s
- average slip = 7.4 m
- $M_W = 7.7$
Tsunami Propagation Animation

N
Santa Barbara
Ventura
Oxnard
Regional Maximum Tsunami Amplitude

Santa Barbara

Santa Cruz Island

Ventura

Oxnard

buried fault scenario (1 km)
Implications

• A local tsunami would provide regional warning times of less than 20 min. or so.
• Dynamic earthquake sources on the Pitas Point and Red Mountain faults should be thoroughly investigated for tsunami hazard assessments offshore California.
• Large northward and eastward tsunami amplitudes from rupture on the Pitas Point and Lower Red Mountain faults.

Some of the Caveats

• These parameterizations result in large earthquakes!
• A range of dynamic earthquake models is needed for this area
  – Different prestress and velocity distributions
  – Different friction distributions
  – Encompass several faults
Much thanks to:

- Scott Marshall
- H. K. Thio
- Rick Wilson
- Tom Parsons
- Judith Hubbard
- James Dolan
- John Shaw
- Andrew Newman
- Andreas Plesch
- Tom Rockwell
- Craig Nicholson
- Surendra Sarkar

Funding:
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
Dynamic Models of earthquakes and tsunamis offshore Ventura
Ryan, Geist, Barall, Oglesby

We use the dynamic finite element method and a hydrodynamic code to generate synthetic earthquakes and tsunamis from the Pitas Point/Lower Red Mountain fault system. Constraining the rupture to die out above a depth of 1 km reduces the fault slip and tsunami inundation somewhat, but amplification in Ventura and Oxnard remains.
Tsunami Propagation Animation

Santa Barbara

Ventura

Oxnard
Tsunami Snapshots

- **1 min.**
  - Surface break
  - Tsunami splits into 2 main waves

- **9 min.**
  - Refraction of tsunami due to change in water depth
  - Reflection of tsunami off coastline

- **21 min.**
  - Edge wave trough
  - Focusing
  - Reflection and wrap around
Model Workflow

Meshed Fault Model (via Cubit/Trelis)

Dynamic Earthquake Rupture (via FaultMod)

Final Vertical Free Surface Displacement

Tsunami Propagation and Inundation (via COMCOT)
Shear Stress for a Point on a Fault During Earthquake Rupture

\[ \tau \leq \mu \sigma \]
Earthquake Energy Budget and Frictional Stress

Energy Partitioning

\[
\tau_y = \text{yield stress} \\
\tau_0 = \text{initial stress} \\
\tau_f = \text{final stress} \\
d_0 = \text{critical slip-weakening distance} \\
d_f = \text{final slip}
\]
Method

Rate- and State-dependent Friction (Dieterich, 1978, 1979; Ruina, 1980):

\[ \mu = \mu_o + a \ln \left( \frac{V}{V_o} \right) + b \ln \left( \frac{\theta}{\theta_o} \right) \]

- \( \mu_o \) is a constant reference value
- \( V_o \) and \( \theta_o \) are constant reference values for slip rate and the state of the sliding surface
- \( a \) and \( b \) are experimentally determined
- Abstractly, \( \theta \) can be thought of as strength of contacts

\[ \sigma_n = 150 \text{ MPa}, \text{ experiment } \# 11u \]
Method

Ageing Law: \[
\frac{d\theta}{dt} = \frac{-1}{\theta_{ss}}(\theta - \theta_{ss}) \quad \text{where} \quad \theta_{ss} = \frac{L}{V}
\]

If \( \psi = b \ln\left(\frac{\theta}{\theta_o}\right) \) then \( \mu = \mu_o + a \ln\left(\frac{V}{V_o}\right) + b \ln\left(\frac{\theta}{\theta_o}\right) = \mu_o + a \ln\left(\frac{V}{V_o}\right) + \psi \)

Slip Law: \[
\frac{d\psi}{dt} = -\frac{V}{L}(\psi - \psi_{ss}) \quad \text{where} \quad \psi_{ss} = -b \ln\left(\frac{V}{V_o}\right)
\]

\[
\mu_{ss} = \mu_o + a \ln\left(\frac{V}{V_o}\right) + b \ln\left(\frac{\theta_{ss}}{\theta_o}\right) = \mu_o + (a - b) \ln\left(\frac{V}{V_o}\right)
\]

For \( (a - b) < 0 \quad \Rightarrow \quad \text{rate-weakening} \)
For \( (a - b) > 0 \quad \Rightarrow \quad \text{rate-strengthening} \)

Equations from Barall (2008) and references therein
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)

\[
\frac{\partial \eta}{\partial x}, \frac{\partial \eta}{\partial y} = \text{space coordinates}
\]

\[
t = \text{time}
\]

\[
P, Q = \text{volume fluxes in } x \text{ and } y \text{ directions}
\]

\[
\eta = \text{water surface elevation}
\]

\[
h = \text{water depth}
\]

\[
H = \eta + h
\]

\[
F_x, F_y = \text{bottom friction in } x \text{ and } y \text{ directions}
\]

\[
g = \text{acceleration due to gravity}
\]
The use of slip-weakening (Andrews, 1976) as a proxy for rate-state friction (Dieterich, 1978; Ruina, 1980) in a rate-strengthening zone:

\[ \tau_0 < \mu_d \sigma_0 \]

- \( \tau_0 \) = initial shear stress
- \( \mu_d \) = dynamic friction coefficient
- \( \sigma_0 \) = initial normal stress

Using FEM code FaultMod
Relevant Tsunamis Offshore CA

• Santa Barbara 1812 (a “huge” sea wave reported in newspapers...waves 3 – 4 m high reported)
  – M7 – M7.5 estimation
• Santa Barbara 1854 (inundation reported)
  – Unknown magnitude
• Lompoc 1927 (tide gauges throughout CA coast reported waves 1 – 2 m high)
  – M7.1

Townley and Allen (1939); Hamilton et al. (1969); Lander et al. (1993)
Ocean Surface at 4 seconds (V is infinite)

Ocean Surface at 6 seconds (V is infinite)

Ocean Surface at 150 seconds (V = 1 km/s)

Ocean Surface at 150 seconds (V is infinite)

Distance perpendicular to strike [km]

Distance perpendicular to strike [km]

Elevation [m]

Elevation [m]

ACTIVE

PASSIVE

ACTIVE

PASSIVE

ACTIVE

PASSIVE

Dutykh and Dias 2008
# Model Parameters (Ventura)

## Elastodynamic Parameters

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

## Hydrodynamic Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>Hydrodynamic element size</td>
<td>~30 m – 600 m</td>
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<tr>
<td>Hydrodynamic time step</td>
<td>1.000e-1 s</td>
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<tr>
<td>Manning's coefficient</td>
<td>1.300e-2</td>
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</tbody>
</table>
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
Reverse/Normal Fault Geometry (Profile)

Dip-Slip Model

Legend
- ★ = nucleation zone
- Red = reverse fault shear stress
- Blue = normal fault shear stress

- 2-D
- Planar fault
- Shear stress direction is variable to simulate either a reverse (red) or normal (blue) fault
45 degree dipping Reverse Fault

Reverse Fault Particle Motion [m/s]

Depth [km]

Perp. to Strike [km]

time = 0.1 seconds
Future Directions: Rayleigh-wave breakouts
Maximum amplitude tsunami in and around the Ports of Los Angeles and Long Beach (courtesy: Hong Kie Thio, 2014).
Maximum Tsunami Amplitude of SAFRR Tsunami Scenario (North East Pacific Ocean, 0-10 meter colorbar)

(Southern California coastal area)

(Courtesy: Vasily Titov, NOAA/PMEL, the Method of Splitting Tsunami (MOST) model)
Planar and Curved Fault Geometries

Initially, we analyzed the effects from either a planar fault geometry or a curved fault geometry.