Characterizing Seismic Hazard Using 3-D Ground-Motion Simulations of Scenario Earthquakes

Brad Aagaard

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Overview

- Role of 3-D ground-motion simulations in characterizing seismic hazard
- Case study: Hayward fault
- Looking ahead: urban seismic hazard maps
- Cyberinfrastructure needs
  - Tools for querying and storing geologic structure and properties
  - Extensible state-of-the-art modeling codes
  - Archiving of simulations
Seismic Hazard from 3-D Simulations

3-D simulations allow more detail but require greater understanding

- National Seismic Hazard Maps
  - Earthquake description: magnitude and fault boundary
  - Ground motions from empirical regressions
    - Fault orientation, slip direction, dist. from fault
    - Path and site corrections
  - Ground-motion metrics: PGV, PGA, SA
- 3-D ground-motion simulations
  - Earthquake description: earthquake rupture time history
    - Complex fault geometry
    - Spatial and temporal evolution of slip
  - Ground motions from wave propagation
    - 3-D physical properties (basin effects)
    - Rupture directivity
  - Velocity and acceleration time histories
Ground-Motion Simulations

3-D ground-motion simulations can include rupture physics

- Prescribed slip rupture models
  - Complex nonplanar fault geometry
  - Deterministic + stochastic slip fields
  - Complex rupture paths
  - Driven by source inversions and spontaneous rupture simulations
  - Not necessarily consistent with underlying physics

- Spontaneous rupture models
  - Slip evolves based on stress conditions and fault constitutive model
  - Complex nonplanar fault geometry
  - Deterministic + stochastic stress fields
  - Involves more parameters and knowledge of conditions in the lithosphere
UCERF Bay Area Probabilities

30 yr probability for Hayward / Rodgers Creek is now 31%
Hayward Fault
Fault runs along the edge of the densely populated East Bay
Hayward Fault
Fault runs underneath UC Berkeley’s Memorial Stadium
Creep on Hayward Fault
Fault exhibits significant surface creep at many locations
Jim Lienkaemper’s Tyson’s Lagoon Trench
Evidence for 12 ruptures over the past 1900 years

Lienkaemper et al. OFR 03-488
Paleoseismic Record at Tyson’s Lagoon
Currently in middle of time window for next expected event

**Mean Recurrence Intervals:**
- Past 12 earthquakes: 161 ± 65 yr (1σ error bars)
- Past 5 earthquakes: 138 ± 58 yr (1σ error bars)

Past 9 earthquakes: 151 ± 64 yr (1σ error bars)

**Historical Record:**
- 2009.0 ± 55 yr
- Predicted event in 2056
- Future

Version 080109 (SSA Mtg. abstract)

*R. W. Simpson, Monte Carlo regression of Oxcal data*
Hayward Scenario Earthquakes Project

- Compute ground motions for a suite of 39 scenario earthquakes involving the Hayward fault
  - Rupture length
  - Hypocenters
  - Distribution of slip
  - Rise time
  - Rupture speed
- Develop rupture models based on geophysical data consistent with NGA ground-motion prediction models
  - Spatial variation in slip
  - Spatial variation in rise time
  - Slower rupture speed in areas with little slip
- Account for aseismic creep in prescribed slip rupture models
Project Personnel
Collaborative effort to develop realistic ruptures and ground motions

**USGS Menlo Park**  Brad Aagaard, John Boatwright, Thomas Brocher, Russell Graymer, Ruth Harris, Thomas Holzer, Dave Keefer, Jim Lienkaemper, David Ponce, David Schwartz, Robert Simpson, Paul Spudich, Janet Watt

**Lawrence Livermore National Laboratory**  Shawn Larsen, Arthur Rodgers

**URS Pasadena**  Robert Graves (now at USGS Pasadena)

**UC Berkeley**  Doug Dreger

**Stanford University**  Shuo Ma (now at SDSU)
Geometry of Hayward and Rodgers Creek Faults
Constrained by micro-seismicity, mapping, and geophysical modeling

Watt, J.T. et al., AGU Fall Meeting, 2007
Creep on Hayward Fault: Funning et al. Model
Rate and distribution of creep constrained by geodetic data
Slip-Gradient Approach
Simple model to reduce coseismic slip in creeping areas

- Model from Funning et al. (2007) delineates creeping patches
- Force a linear taper in the background slip in areas with creep

Features
- Slip more likely to reach surface in larger events
- More of the creeping areas rupture coseismically in larger events
Hayward South + North: Background Slip

Apply vertical gradient in slip field in creeping areas

(NW) San Pablo Bay

San Jose (SE)

Elev. (km)

Dist. South From Point Pinole (km)

 Slip (m)
Hayward South + North: Background + Stochastic Slip

Apply vertical gradient in slip field in creeping areas

(NW) San Pablo Bay

(Elev. (km))

San Jose (SE)

Dist. South From Point Pinole (km)

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0

Slip (m)
Hayward South + North Rupture Model

Slip distribution with 1 s rupture time contours

(NW) San Pablo Bay

San Jose (SE)

Elev. (km)

Dist. South From Point Pinole (km)

Slip (m)

Hayward Fault Scenarios

Rupture Models
Hayward South + North Rupture Model

Animation of slip rate and slip
Animation of Shaking Intensity
Shaking Intensity: Effect of Creep

M6.6 Scenario F01

Shaking Intensity (MMI)

Hayward Fault Scenarios  Ground Motions
Shaking Intensity: Effect of Creep

M6.8 Scenario G01

Shaking Intensity (MMI)

Hayward Fault Scenarios  Ground Motions
Shaking Intensity: Effect of Creep

M6.9 Scenario N01

Hayward Fault Scenarios Ground Motions
Comparison with Boore-Atkinson NGA GMPE

Very little bias (on average) with NGA ground-motion prediction models

Hayward Fault Scenarios

Comparison w/NGA
Directivity and basin effects control distribution of shaking
- Livermore, San Pablo Bay, and Evergreen basins sit close to fault
- Softer materials (large length scales) are east of Hayward fault
- Distribution of slip also locally influences distribution of shaking

NGA ground-motion prediction models
- May under-predict shallow basin effects and amplification in thick soils
- Need to extend Spudich-Chiou directivity model

Hayward fault behavior
- Paleoseismic record only provides timing of recent large events; no estimate of slip per event
- Creep will likely affect coseismic rupture; large uncertainty in details of influence
Urban Seismic Hazard Maps
High resolution alternative to National Seismic Hazard Maps

- Reduce uncertainty in ground-motions by including
  - Basin amplification
  - Rupture directivity
  - Complex interaction between rupture directivity and basins
- Requires propagating uncertainties
  - Median values of most parameters are well-constrained
  - More work needed to constrain probability distributions and incorporate them into models and simulations
- Requires at least hundreds to thousands of simulations
- Storing waveform output with proper metadata is challenging
- Gaining momentum in USGS and SCEC
Cyberinfrastructure Challenges

- Simulation accuracy limited by knowledge of:
  - Physical properties (e.g., resolution of seismic velocity models)
  - Fault geometry
  - Earthquake rupture dynamics
    - Fault constitutive behavior
    - Stress/strain in the lithosphere

- Higher resolution characterizations of Earth’s lithosphere:
  - Acquisition of high-quality observations is just one component
  - Need efficient, flexible tools for storing and querying models:
    - Physical properties (e.g., seismic velocity models)
    - Fault geometry (e.g., SCEC Community Fault Model)
    - Stress/strain (e.g., SCEC Community Stress Model)
  - Stochastic representations of Earth’s structure
    - Need fine resolution and multiple realizations
    - Need tools to combine deterministic and stochastic models
Cyberinfrastructure Needs
Need flexible tools for storing and querying Earth models w/standard interfaces

- **Earth models**
  - Geologic structure (e.g., faults)
  - Physical properties
  - State variables (e.g., stress and strain)

- **Features**
  - Support quantification of uncertainty in models
  - Allow multiscale models with various parameters
    - Seismic velocity models with and without Qp, Qs
    - Isotropic versus anisotropic
  - Ability to merge deterministic + stochastic models

- **Standard interfaces**
  - Simulation codes need common interface for interaction
  - Query models on the fly from HPC resources or laptop
Cyberinfrastructure Needs
Extensible, state-of-the-art community modeling codes

- Open-source community codes expedite scientific discovery
  - Need to support HPC computers as well as laptops
  - Accessible to new users (binaries, documentation, training)
  - Extensible by expert users (new rheologies, interfaces to other models)

- State-of-the-art modeling codes
  - Collaborations between computational scientists and geoscientists
  - Support for multiscale and multiphysics simulations
  - Lithospheric modeling often involves complex geometry
    Earth’s surface is not flat & faults are not planes!
Cyberinfrastructure Needs

Need to archive simulations in databases

- Reproducibility and verification
  - Compare results from multiple codes for verification
  - Facilitate regression testing

- Data-mining of results
  - Propagating uncertainties $\Rightarrow$ suite of models
  - Augment empirical models with synthetic data

- Improve access for users of simulation-based models
  - Synthetic data requires more metadata than observations
  - Scenario ground motions need description of the earthquake
  - Document chain of models used to develop end products