UCSB Broadband Method for Computing Strong Ground Motion

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Motivation

We use the representation theorem to compute broadband ground motion for a unique source.

\[ u_n(x, t) = \int_{-\infty}^{\infty} d\tau \int_{\Sigma} s_i(\xi, \tau) c_{ijpq} v_j G_{npq}(x, t - \tau; \xi, 0) d\Sigma \]
Source
Database

>300 strike slip ruptures of various sizes in simple 1D velocity structures with slip weakening friction law

Rupture dimensions:
- 30km x 15km, 30km x 20km
- 60km x 12km, 60 km x 15 km , 60km x 20km
- 120 km x 15 km

6  300km long strike slip ruptures in 3D velocity model of southern CA (DynaShake)

Schmedes et al. (2010)
Sliprate Function

\[ \text{Re}\left(\frac{\sqrt{T_{\text{start}} + T_{\text{rise}} - T_{\text{peak}} - t}}{\sqrt{t - T_{\text{start}}}}\right) \]

\[ \begin{cases} \sin\left(\pi \frac{t}{T_{\text{peak}}}\right) & , t \leq T_{\text{peak}} \\ 0 & , \text{else} \end{cases} \]

- Fit new slip rate function to 5 Hz filtered computed slip rate functions (about 60 Million)
- Rectangle shows area that was used to compute the correlations. It excludes the boundaries and nucleation zone
Figure 1. Slip-velocity functions of delta, boxcar, Gaussian, truncated Kostrov, and Yoffe are shown on the left. The corresponding slip functions of Heaviside, ramp, smoothed ramp, square root, and Yoffe in slip are shown on the right. The normalized slip-rate function is given by:

\[
\dot{s}(\xi, t) = C \left( \frac{t}{T_r} \right)^p \left( 1 - \frac{t}{T_r} \right)^{5-p}
\]

where \( T_p = pT_r / 5 \).

Sliprate Functions from Dynamic Rupture

Liu, Q. and Archuleta, 2013
Sliprate Spectra

Results from dynamic rupture, normal fault, Q. Liu, 2013
Influence of Autocorrelation of Initial Stress

Strong dependency of rupture dynamics on autocorrelation of stress. Smooth ruptures have larger likelihood to transition to supershear speed (Schmedes et al., 2010)
Power Spectrum Relationships for Different Parameters

We use a von Karman PSD such that after $k_c$ the behaves like a power law:

$$\nu_{FS}(V_r) = 0.23 \nu_{FS}(s) + 0.370$$

$$\nu_{FS}(T_r) = 0.54 \nu_{FS}(s) + 0.675$$

$$\nu_{FS}(T_p) = 0.29 \nu_{FS}(s) + 0.415$$

$$P(k) = k^{-\nu(s)}$$

$$\nu(s)/2 = \nu_{FS}(s)$$
For slip, we use a truncated Cauchy, with limit values of 0 and maximum slip proposed by McGarr and Fletcher (2003)

\[ D_{\text{max}} [\text{m}] = 10^{-5.83} M_0^{1/3} [\text{Nm}] \]
For slip, we use a truncated Cauchy, with limit values of 0 and maximum slip proposed by McGarr and Fletcher (2003)
Correlations Between Source Parameters

For each dynamic rupture and each possible pair of source parameter we calculated correlation.
Correlations

The correlations were calculated for 315 dynamic rupture scenarios.
Correlation Matrix

This shows the mean correlation for the 315 dynamic rupture scenarios
UCSB Kinematic Source Component

M 6.6 Finite Fault Source

Avg/Max Slip = 69/332

Normalized moment-rate function

Normalized moment-rate spectrum

Synthetics
Target

slip
Tr
Tp
Y

f_c

Time [s]
Frequency [Hz]

Green’s Functions
1D Velocity Structures

$\alpha_i, \beta_i, \rho_i, Q_p, Q_s$
UCSB Hybrid Method

SoCal Velocity Structure

SoCal Shallow Velocity Structure

Depth [km]

Velocity [m/s], Density [kg/m³] and Q

HF S-wave

HF P-wave
UCSB Hybrid Method

Low frequency

Moho discontinuity

High frequency

Amplify high-frequency portion of ground motion with quarter wavelength amplification method (Boore & Joyner, 1997)
Quarter wavelength amplification

We apply the quarter wavelength amplification method to the high-frequency portion of ground motion, using the S-wave low-frequency velocity structure.

Average shear-wave above depth $z$ is inversely proportional to two-way travel-time.

\[
\tilde{\beta}(z) = \frac{z}{S_{tt}(z)}
\]

Frequency is inversely proportional to the two-way travel-time.

\[
f(z) = [4S_{tt}(z)]^{-1}
\]

Frequency dependent amplification

\[
A(f(z)) = \frac{\rho_s \beta_s}{\sqrt{\tilde{\rho}(z) \tilde{\beta}(z)}}
\]
Q in Eastern North America (ENA)

Benz et al. (1997) \( Q(f) = 1052f^{0.22} \)

\( Q(f) = 751f^{0.28} \)

McNamara et al. (2014)
Q in Japan

Oth et al. (2011)

<table>
<thead>
<tr>
<th>Polygon</th>
<th>$Q_0$</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polygon 1 crustal</td>
<td>91 ± 8</td>
<td>0.64 ± 0.05</td>
</tr>
<tr>
<td>Polygon 2 crustal</td>
<td>127 ± 13</td>
<td>0.61 ± 0.06</td>
</tr>
<tr>
<td>Polygon 3 crustal</td>
<td>55 ± 4</td>
<td>0.77 ± 0.04</td>
</tr>
<tr>
<td>Polygon 4 crustal</td>
<td>51 ± 3</td>
<td>0.82 ± 0.04</td>
</tr>
<tr>
<td>Polygons 1–4 subcrustal</td>
<td>117 ± 9</td>
<td>0.74 ± 0.04</td>
</tr>
<tr>
<td>Polygon 5 subcrustal</td>
<td>88 ± 6</td>
<td>0.89 ± 0.04</td>
</tr>
</tbody>
</table>
Ground Motion
Random Perturbation to the Focal Mechanisms of Subsources

\[ \varphi_i = \begin{cases} 
\varphi_0, & f \leq f_1 \\
\varphi_0 + \frac{f - f_1}{f - f_2} (2r_i - 1) \varphi_p, & f_1 < f < f_2 \\
\varphi_0 + (2r_i - 1) \varphi_p, & f \geq f_2 
\end{cases} \]

\cite{pitarka2000}

Pitarka et al. (2000)
UCSB Hybrid Method

We align HF and LF at the S-wave arrival

For both HF and LF we use a unique source

We stitch HF and LF in the wavelet domain
Results RV $M_{\text{w}}$ 6.6

GOF Comparison for GMPE66RV20SOCAL
50 Realizations
UCSB Method

Period = 0.010 s
Period = 0.050 s
Period = 0.100 s
Period = 0.200 s
Period = 0.500 s
Period = 1.000 s
Period = 2.000 s
Period = 5.000 s

$\ln(\text{data/obs})$

20 km
Under-prediction of high frequencies

1D Velocity Structure

Hybrid

UCSB, Scenario: M6.2, SS, R=50 km, LOMAP

UCSB, Scenario: M6.2, SS, R=50 km, NOCAL

Ratio (50 km/20 km) Response Spectrum M6.6&6.2

Red: M6.6
Blue: M6.2
Over-prediction of low frequencies

1D Velocity Structure

Hybrid

UCSB, Scenario: M6.2, SS, R=50 km, LOMAP

Median of 4 NGA Models
Acceptance Criteria

UCSB, Scenario: M6.2, SS, R=50 km, NOCAL

AS08
BA08
CB08
CY08
Median of 4 NGA Models
Acceptance Criteria

Ratio (50 km/20 km) Response Spectrum M6.6 & 6.2

Red: M6.6
Blue: M6.2
Results RV $M_{\text{w}}$ 6.6 at 20 km
2000 Tottori M 6.59
2000 Tottori $M$ 6.59

GOF Comparison for Tottori
50 Realizations
UCSB Method
2000 Tottori M 6.59

GOF Comparison for Tottori
SD Realizations
UCSB Method

Distance [km]
2000 Tottori $M$ 6.59

![Graph showing RotD50 vs. Period [s]]
$M_o \propto A \text{ scaling and } \Delta \sigma$

Something to Keep in Mind
Estimating Stress Drop

\[ \Delta \tau_B = \frac{7M_0}{16r^3} = \frac{7M_0f_c^3}{16(kV_S)^3} \]

\[ \Delta \tau_{a_{rms}} = a_{rms} \frac{106 \rho R}{2\mathcal{K}_{\theta\phi}(2\pi)^2} \sqrt{\frac{f_c}{f_{\max}}} \]
Leonard (2010)

\[ \log(M_0) = \frac{2}{3} \log(A) + \log(0.35\Delta\sigma) \]

- LSR (5.8 MPa)
- 0.1 MPa
- 1.0 MPa
- 10.0 MPa
- 100.0 MPa

\( \log \text{Seismic Moment [Nm]} \)

\( \log \text{Area [km}^2] \)
We have computed the corrected acceleration spectra for stations CVVA, CBN and 2555, using the methodology presented by Boatwright and Seekins (2011). We used Brune's (1970) and Eshelby's (1954) expressions to compute stress is a constant that is equal to 0.37. For Madariaga. This means that Madariaga's relationship estimates stress drops ~5.5. We log averaged the individual values of stress drop to obtain a corner frequency of ~0.58 Hz. This value of \( \sigma_B \approx 23 \text{ MPa} \)
The 2011 Virginia earthquake is dominated by two major asperities separated by ~2.2 km in space and by ~1s in time.
Other Values of Dynamic Stress Drops for ENA

Boatwright and Seekins (BSSA, 2011)
Other Values of Dynamic Stress Drops for ENA

\[ y = 1.1179x + 6.6085 \]
\[ R^2 = 0.8019 \]

Boatwright and Seekins (BSSA, 2011)
Results

Stress Drop of 20 MPa on a 3.7x4.6 km Fault

Stress Drop of 5.8 MPa on a 5.2x7.5 km Fault
Results

Stress Drop of 20 MPa on a 3.7x4.6 km Fault

Stress Drop of 5.8 MPa on a 5.2x7.5 km Fault
Proposed Scaling

\[ \log(M_0) = \frac{2}{3} \log(A) + \log(0.35\Delta \sigma) \]

- LSR (5.8 MPa)
- 0.1 MPa
- 1.0 MPa
- 10.0 MPa
- 100.0 MPa
Conclusions

Modeling of wave-propagation with 1D velocity structures has the following problems:

- Under-prediction of high-frequency strong ground motion due to glancing of high incident angle rays off of shallow layers.
- Over-prediction of surface waves due to trapping of energy in upper shallow layers.

✓ To overcome this we have constructed a new method that separates high- and low- frequencies wave-propagation.
✓ We use a unique source for both high- and low-frequency wave propagation. The source parameters are stochastic but correlated.
Future Research

• Inclusion of Scattering functions in the Green’s functions using Zeng (1991) method.

• Incorporation of statistics of dynamic rupture simulations on rough faults.

Fang and Dunham, 2013; Trugman and Dunham, 2014
Future Research
Acknowledgments

We thank Chen Ji for fruitful discussions on this topic and Scott Callaghan, Fabio Silva and Tom Jordan for technical help.

Thank You!
Questions?
Input Files

Velocity model

- **numberLayers**, **placeholder** [the number of layers (including halfspace) in the 1D model, an input that is of no importance for the 1D broadband modeling]
- **Vp**, **Vs**, **density**, **thickness**, **Qp**, **Qs** [P-wave velocity, S-wave velocity, density, thickness of layer, quality factor for P-wave, quality factor for S-wave]
- **numberLayers line**: **Vp**, **Vs**, **density**, **0.0**, **Qp**, **Qs** [P-wave velocity of halfspace, S-wave velocity of halfspace, density of halfspace, for halfspace use thickness 0.0, quality factor for P-wave in halfspace, quality factor for S-wave in halfspace]
## Input Files

**Example input:**

<table>
<thead>
<tr>
<th>1.2 0.3 1.7 0.1 27.0 18.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6 0.5 1.8 0.2 45.0 30.0</td>
</tr>
<tr>
<td>1.9 1.0 2.1 0.2 90.0 60.0</td>
</tr>
<tr>
<td>4.0 2.0 2.4 1.0 420.0 280.0</td>
</tr>
<tr>
<td>4.7 2.7 2.6 2.5 567.0 378.0</td>
</tr>
<tr>
<td>6.3 3.6 2.8 23.0 864.0 576.0</td>
</tr>
<tr>
<td>6.8 3.9 2.9 13.0 936.0 624.0</td>
</tr>
<tr>
<td>7.8 4.5 3.3 0.0 1080.0 720.0</td>
</tr>
</tbody>
</table>
**Input Files**

GreenFar.in

- **nameVelmod** [name of file containing velocity model]
- **minDepth, dz1, Nz1, dz2, Nz2** [minimal depth for Greens functions, depth sampling increment for first Nz1 sources, Number of sources with dz1 sampling, depth sampling increment for Nz1+1...Nz1+Nz2 sources, Nz2 number of sources with dz2]
- **minEpi, dx1, Nx1, dx2, Nx2** [minimal epicentral distance for Greens functions, epicentral distance sampling increment for first Nx1 sources, Number of sources with dx1 sampling, epicentral distance sampling increment for Nx1+1...Nx1+Nx2 sources, Nx2 number of sources with dx2]
- **Nt, dt, tBefore** [number of time steps, time increment, seconds to be saved before first arrival. This should never be set to 0 (because of wrap-around artifacts!!!)
- **nameGreenDB** [name of the file containing the Greens function database]
- **minDepthFar, NFar** [for sources with epicentral distance index NFar... Nt+Nx2 every source that is more shallow than minDepthFar, the Greens Function will be replaced with a source that is at the closest but larger depth than minDepthFar. This is done, because for larger distances there can be a problem with too shallow sources.]
Input Files

Example Input:
velocity.soil2
5.0 0.3 15 0.5 25
0.05 0.5 30 1. 100
4000 0.01 3.0
Green_1d.soil
0.4 35
Input Files

KinModel.inp
1. line: rupL, ddW [rupture length, down-dip width, i.e., dimensions of fault plane in m]
2. line: hypoStrike, hypoDip [position of hypocenter on fault along dip, position of hypocenter on fault along dip, in m]
3. line: hypoX, hypoY, hypo [hypocenter coordinates in m]
4. line: M0, fc [seismic moment in Nm and corner frequency in Hz]
5. line: strike, dip, rake (strike, dip, rake of event)
6. line: dx, dt [grid spacing (m), time increment for slip rate function (has to be same as for Green’s function!)]
7. line: NSources [number of sources]
8. line: seed1, seed2, seed3 [random seeds]
9. line: nameVelMod [name of file containing velocity model]
Input Files

Example Input:
20000 25000
16000 19400
-15782. -2786.9 17500.
1.23e+19 0.2
122. 40. 105.
200 0.01
20
12124224 12421 534234
velocity.soil2
Input Files

**syn1D_LAH.inp**
1. line: `subStrike, subDip` [# point sources for each subfault (subfaults are interpolated)]
2. line: `perturbAz, perturabRake, perturbDip` [perturbation of azimuth, rake and dip for the high frequencies]
3. line: `fDeterministic, fStochastic, kappa` [until frequency `fDeterministic` radiation pattern is deterministic, above `fStochastic` it is stochastic. In between there is a linear transition, kappa value in s]
4. line: `nameSources` [name of file containing names of source model files]
5. line: `nameStation` [name of file containing station locations]
6. line: `switchTimeSeries` [1: displacement, 2: velocity, 3: acceleration. Note that the post processing programs work on velocity]
7. line `switchFormat` [1:SAC, 2: TXT. Post processing works on TXT]
Example input:
2 2  ! # of point source for each subfault
60.0, 30.0, 15.0  ! Perturbation on strike, rake, and dip
1.0, 3.0, 0.03
source_SCEC.list
stations25
2  ! 1 for Displacement, 2 for Vel., 3 for Acc
2  ! 1 for SAC; 2 for TXT; 3 for Binary
**Exercise**

FAULT_WIDTH = 27.00  
HYPO_ALONG_STK = 6.00  
DLEN = 0.5  
HYPO_DOWN_DIP = 19.40  
DWID = 0.5  
RAKE = 105.00  
FAULT_LENGTH = 20.00  
DEPTH_TO_TOP = 5.00  
CORNER_FREQ = 0.2  
MAGNITUDE = 6.73  
LAT_TOP_CENTER = 34.344  
STRIKE = 122  
LON_TOP_CENTER = -118.515  
DIP = 40  
SEED = 1343642

1) Go to /home/cme/CME/bbp/bbp_val/  
   NR-5sta/input_files

2) Copy nr_v14_02_1_ucsb.src and .stl file into /  
   home/cme/CME/bbp/bbp_sims/start

3) Modify the .stl file keep the furthest station  
   from the fault

4) Make a run with run_bbp.py

5) Choose the UCSB method (2)

```
[cme@ssec-cme start]$ run_bbp.py
Welcome to the SCEC Broadband Platform.
Please select the modules you want to run.
Do you want to perform a validation run (y/n)? n

Please select a velocity model (number or name are ok):

(1) LABasin
? 1

Choose a Method to use in a Broadband forward simulation:

(1) GP (Graves & Pitarka)
(2) UCSB
(3) SDSU
(4) EXSIM
(5) CSM
(6) Irikura
? 2

Do you want to run a rupture generator (y/n)? y

Do you want to

(1) select a source description in /home/cme/CME/bbp/bbp_sims/start
(2) enter a path of a source description file
? 1
```
Exercises

6) Go to /home/cme/CME/bbp/
   bbp_gf/LABasin/ucsb
7) Open the file syn1D_LAH.inp
8) The kappa value is 0.03, change it to 0.005
9) Do run_bbp.py with the same SRC file.
10) After the runs are done, you can rename the folders reflecting the different value of kappa and compare ground motions with bbp2sac.py and SAC.
11) Redo step 6 varying the perturbation of strike, dip and rake and rerun run_bbp.py
12) Do the validation for all 5 stations