Virtual Quake: Earthquake Statistics, Surface Deformation Patterns, Surface Gravity Changes and InSAR Interferograms for Arbitrary Fault Geometries

Kasey Schultz¹, Michael Sachs¹, Eric Heien¹, Mark Yoder¹, John Rundle¹, Don Turcotte¹, Andrea Donnellan²

¹University of California, Davis
²NASA Jet Propulsion Laboratory

AGU —— 15 December 2014 —— San Francisco, CA
Outline

• Virtual Quake Simulator
  • Fault Model
  • Basics of the simulation physics

• Earthquake Probabilities
  • Probability distributions
  • Waiting times

• Co-seismic Gravity Changes

• Future Directions

• Download Virtual Quake
Virtual Quake (VQ)

- C++ boundary element code, explores statistics of earthquakes on today’s fault systems

- Simulations can be done for any fault model (hence the rename Virtual California -> Virtual Quake)

- VQ assumes a geometrically static fault system, uses back-slip loading to build stress by accumulating a slip deficit

- Output is a simulated seismic history (earthquakes, co-seismic slips, stresses), can be used to generate gravity changes, surface deformations, In-SAR, earthquake probabilities
For simulation data used in this talk:
UCERF2 Fault Model

- Strike-slip, normal and thrust faults
- 14,474 square elements, 3km by 3km
- Fault parameters (slip rate, rake vector, etc) taken from UCERF2 deformation model (derived from observational and paleoseismic data)
Element Interaction Model

Simplifications when deriving stress tensor from Green’s function tensor and slip vector:

- Stress $\sigma(t)$ is only evaluated at center of fault elements.
- Slip $s(t)$ is applied uniformly across the element.

Shear stress along fixed rake vector:

$$\sigma_s^A(t) = \sum T_{s}^{AB} s_B(t)$$

Normal stress:

$$\sigma_n^A(t) = \sum T_{n}^{AB} s_B(t)$$

Stress Green’s functions $T_n^{AB}$ and $T_s^{AB}$ from Okada’s [1985] equations for an elastic half-space.
Rupture\Earthquake Model

Static Failure

\[ CFF^A(t) = \sigma^A_s(t) - \mu_s A \sigma^A_n(t) \]

Element slips when \( CFF=0 \)
(Coulomb Failure Function)

\( \mu_s \) coefficient of static friction, derived from fault element parameters

Dynamic Failure

\[ \frac{CFF_{\text{init}} - CFF_{\text{final}}}{CFF_{\text{init}}} > \eta \]

Elements on same fault as the initial failed element can slip even if \( CFF \neq 0 \)

Dynamic triggering factor \( \eta \) controls rupture propagation.

\( \eta = 0.5 \) for simulation data used here
Computing Earthquake Probabilities with Virtual Quake
Northern California Earthquake Forecast, $M \geq 7.5$

- 500,000 years simulated time
- 482 earthquakes, $M \geq 7.5$
- Average recurrence 98.4 years

- 108 years since 1906 San Francisco, $M 7.9$, the last great northern California earthquake

- 50% prob. of $M \geq 7.5$ in next 55 years
- 75% prob. of $M \geq 7.5$ in next 94 years
Southern California Earthquake Forecast, M ≥ 7.0

- 50,000 years simulated time
- 1,454 earthquakes, M ≥ 7.0
- Average recurrence 22.1 years

- 4 years since 2010 El Mayor-Cucapah, M 7.2, the last great southern California earthquake

- 50% prob. of M ≥ 7.0 in next 16 years
- 75% prob. of M ≥ 7.0 in next 30 years
Computing Co-Seismic Gravity Changes with Virtual Quake
\[ \Delta g(r,s) = \{ \rho G[U_1 S_g(\xi, \eta) + U_2 D_g(\xi, \eta) + U_3 T_g(\xi, \eta)] \\
+ \Delta \rho G U_3 C_g(\xi, \eta) \} \parallel -\beta \Delta h(x_1, x_2) \]

strike-slip, dip = 90°  
normal, dip = 60°  
thrust, dip = 30°

Fault parameters: element size 10km by 10km, 5m slip, depth to top of fault is 1km, density is 2670 kg/m$^3$, Poisson’s ratio $\nu = 0.258$

$g_0 \approx 9.81 \times 10^8 \mu\text{Gal}, \hspace{1cm} 1\mu\text{Gal} = 10^{-8} \text{m/s}^2$
Total gravity changes for simulated earthquake similar to:
1906 San Francisco

- Strike-slip, M = 7.88
- Avg. slip 2.2m
- Surface Rupture Length 712km
Dilatational gravity changes for simulated earthquake similar to:

1906 San Francisco

- Strike-slip, $M = 7.88$
- Avg. slip 2.2m
- Surface Rupture Length 712km
Future Directions

• Run high resolution simulations using the UCERF3 model

• Develop forecasting algorithms based on conditional probabilities

• Support the GNSS Tsunami early warning system by developing libraries of scenario earthquakes and tsunamis, after coupling VQ output to tsunami-generating code

• Simulate a subduction zone fault model to identify any observable changes in sea level caused by gravitational potential changes associated with the earthquake cycle
Acknowledgments:
NASA Earth & Space Sciences Fellowship (NNX11AL92H), NSF Grant EAR-0949446

I would like to thank my group Prof. John Rundle, Michael Sachs, J. Quinn Norris, Mark Yoder, Eric Heien, and Prof. Don Turcotte

VQ **Now available** for download: www.geodynamics.org/software/vq
Includes User Manual

Visualizations and forecasting plots/scripts: PyVQ (**in development**) will be released in a future version of VQ by Spring 2015

More than 170 downloads worldwide
Total gravity changes for simulated earthquake similar to:
2010 El Mayor-Cucapah

- Strike-slip, M = 7.28
- Avg. slip 0.82m
- Surface Rupture Length 138km
Dilatational gravity changes for simulated earthquake similar to:

2010 El Mayor-Cucapah

- Strike-slip, $M = 7.28$
- Avg. slip 0.82m
- Surface Rupture Length 138km
We have assimilated and are currently running simulations for: UCERF3 Fault Model

- Strike-slip, normal and thrust faults
- 14,474 square elements, 2km by 2km
- Fault parameters taken from UCERF3 deformation model
UCERF2 (14.5k elements, 3km x 3km) vs UCERF3 (21.3k elements, 2km x 2km)
Virtual Quake Simulation Physics

Deriving the Failure Stresses for Faults

Instead of prescribing failure stresses for the faults, we derive them from element interaction and known earthquake scaling relations (Wells & Coppersmith 1994)

\[ \Delta \sigma_A = s_A^{\text{max}} \sum_B \frac{\dot{s}_B}{\dot{s}_A} \sigma_{AB} \]  

\[ s_A^{\text{max}} = \frac{10^{3/2} (M_m + 10.7)}{10^7 \mu_A A_A} \]  

\[ M_m = 4.07 + 0.98 \log_{10}(A) \]

\[ \Delta \sigma_A \] is the failure stress for fault element A

\[ \sigma_{AB} \] is the shear stress per unit distance between elements A and B

\[ s_A^{\text{max}} \] is the maximum slip for fault A

\[ M_m \] is the expected magnitude given fault area of the fault containing element A

\[ \dot{s}_A \] is the geologically observed slip rate for element A