Summary of Ground Motion Simulations
Methods: Finite-Source and Point-Source

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Douglas Dreger (UCB)
Questions for Resource Expert

• Summarize ground motion simulation models
• Provide an overview of the technical bases for the methods considered.
• What features are common among the methods?
• What features are specific to a given method?
• What models are ready for forward simulations application?
• Which models or types of models are most appropriate for what range of magnitude and distance?
• What part of the validation is most informative in the assignment of a pass/fail grade?
Models Considered

• Point-Source Stochastic

• Finite-Source
  – Stochastic Finite Fault Method (Silva et al., 1990)
  – EXSIM (Motazedian and Atkinson, 2005; Atkinson and Assatourians, 2014)
  – SDSU (Mena et al., 2010; Mai et al., 2010; Olsen and Takedatsu, 2014)
  – UCSB (Liu et al., 2006; Schmedes, 2010, 2013; Crempien and Archuleta, 2014)
Models Considered

• Point-Source Stochastic
  – **SMSIM** (Boore, 1983, 2005, 2014)

• Finite-Source
  – **Stochastic Finite Fault Method** (Silva et al., 1990, 1997)
  – **EXSIM** (Motazedian and Atkinson, 2005; Atkinson and Assatourians, 2014)
  – **SDSU** (Mena et al., 2010; Mai et al., 2010; Olsen and Takedatsu, 2014)
  – **UCSB** (Liu et al., 2006; Schmedes, 2010, 2013; Crempien and Archuleta, 2014)
  – **CSM** (Zeng et al., 1994, 1995, 1996; Anderson, 2014)
Stochastic Simulation of Time Histories

1) Employs linear filter theory and simplified propagation models to scale and shape random phase time histories and spectra.

\[ Y(M_0, R, f) = E(M_0, f) P(R, f) S(f) I(f) \]

From SCEC BBP EXSIM Documentation
Stochastic Simulation of Time Histories

2) Empirically calibrated shape and scaling functions include:

A) Region specific geometrical spreading
B) Region specific Q
C) Site corrections
D) Application of site kappa or fmax
E) Corrections for a magnitude-dependent double corner frequency

\[ Y(M_0, R, f) = E(M_0, f) P(R, f) S(f) I(f) \]

From SCEC BBP EXSIM Documentation
Stochastic Simulation of Time Histories

\[ Y(M_0, R, f) = E(M_0, f) \times P(R, f) \times S(f) \times I(f) \]

\[ C = \frac{\langle R_{\theta \phi} \rangle VF}{4\pi \rho_s \beta_s^3 R_0} \]

\[ S(f) = \frac{4\pi^2 f^2}{1 + \frac{f^2}{f_0^2}} \]

\[ P(f) = e^{\frac{\pi R f}{Q(f) \beta}} \]

\[ Q(f) = Q_0 f^n \]

\[ D(f) = \sqrt{1 + \left( \frac{f}{f_{max}} \right)^8} \]

\[ D(f) = \exp(-\pi \kappa_0 f) \]

From SCEC BBP EXSIM Documentation
EXSIM – Stochastic Simulation of Time Histories

EXSIM introduces a dynamic corner frequency to model a propagating slip pulse.

\[ f_{oi} = 4.9 \times 10^6 \beta \left( \frac{N \times \Delta \sigma}{N_R \times M_0} \right)^{1/3} \]
EXSIM – Stochastic Simulation of Time Histories

Atkinson and Silva Double Corner and Brune
Source Models for M6.04 Earthquake and Their Ratio

Empirical Filter for Different Magnitudes
EXSIM – Stochastic Simulation of Time Histories

Sa is calculated from the time histories.

Bias (ln residual) plots are used to compare the observed and simulated Sa.

BBP V13.6 validation compared simulated motions for 7 earthquakes recorded at ~40 stations each.
SMSIM – New Generalized Double Corner Frequency Models

Multiplicative

\[ A \propto M_0 f^2 \frac{1}{1 + (f/f_a)^{p_{f_a}}} \frac{1}{1 + (f/f_b)^{p_{f_b}}} \]

Additive

\[ A \propto \frac{M_0 f^2 (1 - \varepsilon)}{1 + (f/f_a)^{p_{f_a}}} + \frac{M_0 f^2 \varepsilon}{1 + (f/f_b)^{p_{f_b}}} \]

- \(f_a < f_c < f_b\)
- \(f_c = 4.906 \times 10^6 \beta (\Delta \sigma/M_0)^{1/3}\)
- \(f_b = f_a \sqrt{\left(\frac{f_c}{f_a}\right)^2 - (1 - \varepsilon)} / \varepsilon\)
- \(\log f_a = C_{1f_a} + C_{2f_a} (M - M_{f_a})\)
- \(\log \varepsilon = C_{1\varepsilon} + C_{2\varepsilon} (M - M_{\varepsilon})\)

Boore, Di Alessandro, and Abrahamson, 2014
SMSIM – New Generalized Double Corner Frequency Models

Behavior of Multiplicative Model

Boore, Di Alessandro, and Abrahamson, 2014
SMSIM – New Generalized Double Corner Frequency Models

Behavior of Additive Model

Boore, Di Alessandro, and Abrahamson, 2014
SMSIM – ADFC

GoF Plot for LOMAP, 40 Validation Stations, SMSIM Method

Kappa = 0.035; C1, f = 15.6489 km; Stress = 150; epsilon = 0.0427

Attenuation calibration at 50km, Mw = 6.2 SS, Vs30 = 863 m/s
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• Finite-Source
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Classes of Finite-Fault Simulation Approaches

• Stochastic (EXSIM, Silva & Darragh)
  – Utilizes temporally and spectrally shaped white noise to generate time series used to estimate Sa.
  – Shape functions are empirically calibrated

• Deterministic (CSM and UCSB)
  – Applies the representation theorem for a fault dislocation utilizing Green’s functions for simplified 1D velocity structures
  – Differences in the methods are in terms of the description of the kinematic source model

• Hybrid (G&P and SDSU)
  – Applies representation theorem for the low frequency deterministic part
  – Uses a stochastic component to characterize high frequency portion of the spectrum
    • SDSU uses scattering functions Zeng et al. (1991, 1993)
Seismic Representation Theorem

\[ u_n (\vec{x}, t) = \int_{-\infty}^{\infty} d\tau \int_{\Sigma} \left[ u_i (\vec{\xi}, \tau) \right] c_{ijpq} \nu_j \frac{\partial G_{np} (\vec{x}, t - \tau, \vec{\xi}, 0)}{\partial \xi_q} d\Sigma \]

\[ \left[ u_i (\vec{\xi}, \tau) \right]^- = u_i^+ (\vec{\xi}, \tau) - u_i^- (\vec{\xi}, \tau) \]

Displacement discontinuity across fault

\[ c_{ijpq} = \lambda_L \delta_{ij} \delta_{pq} + \mu \left( \delta_{ik} \delta_{jl} + \delta_{il} \delta_{jk} \right) \]

Isotropic elastic tensor

\[ G_{np} (\vec{x}, t - \tau, \vec{\xi}, 0) \]

Unit-force Green’s function representing source to receiver transfer function for prescribed velocity model
Composite Source Model – V13.6

1) Utilizes Green’s functions that are complete in terms of body and surface waves, and near-, intermediate- and far-field terms.

2) 1D velocity models are used with a frequency independent Q model.

3) The source model is built from a distribution of randomly placed point-sources in which the distribution satisfies a Gutenberg-Richter relationship and radius-frequency self-similarity.

4) The timing of the subevents is controlled by a constant velocity rupture front initiating from a hypocenter.

5) Subevents are allowed to overlap.
1) Utilizes Green’s functions that are complete in terms of body and surface waves, and near-, intermediate- and far-field terms.

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Composite Source Model – V13.6

![Graph showing acceleration over time](image)
Composite Source Model – V13.6
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Composite Source Model – V13.6

GOF Comparison between LOMAP and simulation 10000014
R < 85 km

Combined GOF Plot for LOMAP
50 Realizations
CSM Method
1. Informed from dynamic simulations
2. Utilizes 1D Green’s functions with a frequency dependent $Q(f)$.
   a. Layered structure use for $f < 2$ Hz
   b. Single crustal layer structure used for $f \geq 2$ Hz
3. PDF and correlation functions between key kinematic parameters are obtained from more than 300 dynamic simulations
   a. Slip
   b. Rise time
   c. Peak time
   d. Peak slip rate
   e. Rupture velocity
4. A random slip model assuming a $k^{-2}$ spatial distribution is used with slip amplitude scaled by empirical relation is then iteratively adjusted to conform to the PDF and correlation functions.
5. A 2d finite-difference algorithm is used to determine subfault trigger times from the locally prescribed rupture velocity.
Figure 3. (left) Dynamically computed slip rate (blue) and fitted slip rate function (red). After the rupture stopped for the first time, there is no strength, and small perturbations can trigger low velocity sliding. The area under the curve from the start to the first stop of the rupture corresponds to (right) the kinematic slip. (middle) The total slip is the total slip at the end of the rupture. The black rectangles in Figures 3 (middle) and 3 (right) outline the area for which the statistical analysis is performed. The area does not include the nucleation region or the boundaries.

Figure 7. Probability density function for various earthquake source parameters computed using 4000 randomly selected points for each dynamic rupture model. Vertical lines show the median of each distribution.
Graves & Pitarka Method – V14.3

Computes deterministic long-period motions ($T > 1$ sec) using 1D Green’s functions (frequency independent $Q$), and a kinematic model based on empirically calibrated theoretical forms for kinematic parameter scaling.

- Fault area/dimensions scale with magnitude (Leonard, 2010)
- Correlation of slip heterogeneity scales with magnitude (Mai and Beroza, 2002) in which the coefficient of variation is set at 0.85
- Average rise time scales with $M_0^{0.33}$ (Somerville et al., 1999) but is double for $z<5$ km and $z>15$ km
- Background rupture speed scales with local $V_s$
- Local rise time scales with square root of local slip plus a small random component
- Local rupture speed scales with local slip and $M_0^{0.33}$

Short-period ($T < 1$ sec) motions are generated using a stochastic approach very similar to that used by SMSIM
Graves & Pitarka Method

a)

Acc (cm/s/s)  Vel (cm/s)  Disp (cm)

Lengths:
- Acc: 535 cm/s/s
- Vel: 171 cm/s
- Disp: 160 cm

Time:
- 0 to 50 sec

Graphs:
- BB: Black
- HF: Red
- LF: Green

b)

Graphs:
- Fourier Amplitude Spectra
- Spectral Acceleration (g)

Frequency (Hz):
- 0.01 to 10

Period (sec):
- 0.01 to 10
Graves & Pitarka Method

Rupture Model for lomap-gp-0005.srf
Avg/Max Slip = 114/411

Combined GOF Plot for LOMAP
50 Realizations
GP Method
SDSU Method

Utilizes the same low-frequency Green’s functions and source generator as Graves and Pitarka (2010).

Calculates high frequency stochastic response from isotropic radiation scattering functions from Zeng et al. (1991, 1993)

The low-frequency and high-frequency and combined at 1 Hz similarly to G&P
SDSU Method

(a) Scattering Green's function
(b) ... convolved with STF
(c) Amplitude spectra

(d) Hybrid broadband seismogram composition
(e) Amplitude spectra
SDSU Method

Rupture Model for lomap-sdsu-0021.srf
Avg/Max Slip = 114/398

Combined GOF Plot for LOMAP
50 Realizations
SDSU Method

V14.3
Comparison of Run 10000005v13.6 G&P and SDSU: Loma Prieta

Loma Prieta: Lexington Reservoir East West Component

G&P

SDSU

cm/s/s

$\times 10^2$

cm/s

cm

seconds

seconds
Comparison of Run 100000005v13.6 G&P and SDSU: Loma Prieta

Loma Prieta: Lexington Reservoir North South Component

G&P

SDSU

cm/s/s

cm/s

cm

seconds

seconds
Comparison of Best Fit Simulations: Loma Prieta
LEX station - V14.3

EXSIM_v14.3  CSM_v13.6  UCSB_v14.3  G&P_v14.3  SDSU_v14.3

- EW
- NS
- UD
Comparison of Best Fit Simulations: Loma Prieta
LEX station – V14.3

<table>
<thead>
<tr>
<th>EXSIM_v14.3</th>
<th>CSM_v13.6</th>
<th>UCSB_v14.3</th>
<th>G&amp;P_v14.3</th>
<th>SDSU_v14.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW</td>
<td>EW</td>
<td>EW</td>
<td>EW</td>
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<tr>
<td>NS</td>
<td>NS</td>
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<td>NS</td>
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<tr>
<td>UD</td>
<td>UD</td>
<td>UD</td>
<td>UD</td>
<td>UD</td>
</tr>
</tbody>
</table>

velocities (cm/s)

-50 0 50

505 510 515 520

seconds
Comparison of Best Fit Simulations: Loma Prieta LEX station – V14.3
Evaluation of Methods

- Evaluation performed within the computational framework of the BBP and was based on median pseudo spectral acceleration.
  - Part A: Event/station specific PSA comparisons
  - Part B: Comparisons with GMPE

- Eight member evaluation panel held workshops with modelers, reviewed written documentation, and simulation results from the BBP

- Validation report for V13.6 was submitted to SCEC on August 1, 2013.

- Documentation of the process and an update for V14.3 was submitted for publication in an SRL Special Issue
### Combined Metric Performance Level

<table>
<thead>
<tr>
<th>Event (Mx, Mch.)</th>
<th>Combined Goodness of Fit (CGOF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chino Hills (5, 39, ROBL)</td>
<td>0.45 ± 0.13</td>
</tr>
<tr>
<td>Alam Rock (45, 65, SS)</td>
<td>0.70 ± 0.15</td>
</tr>
<tr>
<td>Whittier Narrows (5, 89, REV)</td>
<td>0.35 ± 0.12</td>
</tr>
<tr>
<td>North Palm Springs (6, 12, ROBL)</td>
<td>0.45 ± 0.13</td>
</tr>
<tr>
<td>Tottori (6, 55, SS)</td>
<td>0.45 ± 0.13</td>
</tr>
<tr>
<td>Nigata (6, 65, REV)</td>
<td>0.45 ± 0.13</td>
</tr>
<tr>
<td>Northridge (7, 37, REV)</td>
<td>0.45 ± 0.13</td>
</tr>
<tr>
<td>Loma Prieta (6, 64, ROBL)</td>
<td>0.45 ± 0.13</td>
</tr>
<tr>
<td>Landers (7, 22, SS)</td>
<td>0.45 ± 0.13</td>
</tr>
<tr>
<td>Christiana (8, 61, REV)</td>
<td>0.45 ± 0.13</td>
</tr>
<tr>
<td>Sagozome (8, 81, REV)</td>
<td>0.45 ± 0.13</td>
</tr>
</tbody>
</table>

### Performance
- **Part A: Mean Bias**
- **Combined Goodness of Fit (CGOF)**

\[
CGOF = \frac{1}{2} \left( \ln \left( \frac{\text{data}}{\text{model}} \right) \right) + \frac{1}{2} \left( \ln \left( \frac{\text{model}}{\text{data}} \right) \right)
\]

- **Pass 0.35 ln units**
- **Fail 0.70 ln units**
- **Performance is very good for 5<R<300 km and 0.01 < T < 1 second**
- **<= 20% of cases exceed failure threshold**
- **~80% are better than a factor of 2**
- **~40% are better than the 1.41x pass threshold**
- Part A: Method / GMPE
  - Pass < 1
  - Fail > 1.5
- Performance is very good for 5 < R < 300 km and 0.01 < T < 3 second
Part A: Distance Metric

Ln residual is plotted for each event in discrete distance bins. Ideally the slope is zero.

Test: If a slope of zero lies within the 95% confidence of the slope estimate there is no systematic distance bias and the method passes.

Distance metric is the abs(slope)/95%confidence_slope

<table>
<thead>
<tr>
<th>Period</th>
<th>UCSB</th>
<th>EXSIM</th>
<th>G&amp;P</th>
<th>SDSU</th>
<th>GMPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 to 0.1s</td>
<td>0.38</td>
<td>0.36</td>
<td>0.67</td>
<td>0.57</td>
<td>0.53</td>
</tr>
<tr>
<td>0.1 to 1.0s</td>
<td>0.08</td>
<td>0.23</td>
<td>0.01</td>
<td>0.18</td>
<td>0.03</td>
</tr>
<tr>
<td>1 to 3 s</td>
<td>0.16</td>
<td>0.10</td>
<td>0.05</td>
<td>0.04</td>
<td>0.11</td>
</tr>
<tr>
<td>&gt;3s</td>
<td>1.19</td>
<td>0.34</td>
<td>0.83</td>
<td>0.87</td>
<td>0.13</td>
</tr>
</tbody>
</table>
Part B Evaluation
Questions for Resource Expert

- Summarize ground motion simulation models
- Provide an overview of the technical bases for the methods considered.
- What features are common among the methods
- What features are specific to a given method?
- What models are ready for forward simulations application?
  - SMSIM, EXSIM, G&P, SDSU and UCSB
- Which models or types of models are most appropriate for what range of magnitude and distance?
  - All V14.3 methods within M range of validation (M 4.6 – 7.2)
  - All V14.3 methods for 0 < R <= (200 or 300) km
- What part of the validation is most informative in the assignment of a pass/fail grade?
  - Part B defines a rigid pass/fail, however there is no one metric that is perfect for this purpose.
  - A combination of metrics as implemented provides a more comprehensive analysis of the performance of these complex methods.
  - Additional metrics should be introduced including Fourier amplitude spectra fits, consistency with net omega-2 spectral shape, component specific measures, and limits of static slip to zero fault distance.
References

References


Comparison of Best Fit Simulations: Loma Prieta

V13.6
Comparison of Best Fit Simulations: Loma Prieta – V13.6
Comparison of Best Fit Simulations: Loma Prieta – V13.6

EXSIM  CSM  UCSB  G&P  SDSU

EW

NS

UD

displacement (cm)

505560570  5 10152025  5 10152025  5 10152025  5 10152025

seconds