Physics-Based Ground Motion Simulation

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Content

- Introduction to the Graves and Pitarka (2010;2016) hybrid method
- Modeling of key fault rupture and wave propagation effects on strong ground motion
- Validation of ground motion simulation method
Ground Motion Simulation Method

Representation Theorem
\[ u_j(t) = \sum G_{ij}(t) * D_i(t) \]

- Deterministic approach for low frequencies (<1 Hz)
- Stochastic approach for high frequencies (>1 Hz)
Graves & Pitarka (GP2015) Hybrid Method

**Earthquake Rupture**
- Non-Planar fault randomly heterogeneous rupture
  - GP2015
- Planar fault rupture with multiple asperities
  - IM2011, Japan

**Wave Path**
- LF: 3D, 1D Linear anelastic simulations
- HF: Stochastic GFs
  - Match filter at ~1 Hz
  - BB Acceleration
  - Time History

**Local Site Effects**
- Empirical corrections based on $V_{S}^{30}$

Graves and Pitarka, 2015

Irikura and Miyake, 2011
Hybrid Approach to Broadband Ground Motion Simulations

A) Kinematic Rupture Generator

**Parameters guided by rupture dynamics**
- rise time with depth scaling
- slip velocity function
- rupture speed and spatial variation with depth scaling
- rise time with depth scaling

**Parameters that satisfy empirical relationships**
- Magnitude-fault area
- Average rise time
- Background rupture speed
- Radiation pattern as a function of frequency
- Spatial correlation lengths of stochastic slip variability
B) Wave Path Model

**Physics based Green’s functions up to 1Hz**
- solution of elastic wave equation in 3D heterogenous media
- anelastic wave attenuation

**Stochastic Green’s functions > 1Hz**
- Separate GFs for direct and down-going rays
- Amplitude decays as inverse of ray path length
- Gross impedance effects based on quarter wavelength (Boore and Joyner, 1997)

**Semi stochastic velocity model**
- Spatially correlated random small-scale perturbations
- Surface topography
Finite-fault Rupture Effects

Freq. Depend. Radiation Pattern

SH motion sums coherently in direction of rupture propagation: **Larger Fault Normal**

SV motion is nodal in direction of rupture propagation: **Smaller Fault Parallel**

Rupture Directivity, Segmentation

Low frequency (f < 1 Hz) motions build up in direction of rupture propagation: **rupture directivity**

[Diagram showing fault rupture, SH and SV motions, and radiation pattern]

[Map showing fault rupture propagation and directivity patterns]
Finite-fault Rupture Effects: Rupture Directivity

Rupture directivity can lead to strong pulse-like ground velocity motions (periods of 1-10 seconds) in particular onto Fault Normal component.

Imperial Valley Earthquake
- Addition of deep weak zone between 15-18km (larger fault area) while keeping the seismic moment fixed. Use the magnitude-length and magnitude-area relationships of Leonard (2010).
Rupture Dynamics on Faults with Rough Surface
(Shi and Day, 2013)

\[ \alpha = \frac{h_{\text{rms}}}{L} = 0.001-0.01 \] (Power and Tulis, 1991)
Example of Simulated Earthquake Rupture: 1992 Landers EQ

- Multi-segment jumps (rupture delay)
- Shallow rupture effects
Deterministic 3D Wave Propagation Effects

Frankel (1993)

Basin generated surface wave

- Free surface
- Alluvium: $V_S = 0.6 \text{ km/sec}$
- Bedrock: $V_S = 2.0 \text{ km/sec}$
Stochastic Wave Propagation 3D Velocity Models with Random Perturbations

Random Velocity Perturbations (Pitarka et. al., 2009)

L_h = 2000 m
L_z = 200 m
Perturb = 30%
V_{smin} = 400 m/s
Random Perturbations to the Velocity Model Including Fault Zone

Graves and Pitarka (2016)

$L_x = L_y; L_z = L_x / 10$
Estimation of stochastic variability parameters using LargeN array data

Correlation $\rho$ as a function of separation for time windows $>1$ s computed over 15 frequency bands

\[ \rho = e^{-\frac{\lambda}{s}} \]
SCEC Broadband Platform (BBP)

http://scec.usc.edu/scecpedia/Broadband_Platform

BBP is an open-source distribution

Broadband 0.1-20+ Hz

Simple source and path (1D)

5 alternative simulation codes

Fully validated for spectral response

• 1.5 year project
• Multiple rounds of validation/improvements
• Independent review panel

Used for large ground motion characterization projects

Goulet et al., 2015

SRL Special Focus on BBP
Validation – 9 papers - Jan. 2015
Validation of BB Ground Motion Methods on SCEC BB Platform (Dreger and Jordan, 2015)

PSA evaluation – using 50 source realizations

- **PART A: validation against recorded events**
  - Evaluation of bias \(\frac{\ln(\text{data})}{\ln(\text{model})}\) using various approaches
  - 13 events completed, ~40 stations/event

- **PART B: validation against existing GMMs** in ranges where they are well constrained by data

Goulet et al., 2015
### List of Earthquakes Used in Validations

Goulet et al., 2015

<table>
<thead>
<tr>
<th>Region</th>
<th>Event Name</th>
<th>Year</th>
<th>Mw</th>
<th># Records &lt; 200 km</th>
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- **Large dataset (25 eqs)**
- **Many regions & tectonic environments**
- **Span wide magnitude range (Mw 4.6 to 7.62)**
- ** Variety of mechanisms**
- **Well-recorded** (16 EQs with > 40 records within 200 km)
- **Select large subset of stations (~40) that are consistent with mean and standard deviation PSa of the full dataset.**
Part A Validation: 1989 M6.9 Loma Prieta Earthquake

Graves and Pitarka (2010)
Part A: Validation Using Loma Prieta Earthquake Data

Graves and Pitarka (SRL, 2015)
Multiple realizations nicely replicate observed rupture directivity effects during Imperial Valley earthquake.
Part B: Comparisons with GMPEs

Part B. Northern California (M6.2, SS, Z_{tor}=4 km, R_{jb}=20 km)

[Graphs showing comparisons between different models and acceptance criteria for various locations in Northern California.]
Future Improvements

- Improve parameterization of small-scale heterogeneity in 3D velocity models
- Use of high performance computing and stochastic velocity models to extend the application of deterministic approach to higher frequencies (up to 5Hz)
- Sensitivity analysis for non-linear/linear 3D wave propagation modeling
- Inclusion of surface topography in high frequency ground motion simulations
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