Hybrid Empirical Method

- The hybrid empirical method (Campbell, 1981-2011) is a procedure to develop GMPEs in areas with sparse ground motions.
- In the hybrid empirical method, the target region (ENA in this study) ground motions are predicted from the host region (WNA in this study) empirical GMPEs using modification factors between two regions.
- These theoretical modification factors are calculated as the ratio of stochastic simulations of ground motions for two regions.
- Using regional seismological parameters in simulations, the adjustment factors reflect the regional differences in source, path, and site.
- In the hybrid empirical method, the empirically derived ground-motion models for the host region are mapped onto the target region considering the differences in regional seismological properties.
Hybrid Empirical Method

The hybrid empirical method is used by many authors to develop GMPE in ENA (Campbell 2003, 2007, 2011, 2014; Tavakoli and Pezeshk 2005; Pezeshk, Zandieh, and Tavakoli 2011)

Hybrid Empirical Method

\[
Y_{\text{ENA \ estimated}} = Y_{\text{WNA \ empirical}} \times \frac{Y_{\text{ENA \ stochastic}}}{Y_{\text{WNA \ stochastic}}}
\]

Adjustment Factor
(Accounts for earthquake source, wave propagation, and site-response differences between the two regions)

Hybrid Empirical Method

- The purpose of this study is to update the Pezeshk, Zandieh, and Tavakoli (2011) and Campbell (2007, 2011) models to derive a new hybrid empirical GMPE for ENA using five new ground-motion prediction models developed by the PEER center (NGA-West2).

- Furthermore, recent new information on ENA seismological parameters such as the stress parameter, geometric spreading, anelastic attenuation, and the site response term are used to update the GMPE.
**Stochastic Simulations**

- **Point-source stochastic simulation of ground motion amplitudes for both WNA and ENA are determined.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WNA</th>
<th>ENA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source spectrum model</td>
<td>Single-corner-frequency $\omega$</td>
<td>Single-corner-frequency $\omega$</td>
</tr>
<tr>
<td>Stress parameter, $\Delta \sigma$ (bars)</td>
<td>80</td>
<td>250</td>
</tr>
<tr>
<td>Shear-wave velocity at source depth, $\beta$ (km/s)</td>
<td>3.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Density at source depth, $\rho$ (gm/cc)</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Geometric spreading, $Z(R)$</td>
<td>$R^{-1.2}; R &lt; 40$ km</td>
<td>$R^{-1.4}; R &lt; 70$ km</td>
</tr>
<tr>
<td></td>
<td>$R^{-3}; R \geq 40$ km</td>
<td>$R^{-1.4}; 70 \leq R &lt; 140$ km</td>
</tr>
<tr>
<td></td>
<td>$R^{-1.2}; R \geq 140$ km</td>
<td>$R^{-1.4}; R \geq 140$ km</td>
</tr>
<tr>
<td>Quality factor, $Q$</td>
<td>$180 f^{0.35}$</td>
<td>max(1000,893)$f^{0.35}$</td>
</tr>
<tr>
<td>Source duration, $T_s$ (sec)</td>
<td>$1/f_s$</td>
<td>$1/f_s$</td>
</tr>
<tr>
<td>Path duration, $T_p$ (sec)</td>
<td>0.05$R$</td>
<td>$0; R \geq 10$ km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+0.16; 10 &lt; R \leq 70$ km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-0.03; 70 &lt; R &lt; 130$ km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+0.04; R &gt; 130$ km</td>
</tr>
<tr>
<td>Kappa, $\kappa_s$ (sec)</td>
<td>0.04</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Seismological Parameters for WNA

- Response spectra for WNA earthquakes for $M<6$ can be well described by a simple point-source stochastic model.

- We are finding the best fit for seismological parameters by matching stochastic simulation to the mean GMPEs of NGA-West2 for range of magnitudes and distances.

- We perform a set of inversion to obtain the best and consistent set of parameters by matching stochastic simulations with mean GMPEs for magnitudes from 3.5 to 6.

GMPEs

- **ASK14** Abrahamson & Silva & Kamai 2014 NGA West-2 Model
- **BSSA14** Boore & Stewart & Seyhan & Atkinson 2014 NGA West-2 Model
- **CB14** Campbell & Bozorgnia 2014 NGA West-2 Model
- **CY14** Chiou & Youngs 2014 NGA West-2 Model
- **I14** Idriss 2014 NGA West-2 Model

![Response Spectra](image)
BSSA-14 - NGA West 2 Parameters

- Vs30 = 760 m/s
- Region = 0 (California)
- Basin Depth Z2.5 and Z1 = 999 (use default values)
- $R_{jb}$ is converted to $R_{rup}$ using Scherbaum et al. (2004) distance conversion for generic style of faulting.

Effective Distance

- To mimic the finite-fault effects in point-source simulations, the effective distance, $R'_{rup}$, of Atkinson and Silva (2000) and Yenier and Atkinson (2014) recommendations are used in our stochastic simulations.

$$R'_{rup} = \sqrt{R_{rup}^2 + h^2}$$

$$\log h = \max(-0.05 + 0.15M, -1.72 + 0.43M)$$
Geometric Spreading Vs. Rupture Distance

\[ \log h = \max(-0.05 + 0.15M, -1.72 + 0.43M) \]

\[ R'_{rup} = \sqrt{R^2_{rup} + h^2} \]

Seismological Parameters for WNA

- **Path Duration**
  - We adopted Boore and Thompson (2014) path duration.
  - We followed Yenier and Atkinson (2014) to convert Boore and Thompson (2014) nodal rupture distances using the effective distances:

    - Table 1 of Boore and Thompson (2014) and Yenier and Atkinson (2014) Table 1
      - 0km-0s
      - 6.59km-2.32s
      - 44.7km-8.32s
      - 124.8km-10.9s
      - 175km-17.5s
      - 269km-34.1s
  - Path duration increases with distance at a rate of 0.156s/km after the last nodal point.
Stress Parameter for WNA

- For our inversion for WNA, we use the Brune single-corner frequency model.
- The stress parameter controls the spectral shape at high frequencies along with the site parameter $\kappa_0$.
- Yenier and Atkinson (2014) proposed an average stress parameter based on spectral shape of 100 bars for events of $M \geq 5$ with a significant constant that multiplies predicted source amplitudes. They proposed:

$$\log \Delta \sigma = \min(1.176 + 0.412(M - 3.0), 2) = \begin{cases} 15 & M = 3 \\ 39 & M = 4 \\ 100 & M \geq 5 \end{cases}$$

- We determine the mean value of the stress parameter to be 125 based on our inversion.

$\kappa_0$ Parameter for WNA

- $\kappa_0$ based on the inversion is determined to be 0.0375.
- This is consistent with Linda Al Atik recent work.

<table>
<thead>
<tr>
<th>$M_c$</th>
<th>$R_0$ (km)</th>
<th>Lower Kappa (sec) (weight 0.3)</th>
<th>Central Kappa (sec) (weight 0.4)</th>
<th>Upper Kappa (sec) (weight 0.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>5</td>
<td>0.0384</td>
<td>0.0411</td>
<td>0.0431</td>
</tr>
<tr>
<td>5.5</td>
<td>10</td>
<td>0.0379</td>
<td>0.0406</td>
<td>0.0425</td>
</tr>
<tr>
<td>5.5</td>
<td>20</td>
<td>0.0368</td>
<td>0.0397</td>
<td>0.0419</td>
</tr>
<tr>
<td>6.5</td>
<td>5</td>
<td>0.0369</td>
<td>0.0398</td>
<td>0.0420</td>
</tr>
<tr>
<td>6.5</td>
<td>10</td>
<td>0.0363</td>
<td>0.0390</td>
<td>0.0410</td>
</tr>
<tr>
<td>6.5</td>
<td>20</td>
<td>0.0354</td>
<td>0.0379</td>
<td>0.0398</td>
</tr>
<tr>
<td>7.5</td>
<td>5</td>
<td>0.0366</td>
<td>0.0396</td>
<td>0.0418</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GMPE</th>
<th>ASK14</th>
<th>BSSA14</th>
<th>CB14</th>
<th>CY14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host Kappa</td>
<td>0.045</td>
<td>0.043</td>
<td>0.036</td>
<td>0.040</td>
</tr>
</tbody>
</table>
We considered a bilinear geometric spreading:

\[
Z(R) = \begin{cases} 
R^{b_1} & R \leq R_1 \\
R_1^{b_1-b_2} R^{b_2} & R > R_1 
\end{cases}
\]

We determine the mean value of \( b_1 \) and \( R_1 \) based on our inversion to be.

\[
b_1 = -1.0374 \\
R_1 = 96 \text{ km}
\]

The anelastic attenuation, \( Q(f) \) controls the decay of ground motion amplitude at large distances (especially, at low periods or high frequencies).

\[
Q(f) = 243 f^{0.446}
\]
Residuals

- $f = 0.5 \text{ Hz}$
- $f = 1.0 \text{ Hz}$
- $f = 5 \text{ Hz}$

**M=3.5**

**M=4**

**M=5**

**M=6**

Seismological Parameters for ENA

- The stress parameter of 400 is used in our point source stochastic simulations:
  - Consistent with Boore and Thompson (2014) path duration

**Stress-drop**

- Use of MMI data
  - Shows a large difference between CENA and WUS
  - Implies about a factor of 3 increase in stress drops from WUS
Seismological Parameters for ENA

- **Site Amplification**
  - Table 4 of Boore and Thompson (2014)

<table>
<thead>
<tr>
<th>f (Hz)</th>
<th>A (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00E-03</td>
<td>1.000</td>
</tr>
<tr>
<td>7.68E-03</td>
<td>1.003</td>
</tr>
<tr>
<td>2.33E-02</td>
<td>1.010</td>
</tr>
<tr>
<td>4.00E-02</td>
<td>1.017</td>
</tr>
<tr>
<td>6.34E-02</td>
<td>1.026</td>
</tr>
<tr>
<td>1.08E-01</td>
<td>1.047</td>
</tr>
<tr>
<td>2.34E-01</td>
<td>1.069</td>
</tr>
<tr>
<td>3.65E-01</td>
<td>1.084</td>
</tr>
<tr>
<td>5.08E-01</td>
<td>1.101</td>
</tr>
<tr>
<td>1.06E+00</td>
<td>1.135</td>
</tr>
<tr>
<td>1.37E+00</td>
<td>1.143</td>
</tr>
<tr>
<td>1.69E+00</td>
<td>1.148</td>
</tr>
<tr>
<td>1.97E+00</td>
<td>1.150</td>
</tr>
<tr>
<td>2.42E+00</td>
<td>1.151</td>
</tr>
</tbody>
</table>

Values for non-subalated frequencies are given by linear interpolation of the logarithms of the tabulated values.

Seismological Parameters for ENA

- **Path Model:**

Table 2 of Boore and Thompson (2014) for ENA

<table>
<thead>
<tr>
<th>Rₚₑ (km)</th>
<th>Dₑ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>15.0</td>
<td>2.6</td>
</tr>
<tr>
<td>35.0</td>
<td>17.1</td>
</tr>
<tr>
<td>50.0</td>
<td>25.1</td>
</tr>
<tr>
<td>125.0</td>
<td>25.1</td>
</tr>
<tr>
<td>200.0</td>
<td>28.5</td>
</tr>
<tr>
<td>392.0</td>
<td>46.0</td>
</tr>
<tr>
<td>600.0</td>
<td>69.1</td>
</tr>
</tbody>
</table>

Slope of last segment: 0.111
Bilinear Seismological Parameters for ENA

Path Attenuation:

\[
Z(R) = \begin{cases} 
R^{b_1} & R \leq R_1 \\
R_1^{b_1-b_2} R^{b_2} & R > R_1 
\end{cases}
\]

\[
b_1 = -1.3 \\
R_1 = 50 \text{ km} \\
Q(f) = 525 f^{0.45} \text{ Atkinson and Boore (2014)}
\]

Seismological Parameters for ENA

Kappa:

The kappa value recommend by Hashash et al. (2014) for hard-rock reference sites \(V_{s30}=3,000 \text{ m/s}\) is used in the simulations:

\[
\kappa_o = 0.006
\]
### Bi-linear Models for ENA and WNA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ENA (from inversion)</th>
<th>WNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source spectrum model</td>
<td>Single-corner frequency $\omega_0$</td>
<td>Single-corner frequency $\omega_0$</td>
</tr>
<tr>
<td>Stress parameter, $\Delta$ (bars)</td>
<td>125</td>
<td>2.7</td>
</tr>
<tr>
<td>Shear-wave velocity at source depth, $\beta_s$ (km/s)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Density at source depth, $\rho_s$ (gm/cc)</td>
<td>2.8</td>
<td>2.8</td>
</tr>
</tbody>
</table>
| Geometric spreading, $Z(R)$            | $R^{-1.475}$ if $R \leq 96$ km  
$R^{-0.5}$ if $R > 96$ km  
Atkinson and Boore (2014):  
$R^{-1.6}$ if $R < 50$ km  
$R^{-0.75}$ if $R \geq 50$ km |
| Quality factor, $Q$                    | $243 f^{0.005}$      | $523 f^{0.65}$ |
| Source duration, $T_s$ (sec)           | $\sqrt{f_s}$         | $\sqrt{f_s}$ |
| Path duration, $T_p$ (sec)              | Table 1 of Boore and Thompson (2014) corrected for depth dependent magnitude  
Boore and Thompson (2014) Table 4 corrected for depth dependent magnitude |
| Site amplification, $A_f$              | $\kappa$ (sec)       | $0.0375$  
$0.006$ (Hashash, et al. 2014) |
| Kappa, $\kappa_s$ (sec)                | 0.0375               | 0.006 |

---

**Boore and Thompson (2014)**
Trilinear Geometric Spreading for WNA

Boore and Thompson (2014)

- We considered a Trilinear geometric spreading:

\[
Z(R) = \begin{cases} 
    R^{b_1}, & R \leq R_1 \\
    R^{b_1} \left( \frac{R}{R_1} \right)^{b_2}, & R_1 < R \leq R_2 \\
    R^{b_1} \left( \frac{R}{R_1} \right)^{b_2} \left( \frac{R}{R_2} \right)^{b_3}, & R > R_2 
\end{cases}
\]

- We determine the mean values of \( b_1, b_2, R_1, \) and \( R_2 \) based on our inversion to be:

\[
\begin{align*}
    b_1 &= -1.0387, \\
    b_2 &= -0.83, \\
    R_1 &= 45 \text{ km}, \\
    R_2 &= 125 \text{ km}
\end{align*}
\]

Residuals

- \( f = 0.2 \text{ Hz} \)
- \( f = 1.0 \text{ Hz} \)
- \( f = 5 \text{ Hz} \)
We determine the mean values of $b_1$, $b_2$, $R_1$, and $R_2$ based on our inversion to be:

\[ Z(R) = \begin{cases} 
R^{b_1} & R \leq R_1 \\
R^{b_1} \left( \frac{R}{R_1} \right)^{b_2} & R_1 < R \leq R_2 \\
R^{b_1} \left( \frac{R}{R_1} \right)^{b_2} \left( \frac{R}{R_2} \right)^{b_3} & R > R_2
\end{cases} \]

\[ b_1 = -1.3, b_2 = 0 \]

\[ R_1 = 60 \text{ km}, R_2 = 120 \text{ km} \]

Chapman, Pezeshk, Hosseini, and Conn (2014)

\[ Q(f) = 440 f^{0.47} \]

Chapman, Pezeshk, Hosseini, and Conn (2014)
Comparison of Bilinear and Trilinear Models for ENA

Tri-linear Models for ENA and WNA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ENA (Bilinear)</th>
<th>ENA (Trilinear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source spectrum model</td>
<td>Single-corner-frequency $\alpha$</td>
<td>Single-corner-frequency $\alpha$</td>
</tr>
<tr>
<td>Stress parameter, $\Delta f$ (Hz)</td>
<td>94.5</td>
<td>400 to be consistent with Path Duration</td>
</tr>
<tr>
<td>Shear-wave velocity at source depth, $v_s$ (km/s)</td>
<td>3.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Density at source depth, $\rho$ (g/cc)</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Geometric spreading, $Z(R)$</td>
<td>$R^{-\alpha}; R &lt; 45$ km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R^{-\alpha}; 45 \leq R &lt; 125$ km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R^{-\alpha}; R \geq 125$ km</td>
<td></td>
</tr>
<tr>
<td>Quality factor, $Q$</td>
<td>$211 f^{1.0}$</td>
<td>$Q^{\text{peak}}$ at depth $&lt; 60$ km</td>
</tr>
<tr>
<td></td>
<td>$Q^{\text{peak}}$ at depth $\geq 60$ km</td>
<td></td>
</tr>
<tr>
<td>Source duration, $T_s$ (sec)</td>
<td>$U_f$</td>
<td>$U_f$</td>
</tr>
<tr>
<td>Path duration, $T_p$ (sec)</td>
<td>Table 1 of Boore and Thompson (2014) corrected for depth dependent magnitude (see below)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Table 2 of Boore and Thompson (2014) corrected for depth dependent magnitude (see below)</td>
<td></td>
</tr>
<tr>
<td>Site amplification, $A_f$</td>
<td>Atkinson and Boore (2006) Table 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boore and Thompson (2014) Table 4</td>
<td></td>
</tr>
<tr>
<td>Kapp, $\kappa$ (sec)</td>
<td>0.0325</td>
<td>0.006 (Hashash, et al. 2014)</td>
</tr>
</tbody>
</table>
Hybrid Empirical GMPEs

- Median hybrid empirical estimates of ENA ground motion are obtained by scaling the WNA empirical relations using theoretical modification factors.

- The hybrid empirical estimates are used in a nonlinear least-square regression to develop the GMPEs.

- Comparing against NGA-East database.
Response Spectra

Distance=10 km

M=8
M=7
M=6
M=5

Response Spectra

Distance=30 km

M=8
M=7
M=6
M=5
Response Spectra

Response spectra from Stochastic scaling for $M>6$ and Empirical scaling for $M>6$
Response spectra from Stochastic scaling for $M>6$ and Empirical scaling for $M>6$

$R_{rup}=30$ km

$R_{rup}=200$ km

$R_{rup}=10$ km

$R_{rup}=100$ km
Response spectra from Stochastic scaling for $M>6$ and Empirical scaling for $M>6$

Comparison with NGA-East Database

- Use the flatfile update 2014-09-08.
- Use data except NERHP Site Class E
- Consider all locations except Gulf
- Made corrections for site
Correction for Site Effects (BSSA2014)

\[ F_{S,B} = \ln(F_{ln}) + \ln(F_{nl}) \]

\[ \ln(F_{ln}) = \begin{cases} 
    c \ln \left( \frac{V_{s30}}{V_{ref}} \right) & V_{s30} \leq V_c \\
    c \ln \left( \frac{V_{s30}}{V_{ref}} \right) & V_{s30} > V_c 
\end{cases} \]

\[ \ln(F_{nl}) = f_1 + f_2 \ln \left( \frac{PGA_{r} + f_3}{f_3} \right) \]

where \(c\) describes the \(V_{s30}\)-scaling in the model, \(V_c\) is the limiting velocity beyond which ground motions no longer scale with \(V_{s30}\) and \(V_{ref}\) is the site condition for which the amplification is unity (taken as 760 m/sec).

\(PGA_{r}\) is the median peak horizontal acceleration for reference rock (taken as \(V_{s30}=760\) m/sec).

- Geographic Regions
  - Appalachians
  - Central N-America
  - Eastern N-America
  - Gulf Coast (Kentucky Foreland & Mississippi Embayment)

Jennifer Dreibel, Walter D. Mooney and Marius P. Iaken
HYBRID EMPIRICAL GROUND-MOTION PREDICTION EQUATIONS FOR EASTERN NORTH AMERICA

\[
\log(\bar{Y}) = c_1 + c_2 M_w + c_3 M_w^2 + \left( c_4 + c_5 M_w \right) \times \min \{ \log(R), \log(R_i) \} + \\
\left( c_6 + c_7 M_w \right) \times \max \{ \min \{ \log(R / R_i), \log(R_2 / R_i) \}, 0 \} + \\
\left( c_8 + c_9 M_w \right) \times \max \{ \log(R / R_2), 0 \} + c_{10} R
\]

where

\[ R = \sqrt{R_{\text{comp}}^2 + c_{11}^2} \]

The mean aleatory standard deviation of to be associated with the predictions is defined as a function of earthquake magnitude

\[
\sigma_{\log(\bar{Y})} = \begin{cases} 
    c_{12} M_w + c_{13} & M \leq 7 \\
    -6.95 \times 10^{-3} M_w + c_{14} & M > 7
\end{cases}
\]

Compare with NGA-East Database:
Residual T=0.01 sec

[Graphs showing inter- and intra-event residuals for different magnitudes and hypocentral distances]
Residual T=1 sec

Residual T=10 sec
Future Work

- Residuals show that we are overestimating data within about 30 km.
- Look at $Q(f)$ more carefully for high frequencies.
- Consider both bilinear and trilinear models.
- Use NGA-East site corrections.
- Calibrate against NGA-East Database.
- Consider induced events separately.

Please send us your comments

- S. Pezeshk, spezeshk@memphis.edu
- A. Zandieh, arash.zandieh@live.com
- K. Campbell, kcampbell@corelogic.com
- B. Tavakoli, btavakol@bechtel.com
Hybrid Empirical GMPEs for ENA using Hybrid Broadband Synthetic

A. Shahjouei and S. Pezeshk
Summary of the Procedure

- We used HEM GMPEs for ENA using a HBB simulation technique.
- HF synthetics using stochastic method are generated and combined with LF synthetics produced from kinematic source model and deterministic wave propagation.
- The most recent proposed seismological and geological parameters in the literature is implemented.
- Variability of some parameters are implemented in the generation approach.
- New GMPEs are based on synthetics generated:
  - Mag: M5.0 to M8.0 with increment of 0.5
  - Distance: Closest distance to the fault (Rjb) in distance range of 2–1000 km.
  - Reference rock velocity of 3000 m/s (HR)
- The results are compared with the other GMPEs and NGA-East database.

The Applied Procedure for Hybrid Broadband Synthetic

Hybrid Broadband (HBB) Synthetic Generation using Finite-Fault Modeling

<table>
<thead>
<tr>
<th>Crustal model</th>
<th>Faulting Mech.</th>
<th>Desired $M_w$</th>
<th>Faulting Area</th>
<th>Station map</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>LF Green’s functions</th>
<th>Slip distribution</th>
<th>Kinematic fault modeling</th>
<th>Stress distribution</th>
<th>HF Green’s functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(DWFE method ~ COMPSYN)</td>
<td>(Sum over fault plane)</td>
<td>(Stochastic method ~ SMSIM)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low freq. synth.</th>
<th>Synchronize</th>
<th>Combine</th>
<th>Matched filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Sum over fault plane)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High freq. synth.</th>
<th>Hybrid broadband synthetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Sum over fault plane, and scaling with magnitude)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max directional response</th>
<th>(GMROT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Stochastic method)</td>
<td></td>
</tr>
</tbody>
</table>
Samples for Kinematic Earthquake Source Models for CENA

**M7.5**

- Slip (cm), Contours are Rupture Time (s)
- Scaled Stress Drop (Bar)
- Rise Time (s)
- Slip Rate (cm/s)

**M6.5**

- Slip (cm), Contours are Rupture Time (s)
- Scaled Stress Drop (Bar)
- Rise Time (s)
- Slip Rate (cm/s)

Summary of Stochastic Simulation Technique:

- Hybrid Broadband (HBB) Synthetic Generation using Finite-Fault Modeling
- Applied Magnitude-dependent transition frequency:
  - following Frankel (2009) for M5.5, M6.5, and M7.5.
  - Interpolation values for between magnitudes

<table>
<thead>
<tr>
<th>Mw</th>
<th>Fcross (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>5.5</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>2.6</td>
</tr>
<tr>
<td>6.5</td>
<td>2.4</td>
</tr>
<tr>
<td>7</td>
<td>1.6</td>
</tr>
<tr>
<td>7.5</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Compare with other GMPEs:
Plots for: $M_5$, $M_6$, $M_7$, and $M_8$

Red: This study (SP14)
Blue: PZCT14
Green: PZT11

Compare with NGA-East Database:
*** Corrected for $V_{s30}=3km/s$
Residuals

Comparison with Frankel
ACKNOWLEDGMENTS

Dr. Paul Spudich, USGS
Dr. Martin Mai, KAUST
Dr. Hugo C. Jimenez, KAUST

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WNA</th>
<th>ENA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source spectrum model</td>
<td>Single-corner-frequency $a R^2$</td>
<td>Single-corner-frequency $a R^2$</td>
</tr>
<tr>
<td>Stress parameter, $\Delta \sigma$ (bars)</td>
<td>80</td>
<td>250</td>
</tr>
<tr>
<td>Shear-wave velocity at source depth, $\beta_s$ (km/s)</td>
<td>3.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Density at source depth, $\rho_s$ (gm/cc)</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Geometric spreading, $Z(R)$</td>
<td>$R^{-1.5}; R &lt; 40$ km</td>
<td>$R^{-1.5}; R &lt; 70$ km</td>
</tr>
<tr>
<td>Quality factor, $Q$</td>
<td>$180 f^{0.05}$</td>
<td>$\max(1000, 893 f^{0.05})$</td>
</tr>
<tr>
<td>Source duration, $T_s$ (sec)</td>
<td>$\frac{f_s}{f_c}$</td>
<td>$\frac{f_s}{f_c}$</td>
</tr>
<tr>
<td>Path duration, $T_p$ (sec)</td>
<td>0.05 $R$</td>
<td></td>
</tr>
<tr>
<td>Kappa, $\kappa_s$ (sec)</td>
<td>0.04</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 4
Alternative Seismological Parameters Used with the Stochastic Method in WNA and ENA*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>WNA</th>
<th>ENA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source spectrum model</td>
<td>SCPS, DCPS</td>
<td>SCPS, DCPS</td>
</tr>
<tr>
<td>Stress drop (bars)</td>
<td>120-90 (SCPS), 90-60 (DCPS)</td>
<td>105 (0.05), 125 (0.25), 150 (0.40), 180 (0.25), 215 (0.05)</td>
</tr>
<tr>
<td>Quality factor</td>
<td>$180 f^{0.05}$</td>
<td>$180 f^{0.05}$</td>
</tr>
<tr>
<td>Kappa</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

*WNA, western North America; ENA, eastern North America; SCPS, single-corner point source; DCPS, double-corner point source.

Thank You