GROUND MOTION PREDICTION EQUATIONS FOR EASTERN NORTH AMERICA USING THE HYBRID EMPIRICAL METHOD

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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

Hybrid Empirical Method:

$$Y^{ENA}_{estimated} = Y^{WNA}_{empirical} \times \underbrace{\frac{Y^{ENA}_{stochastic}}{Y^{WNA}_{stochastic}}}$$

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

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

- 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.

Parameter	WNA	ENA
Source spectrum model	Single-corner-frequency ω^{-2}	Single-corner-frequency ω^{-2}
Stress parameter, $\Delta\sigma$ (bars)	80	250
Shear-wave velocity at source depth, β_s (km/s)	3.5	3.7
Density at source depth, ρ_s (gm/cc)	2.8	2.8
Geometric spreading, $Z(R)$	$\begin{cases} R^{-1.0}; R < 40\,km \\ R^{-0.5}; R \geq 40\,km \end{cases}$	$\begin{cases} R^{-1.3}; R < 70\,km \\ R^{+0.2}; 70 \leq R < 140\,km \\ R^{-0.5}; R \geq 140\,km \end{cases}$
Quality factor, Q	$180 f^{0.45}$	$\max(1000, 893 f^{0.32})$
Source duration, T_s (sec)	$1/f_a$	$1/f_a$
Path duration, T_p (sec)	$0.05R$	$\begin{cases} 0; & R \leq 10\,km \\ +0.16R; & 10 < R < 70\,km \\ -0.03R; & 70 < R \leq 130\,km \\ +0.04R; & R > 130\,km \end{cases}$
Site amplification, $A(f)$	Boore and Joyner (1997)	Atkinson and Boore (2006)
Kappa, κ_0 (sec)	0.04	0.005

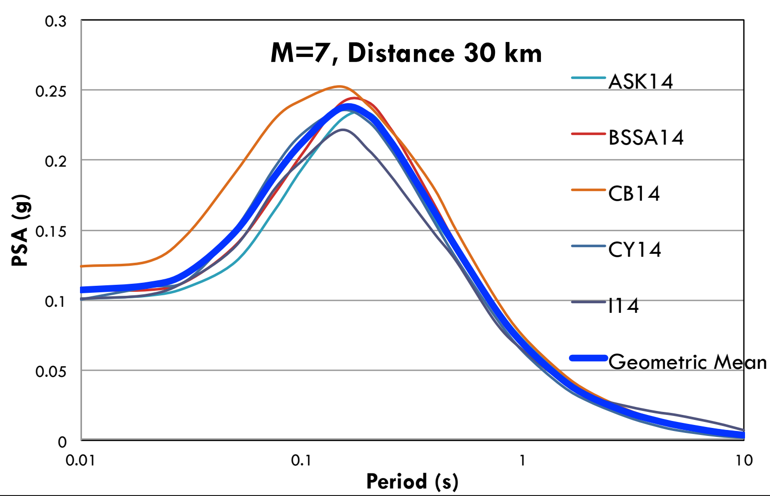
Source: Pezeshk, Zandieh, and Tavakoli (2011), Tavakoli and Pezeshk (2005)

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



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

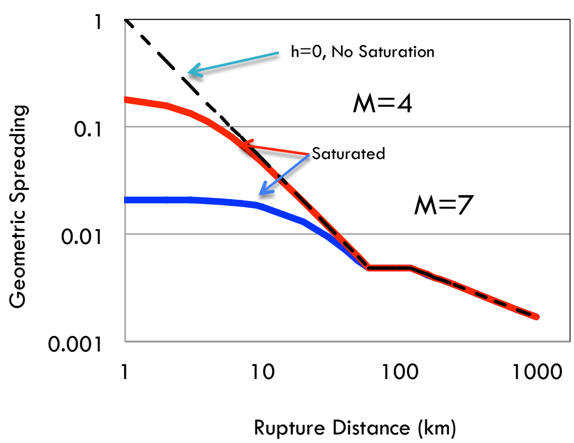
- To mimic the finite-fault effects in point-source simulations, the effective distance, R'_{rup}, of Atkinson and Silva (2000) and Yenier and Atkinson (2014) recommendations are used in our stochastic simulations.

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

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

Geometric Spreading Vs. Rupture Distance

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



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

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 κ_0.
- Yenier and Atkinson (2014) proposed an average stress parameter based on spectral shape of100 bars for events of M ≥ 5 with a significant constant that multiplies predicted source amplitudes. They proposed:

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

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

κ_0 Parameter for WNA

- κ_0 based on the inversion is determined to be 0.0375.
- This is consistent with Linda Al Atik recent work.

Table 9.3.2-1. Host kappa estimates for CY14 estimated using the IRVT approach for the 3 f1-f2 definitions for scenarios with M_w 5.5, 6.5, 7.5 and R_{JB} of 5, 10, and 20 km.

M_w	R_{JB} (km)	Lower Kappa (sec) (weight 0.3)	Central Kappa (sec) (weight 0.4)	Upper Kappa (sec) (weight 0.3)
5.5	5	0.0384	0.0411	0.0431
5.5	10	0.0379	0.0406	0.0425
5.5	20	0.0368	0.0397	0.0419
6.5	5	0.0369	0.0398	0.0420
6.5	10	0.0363	0.0390	0.0410
6.5	20	0.0354	0.0379	0.0398
7.5	5	0.0366	0.0396	0.0418
Average		0.0366	0.0393	0.0414
Standard Deviation		0.0010	0.0011	0.0011

GMPE	ASK14	BSSA14	CB14	CY14
Host Kappa	0.045	0.043	0.036	0.040

Bilinear Geometric Spreading for WNA

- We considered a bilinear geometric spreading:

$$Z(R)=\begin{cases} R^{b1} & R \le R_1 \\ R_1^{b1-b2} R^{b2} & R > R_1 \end{cases}$$

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

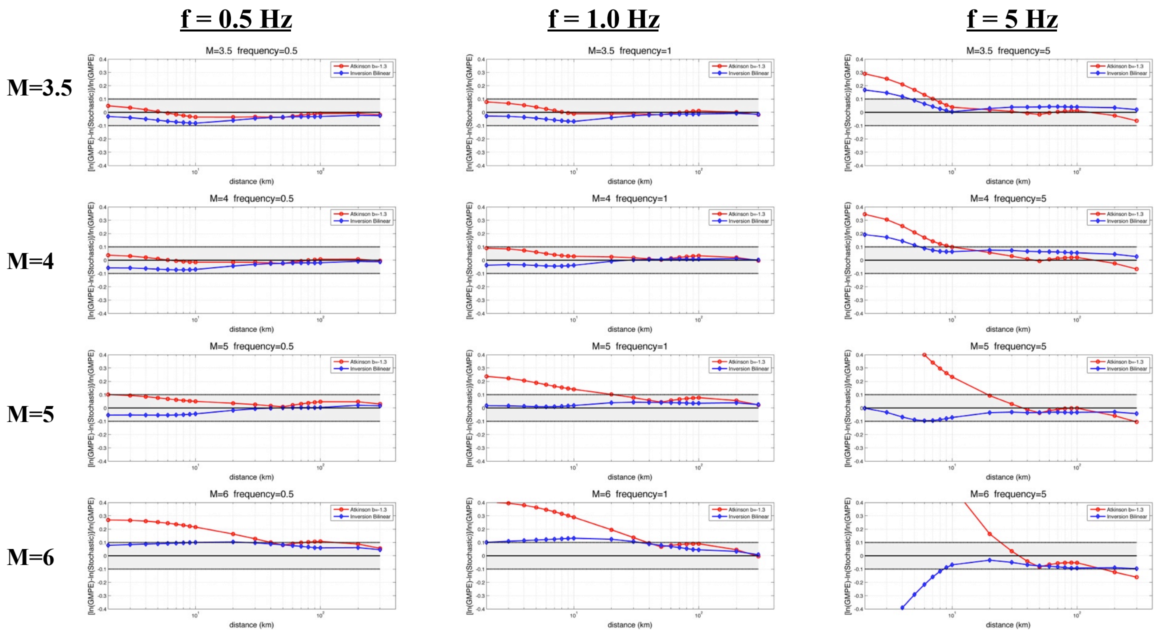
$$b_1 = -1.0374$$
$$R_1 = 96\ km$$

Anelastic Attenuation, Q(f) for WNA

- 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



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 factor of 3 increase in stress-drops from WUS

Seismological Parameters for ENA

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

Table 4. Crustal amplification (A) and frequency (f) pairs for SCRs for a velocity model for which $V_{S30} = 3.0$ km/s (modified from Table 4 in Boore and Joyner, 1997)*.

f	A
1.00E-03	1.000
7.83E-03	1.003
2.33E-02	1.010
4.00E-02	1.017
6.14E-02	1.026
1.08E-01	1.047
2.34E-01	1.069
3.45E-01	1.084
5.08E-01	1.101
1.09E+00	1.135
1.37E+00	1.143
1.69E+00	1.148
1.97E+00	1.150
2.42E+00	1.151

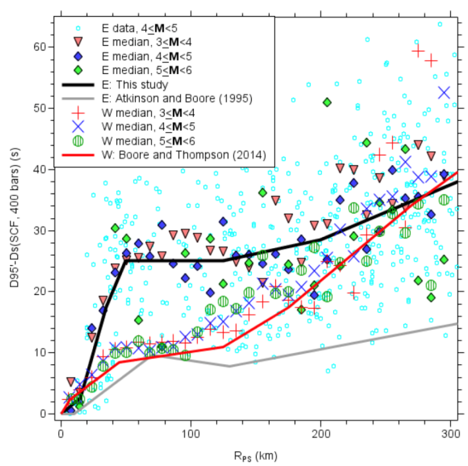
*Values for non-tabulated frequencies are given by linear interpolation of the logarithms of the tabulated values.

Seismological Parameters for ENA

- Path Model:

Table 2 of Boore and Thompson (2014) for ENA

R_{PS} (km)	D_P (s)
0.0	0.0
15.0	2.6
35.0	17.5
50.0	25.1
125.0	25.1
200.0	28.5
392.0	46.0
600.0	69.1
Slope of last segment	0.111



Bilinear Seismological Parameters for ENA

- Path Attenuation:

$$Z(R) = \begin{cases} R^{b1} & R \leq R_1 \\ R_1^{b1-b2} R^{b2} & R > R_1 \end{cases}$$

$$b_1 = -1.3$$

$$R_1 = 50 \quad km$$

$$Q(f) = 525 f^{0.45}$$ Atkinson and Boore (2014)

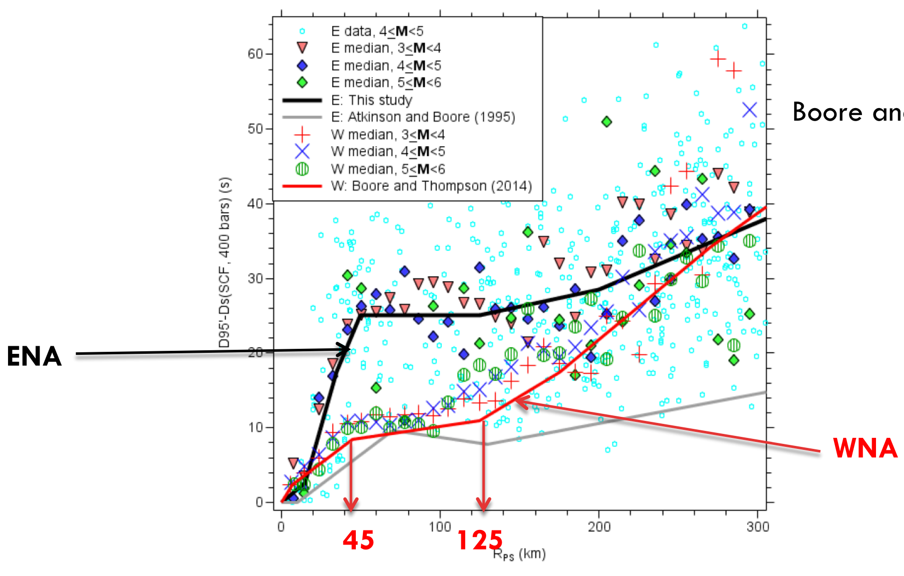
Seismological Parameters for ENA

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

$$\kappa_o = 0.006$$

Bi-linear Models for ENA and WNA

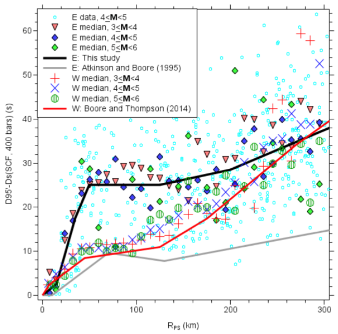
Parameters	WNA (from inversion)	ENA
Source spectrum model	Single-corner-frequency ω^{-2}	Single-corner-frequency ω^{-2}
Stress parameter, $\Delta\sigma$ (bars)	125	400 to be consistent with Path Duration
Shear-wave velocity at source depth, β_s (km/s)	3.5	3.7
Density at source depth, ρ_s (gm/cc)	2.8	2.8
Geometric spreading, $Z(R)$	$\begin{cases} R^{-1.0375}; R \le 96\,km \\ R^{-0.5}; R > 96\,km \end{cases}$	Atkinson and Boore (2014): $\begin{cases} R^{-1.3}; R < 50\,km \\ R^{-0.5}; R \ge 50\,km \end{cases}$
Quality factor, Q	$243 f^{0.446}$	$525 f^{0.45}$ all regions except Gulf Atkinson and Boore (2014)
Source duration, T_s (sec)	$1/f_a$	$1/f_a$
Path duration, T_p (sec)	Table 1 of Boore and Thompson (2014) corrected for depth dependent magnitude.	Table 2 of Boore and Thompson (2014) corrected for depth dependent magnitude.
Site amplification, $A(f)$	Atkinson and Boore (2006) Table 4	Boore and Thompson (2014) Table 4
Kappa, κ_0 (sec)	0.0375	0.006 (Hashash, et al. 2014)



Boore and Thompson (2014)

Trilinear Geometric Spreading for WNA

Boore and Thompson (2014)



- ❑ We considered a Trilinear geometric spreading:

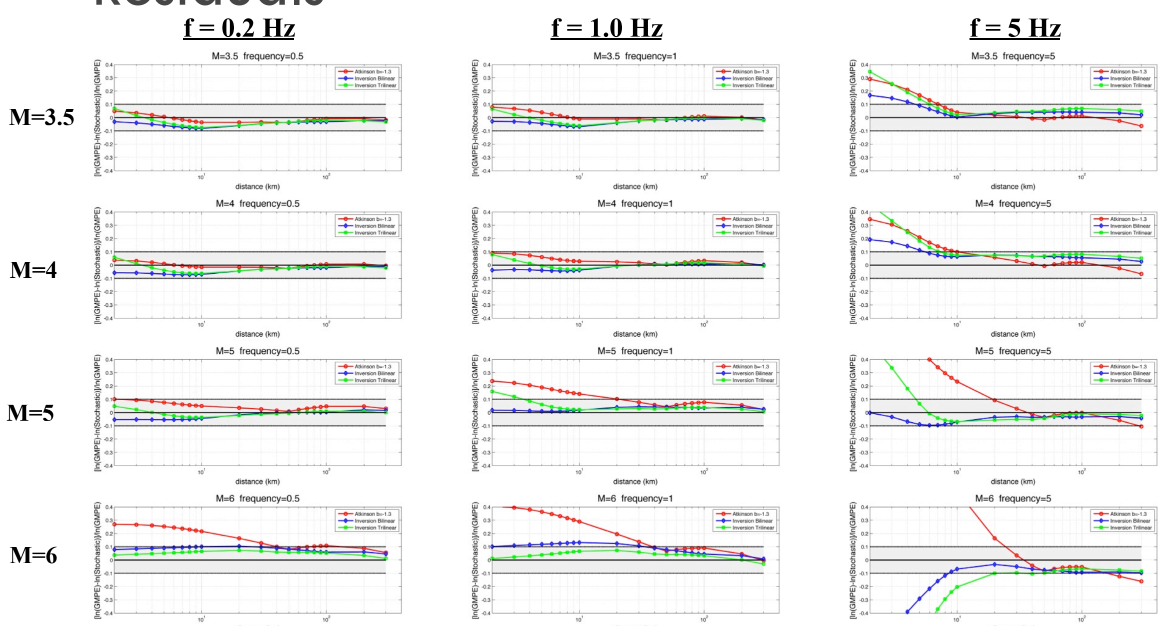
$$Z(R)=\begin{cases} R^{b1} & R \le R_1 \\ R_1^{b1}\left(\dfrac{R}{R_1}\right)^{b2} & R_1 < R \le R_2 \\ R_1^{b1}\left(\dfrac{R_2}{R_1}\right)^{b2}\left(\dfrac{R}{R_2}\right)^{b3} & R > R_2 \end{cases}$$

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

$$b_1 = -1.0387, b_2 = -0.83$$

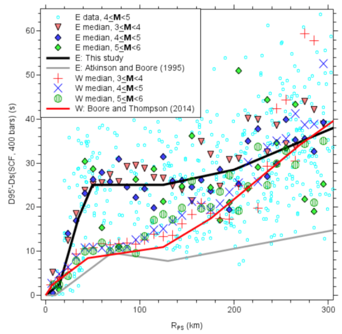
$$R_1 = 45 \quad km, R_2 = 125 \quad km$$

Residuals



Trilinear Geometric Spreading for ENA

Boore and Thompson (2014)



$$Z(R)=\begin{cases} R^{b1} & R\le R_1 \\ R_1^{b1}\left(\frac{R}{R_1}\right)^{b2} & R_1<R\le R_2 \\ R_1^{b1}\left(\frac{R_2}{R_1}\right)^{b2}\left(\frac{R}{R_2}\right)^{b3} & R>R_2 \end{cases}$$

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

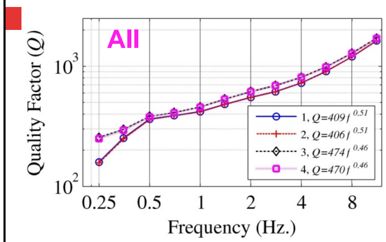
$$b_1=-1.3, b_2=0$$

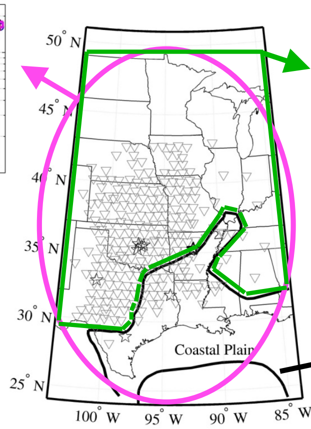
$$R_1=60\ km, R_2=120km$$

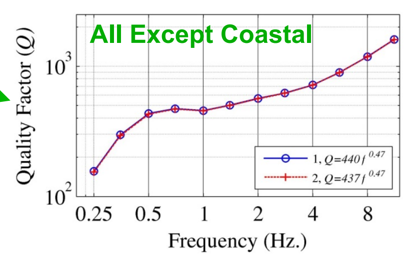
Chapman, Pezeshk, Hosseini, and Conn (2014)

Q and Geometric Spreading for ENA

$$Q(f)=440f^{0.47}$$

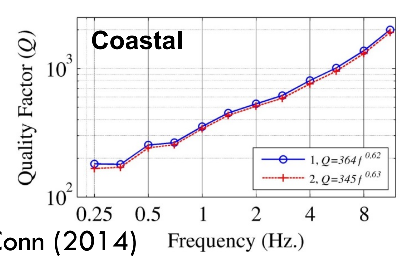






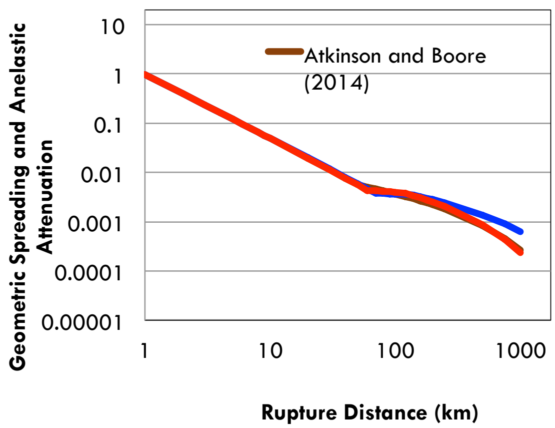
Brune Source + { $R^{-1.3}$ (1), $R^{-1.0}$ (2) }

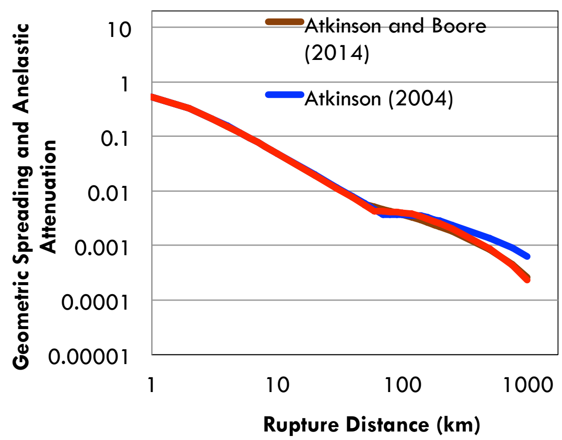
Unknown Source + { $R^{-1.3}$ (3), $R^{-1.0}$ (4) }



Chapman, Pezeshk, Hosseini, and Conn (2014)

Comparison of Bilnear and Trilinear Models for ENA



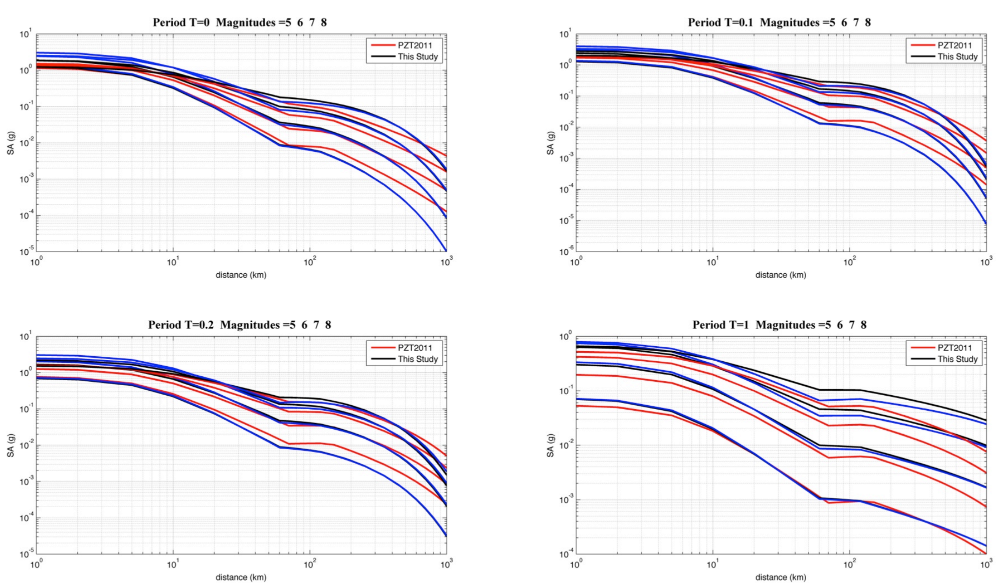


Tri-linear Models for ENA and WNA

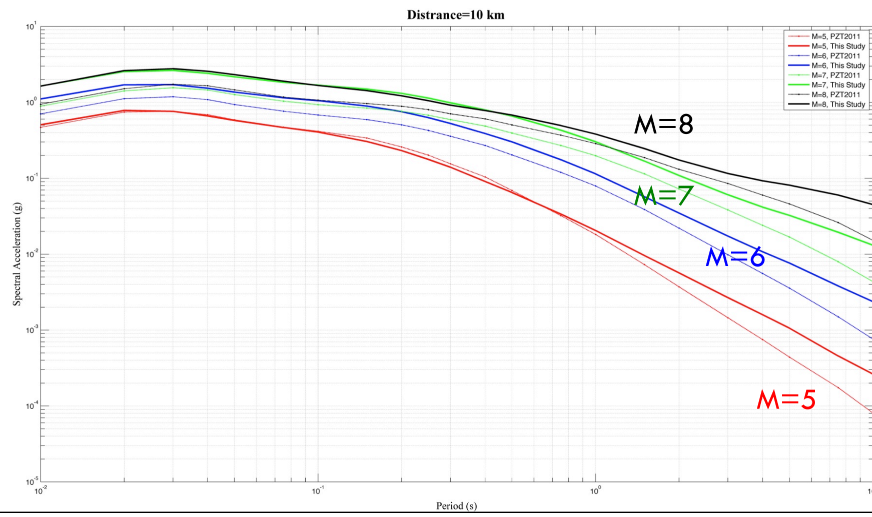
Parameters	WNA (from inversion)	ENA
Source spectrum model	Single-corner-frequency ω^{-2}	Single-corner-frequency ω^{-2}
Stress parameter, $\Delta\sigma$ (bars)	94.5	400 to be consistent with Path Duration
Shear-wave velocity at source depth, β_s (km/s)	3.5	3.7
Density at source depth, ρ_s (gm/cc)	2.8	2.8
Geometric spreading, $Z(R)$	$\begin{cases} R^{-1.0387}; R < 45\,km \\ R^{-0.83}; 45 \le R < 125\,km \\ R^{-0.5}; R \ge 125\,km \end{cases}$	Pezeshk and Chapman Communications (2014) $\begin{cases} R^{-1.3}; R < 60\,km \\ R^{0}; 60 \le R < 120\,km \\ R^{-0.5}; R \ge 120\,km \end{cases}$
Quality factor, Q	$211 f^{0.592}$	Pezeshk and Chapman Communications (2014) $440 f^{0.470}$ all regions except Gulf
Source duration, T_s (sec)	$1/f_a$	$1/f_a$
Path duration, T_p (sec)	Table 1 of Boore and Thompson (2014) corrected for depth dependent magnitude (see below).	Table 2 of Boore and Thompson (2014) corrected for depth dependent magnitude (see below).
Site amplification, $A(f)$	Atkinson and Boore (2006) Table 4	Boore and Thompson (2014) Table 4
Kappa, κ_0 (sec)	0.0325	0.006 (Hashash, et al. 2014)

Hybrid Empirical GMPEs

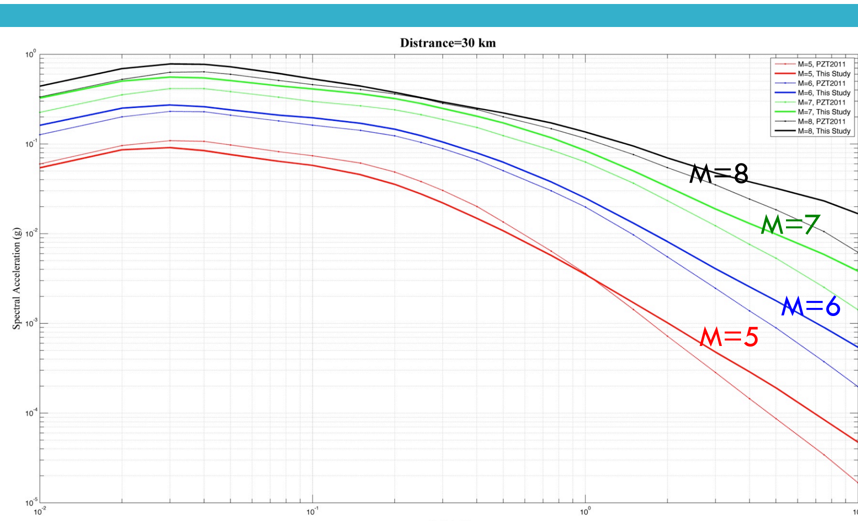
- Median hybrid empirical estimates of ENA ground motion are obtained by scaling the WNA empirical relations using theoretical modification factors.
- The hybrid empirical estimates are used in a nonlinear least-square regression to develop the GMPEs.
- Comparing against NGA-East database.



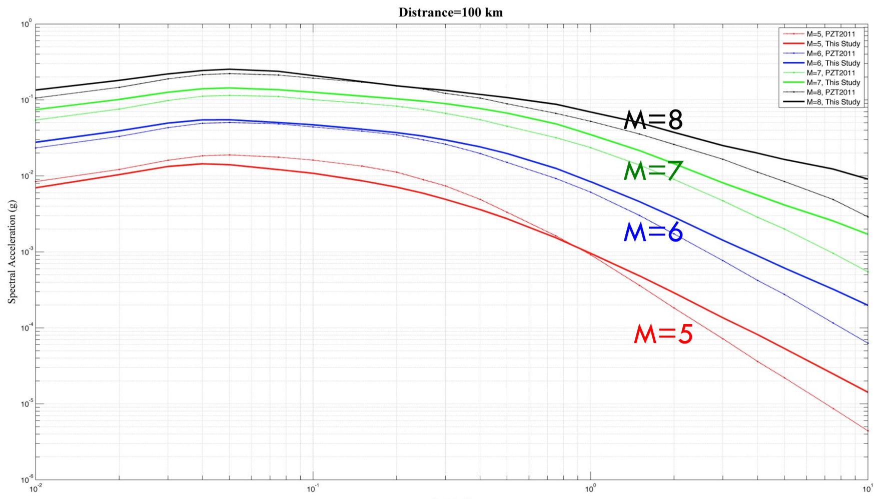
Response Spectra



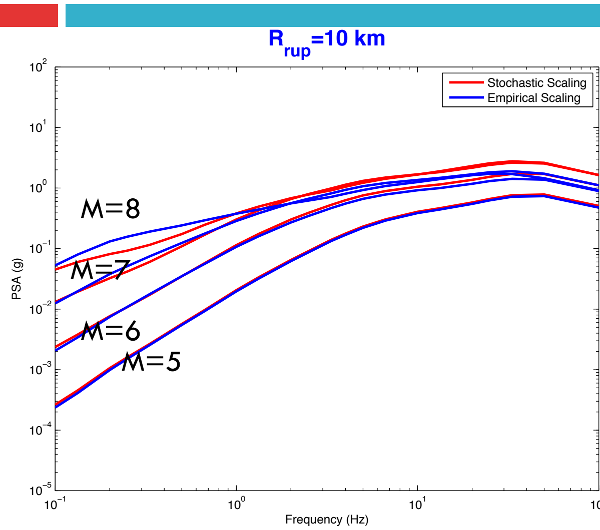
Response Spectra

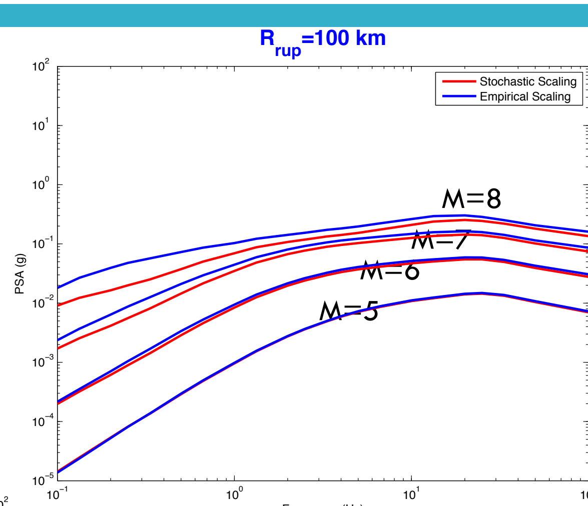


Response Spectra

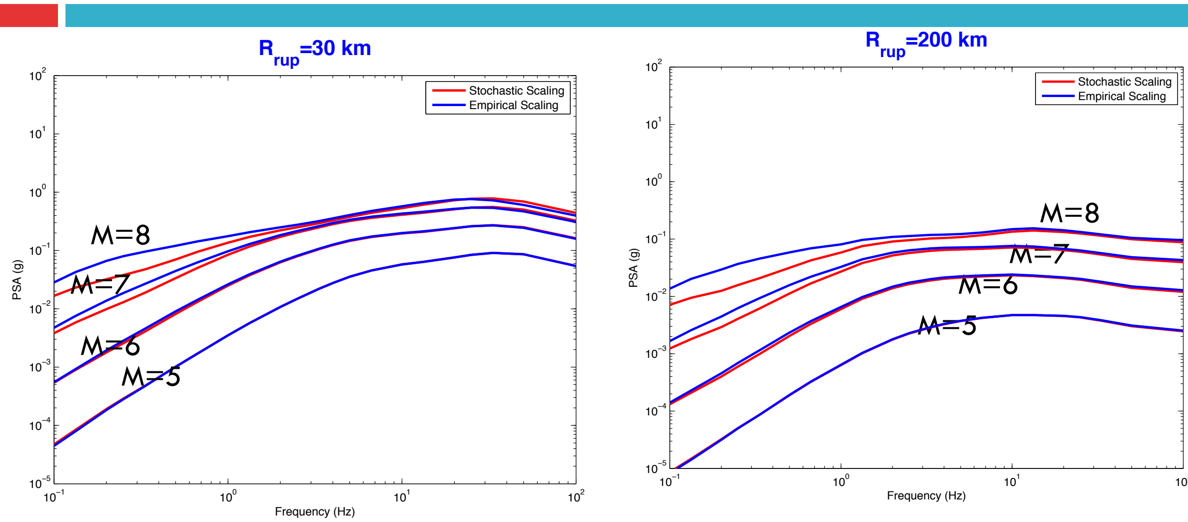


Response spectra from Stochastic scaling for M>6 and Empirical scaling for M>6

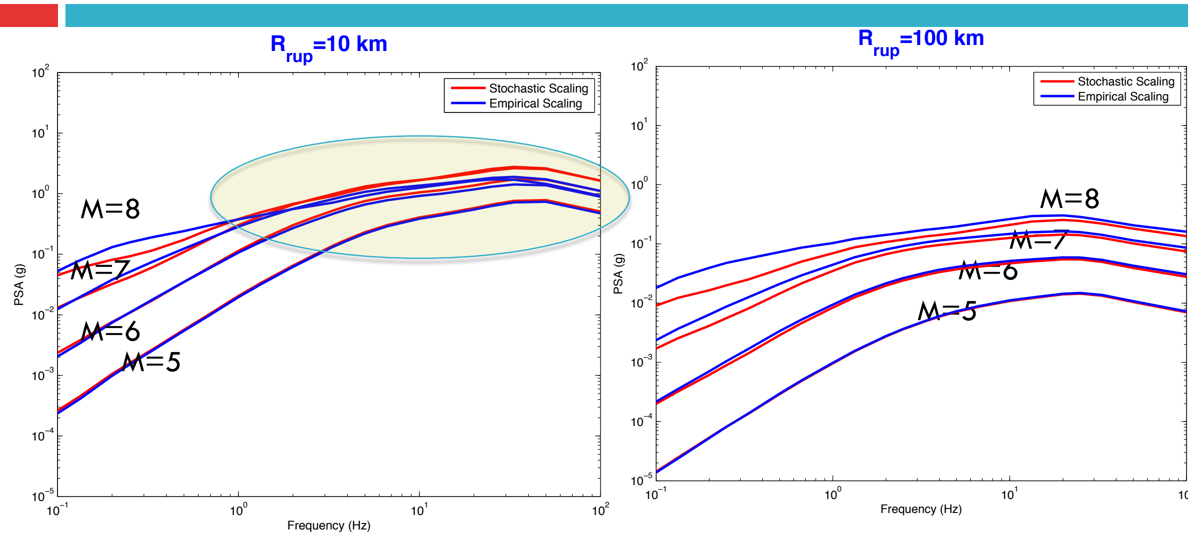




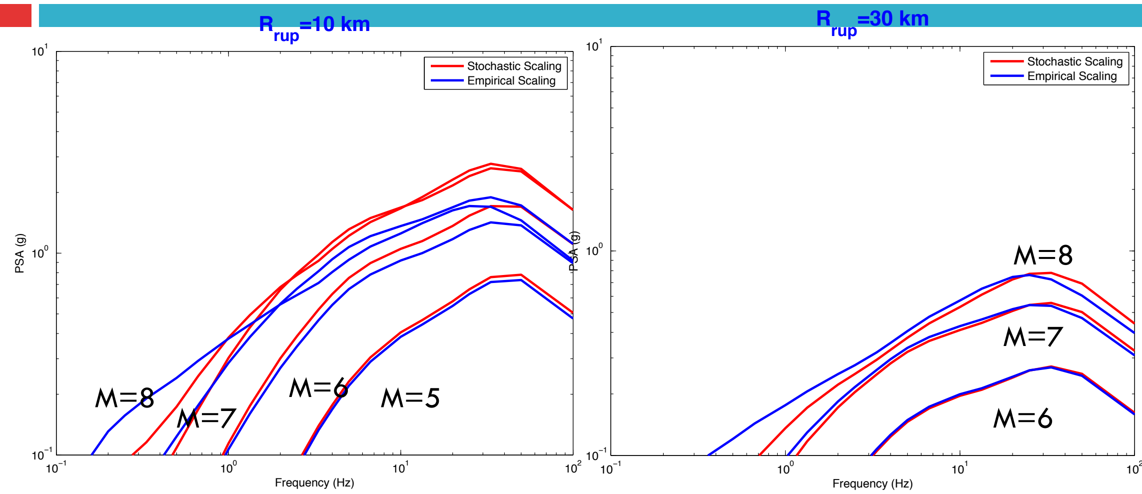
Response spectra from Stochastic scaling for M>6 and Empirical scaling for M>6



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



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)

$$F_{S,B} = \ln\left(F_{lin}\right) + \ln\left(F_{nl}\right)$$

$$\ln(F_{lin}) = \begin{cases} c\ln\left(\dfrac{V_{s30}}{V_{ref}}\right) & V_{s30} \le V_c \\ c\ln\left(\dfrac{V_{s30}}{V_{ref}}\right) & V_{s30} > V_c \end{cases}$$

$$\ln(F_{nl}) = f_1 + f_2 \ln\left(\frac{PGA_r + f_3}{f_3}\right)$$

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).

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- Geographic Regions

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

USGS science for a changing world Jennifer Dreiling, Walter D. Mooney and Marius P. Isken

HYBRID EMPIRICAL GROUND-MOTION PREDICTION EQUATIONS FOR EASTERN NORTH AMERICA

$$\log(\overline{Y}) = c_1 + c_2 M_w + c_3 M_w^2 + \left(c_4 + c_5 M_w\right) \times \min\left\{\log(R), \log(R_1)\right\} + \left(c_6 + c_7 M_w\right) \times \max\left[\min\left\{\log(R/R_1), \log(R_2/R_1)\right\}, 0\right] + \left(c_8 + c_9 M_w\right) \times \max\left[\log(R/R_2), 0\right] + c_{10} R$$

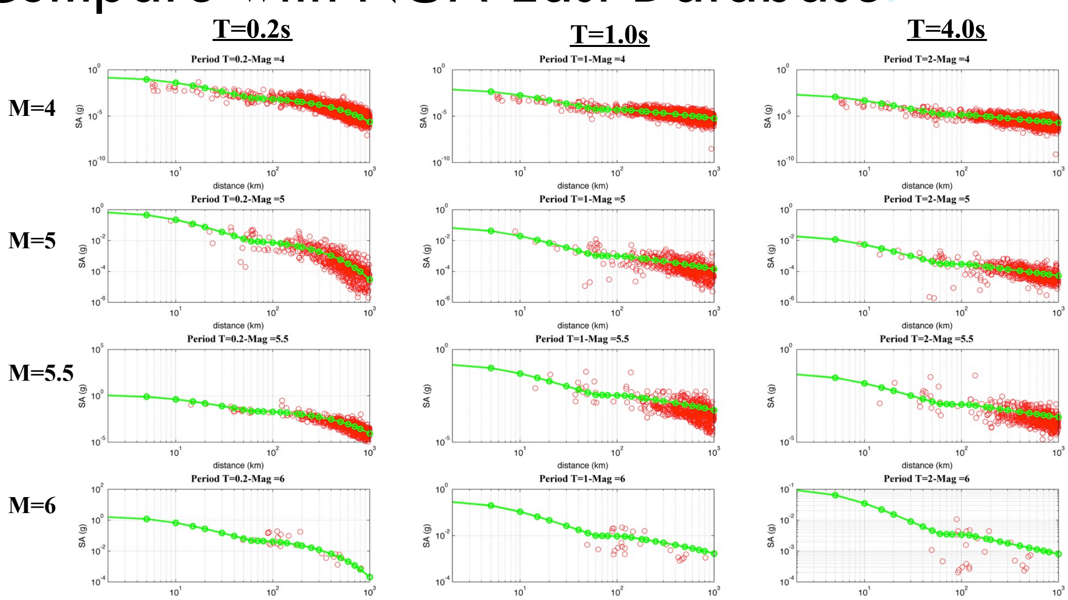
where

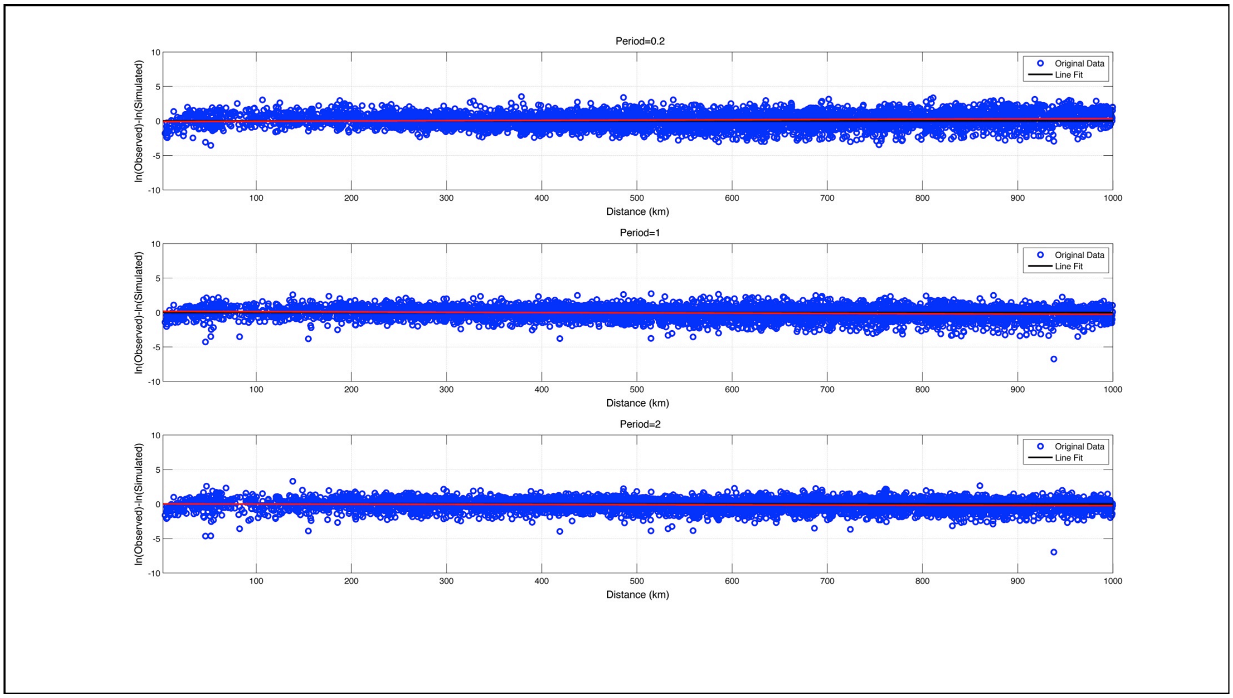
$$R = \sqrt{R_{rup}^2 + c_{11}^2}$$

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

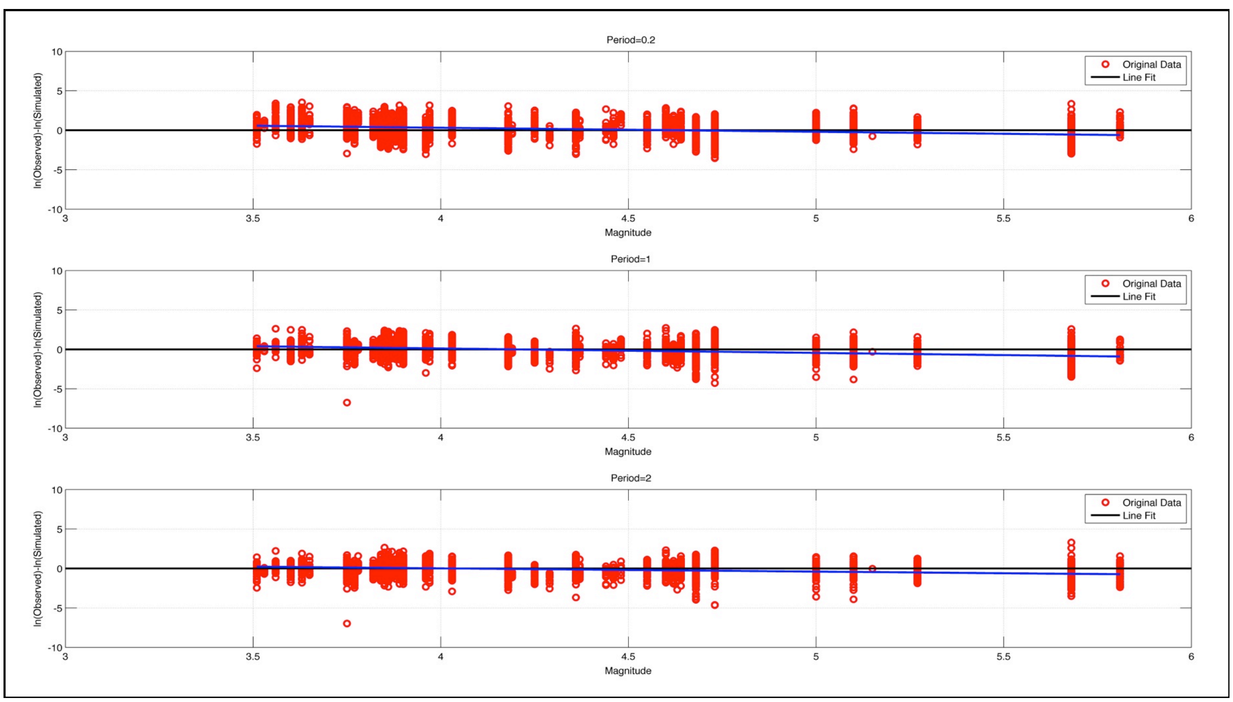
$$\sigma_{\log(\overline{Y})} = \begin{cases} c_{12} M_w + c_{13} & M \le 7 \\ -6.95 \times 10^{-3} M_w + c_{14} & M > 7 \end{cases}$$

Compare with NGA-East Database

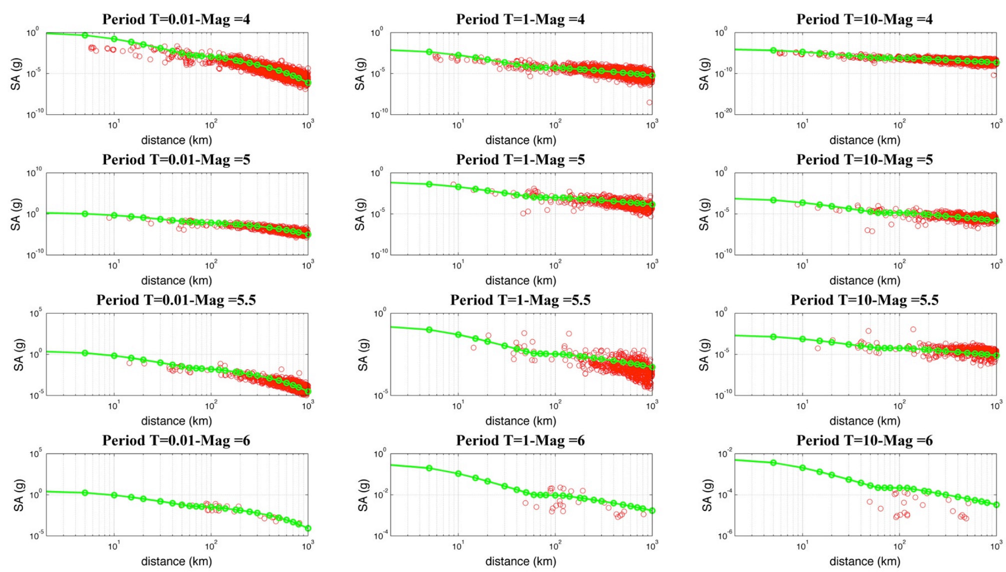


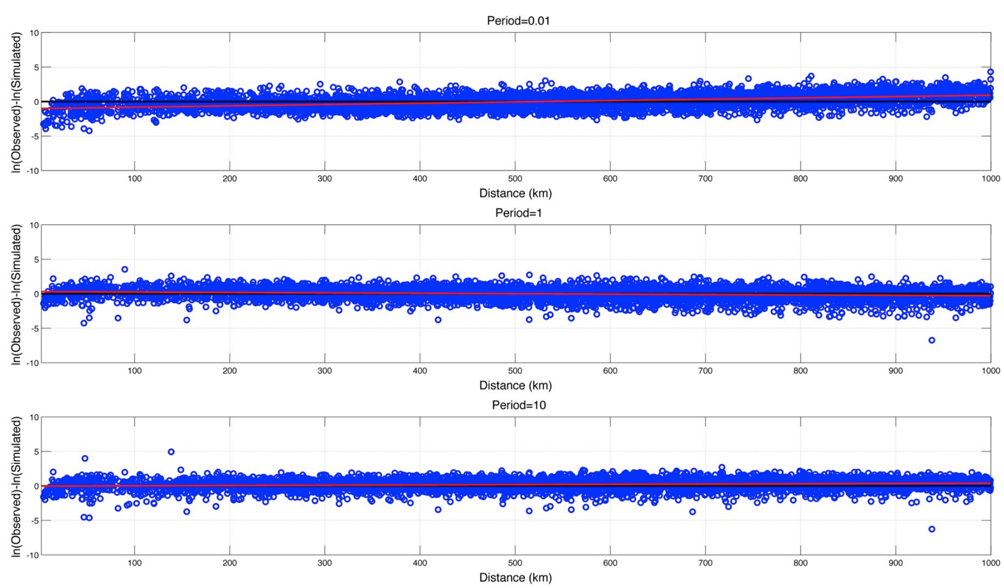


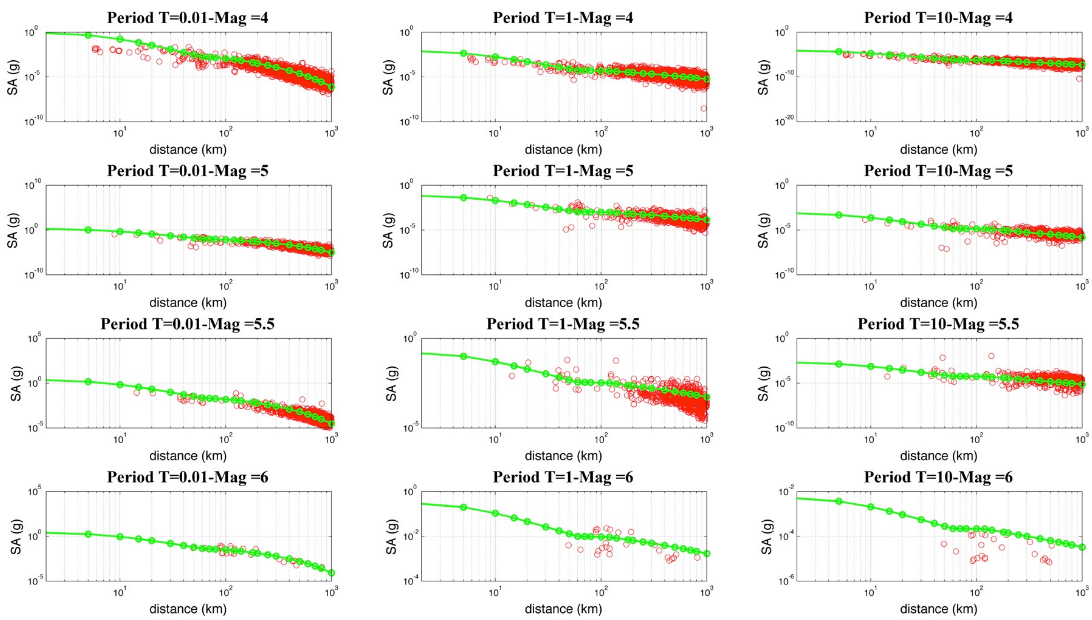
Period=0.2
Period=1
Period=2
ln(Observed)-ln(Simulated)
Distance (km)
Original Data
Line Fit



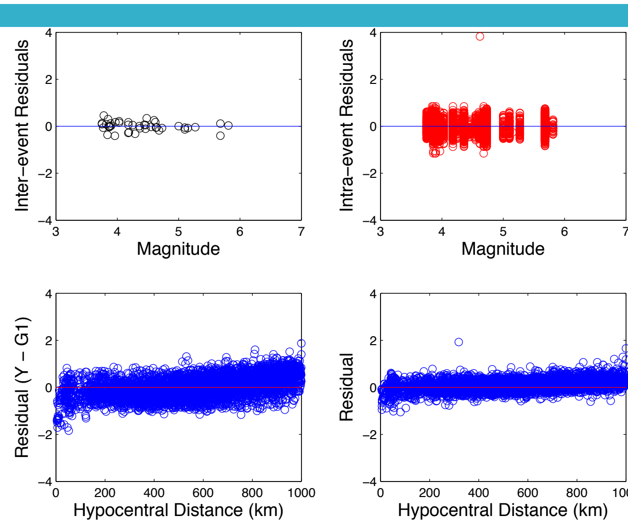
Period=0.2
Period=1
Period=2
ln(Observed)-ln(Simulated)
Magnitude
Original Data
Line Fit


Period T=0.01-Mag =4
Period T=1-Mag =4
Period T=10-Mag =4
Period T=0.01-Mag =5
Period T=1-Mag =5
Period T=10-Mag =5
Period T=0.01-Mag =5.5
Period T=1-Mag =5.5
Period T=10-Mag =5.5
Period T=0.01-Mag =6
Period T=1-Mag =6
Period T=10-Mag =6
SA (g)
distance (km)

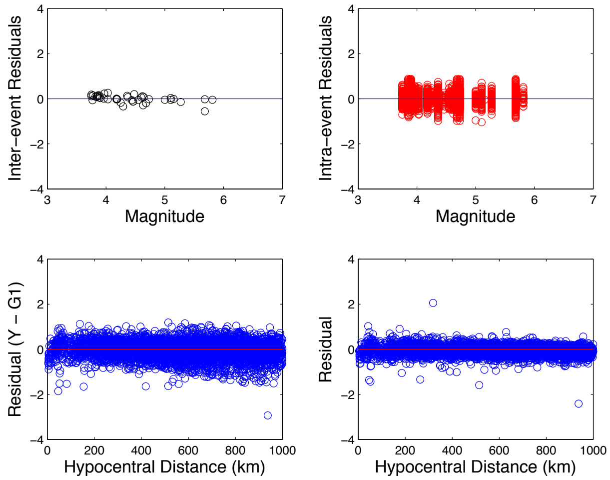

Period=0.01
Period=1
Period=10
ln(Observed)-ln(Simulated)
Distance (km)



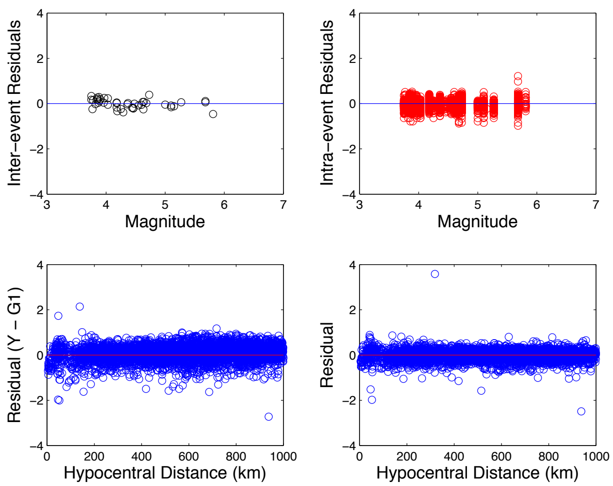
Residual T=0.01 sec



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

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Thank You

Hybrid Empirical GMPEs for ENA using
Hybrid Broadband Synthetic

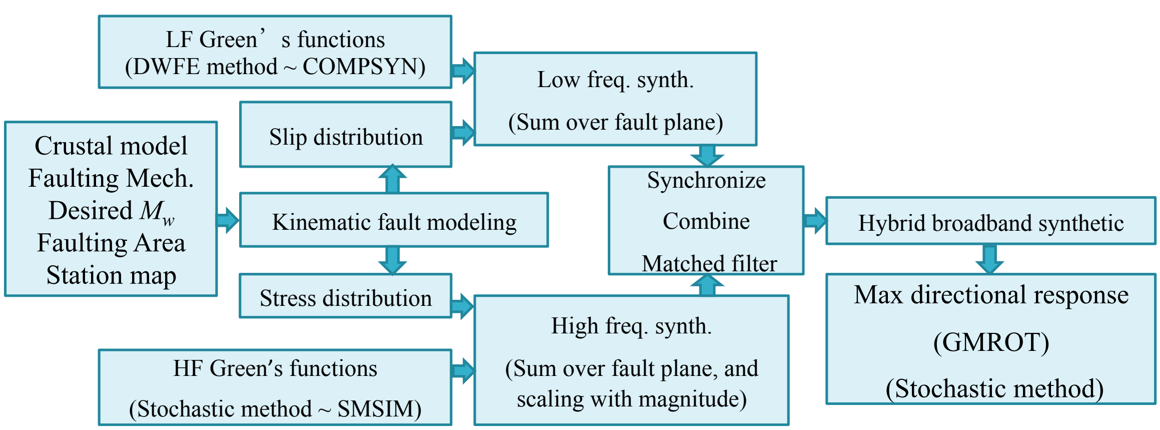
A. Shahjouei and S. Pezeshk

Summary of the Procedure

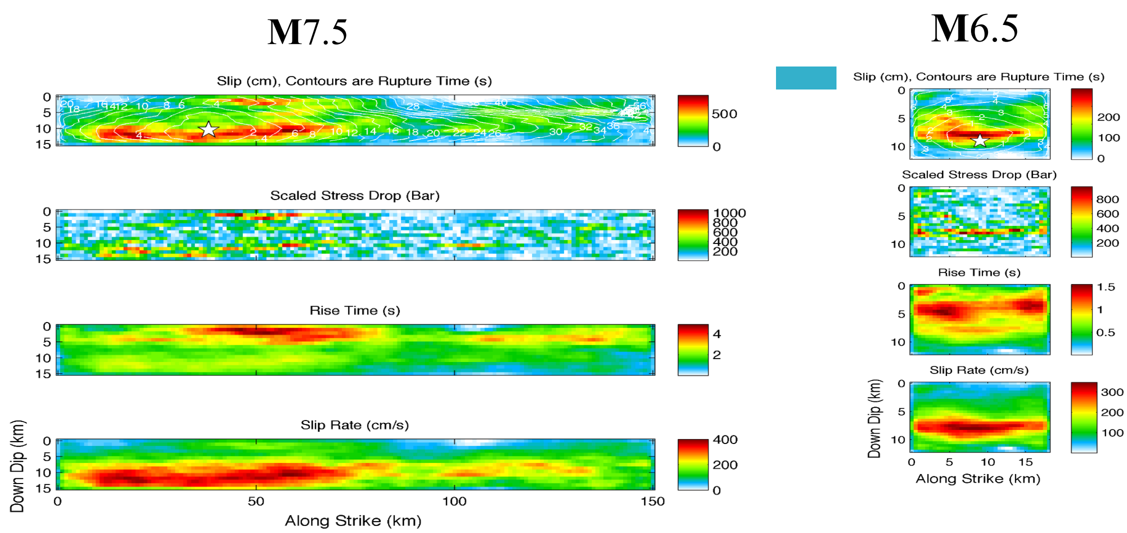
- We used HEM GMPEs for ENA using a HBB simulation technique
- HF synthetics using stochastic method are generated and combined with LF synthetics produced from kinematic source model and deterministic wave propagation.
- The most recent proposed seismological and geological parameters in the literature 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

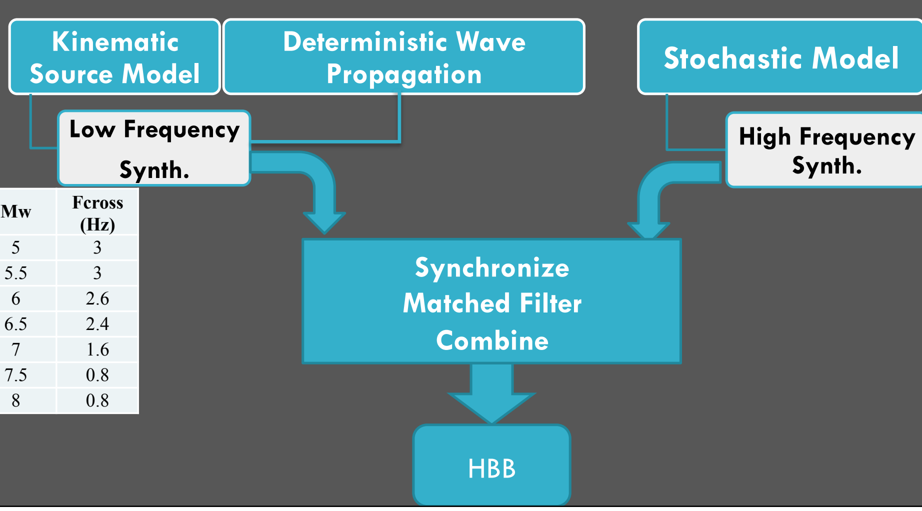


Samples for Kinematic Earthquake Source Models for CENA



Summary of Stochastic Simulation Technique:

- ✓ Hybrid Broadband (HBB) Synthetic Generation using Finite-Fault Modeling
- ✓ Applied Magnitude-dependent transition frequency:
  - ✓ following Frankel (2009) for **M**5.5, **M**6.5, and **M**7.5.
  - ✓ Interpolation values for between magnitudes

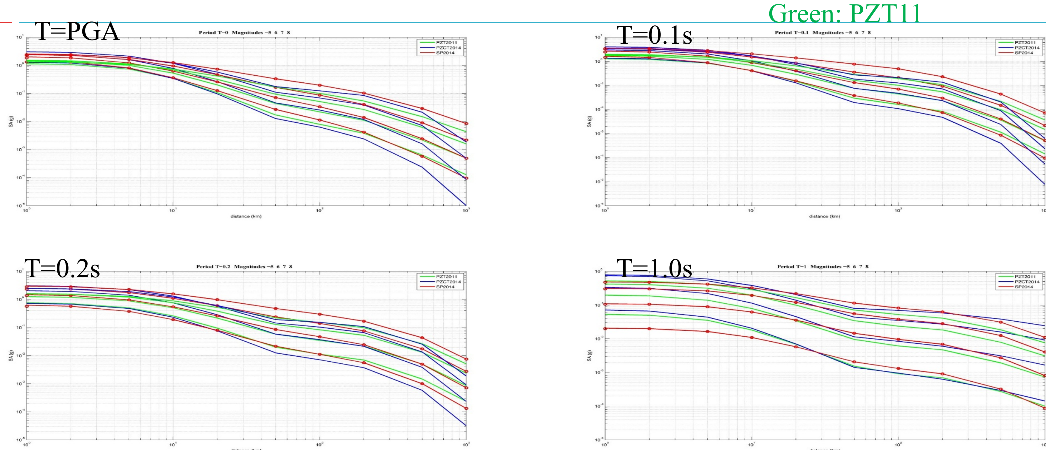


Mw	Fcross (Hz)
5	3
5.5	3
6	2.6
6.5	2.4
7	1.6
7.5	0.8
8	0.8

Compare with other GMPEs:

Plots for: **M**5, **M**6, **M**7, and **M**8

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

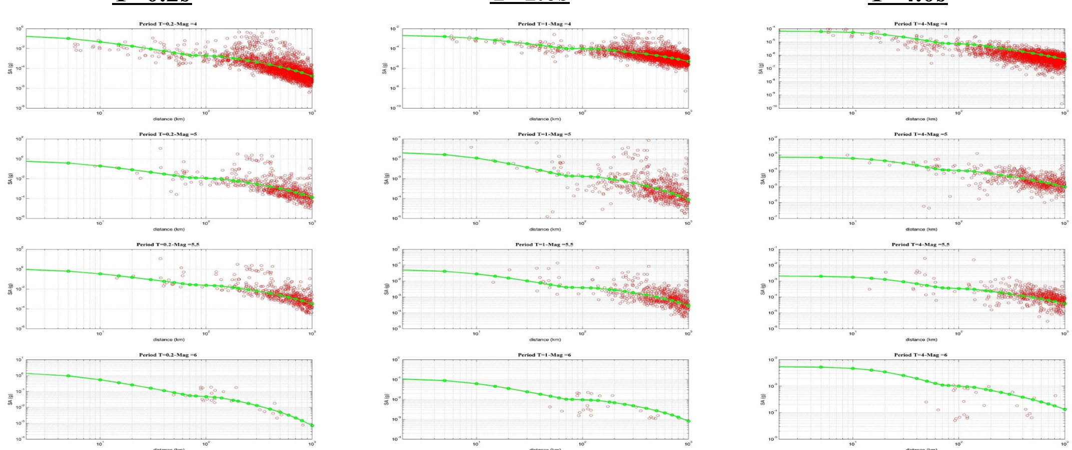


Compare with NGA-East Database:

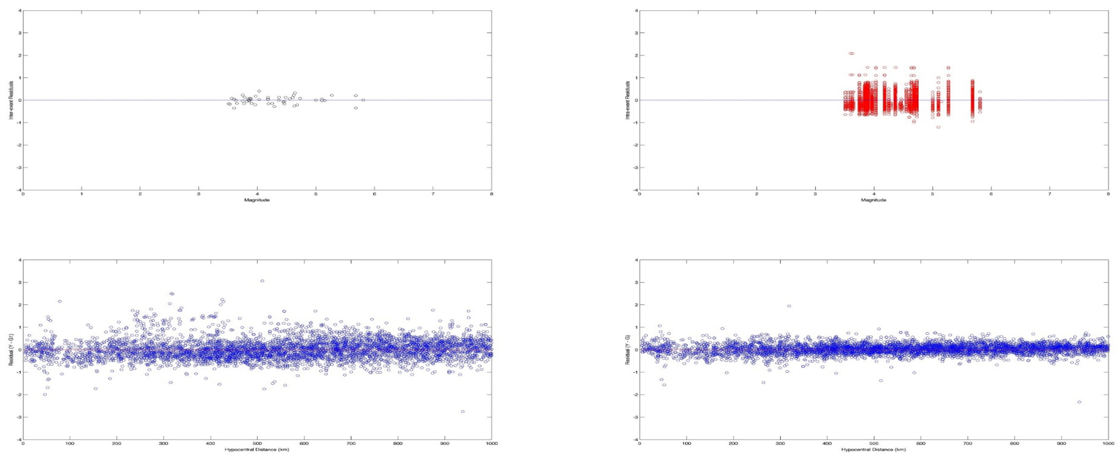
*** Corrected for Vs30=3km/s

T=0.2s **T=1.0s** **T=4.0s**

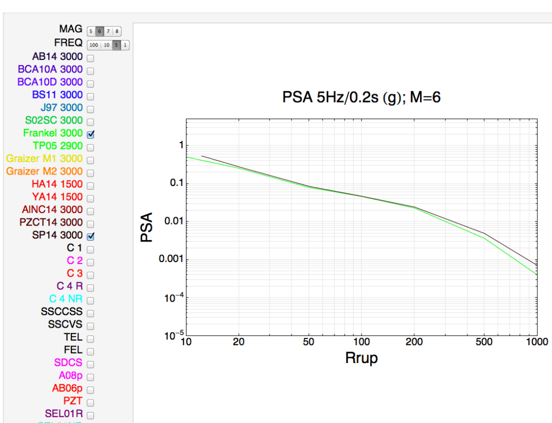
M=4
M=5
M=5.5
M=6

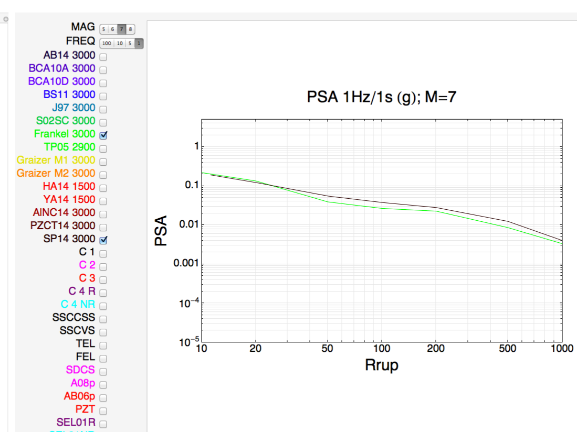


Residuals



Comparison with Frankel





ACKNOWLEDGMENTS

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Parameter	WNA	ENA
Source spectrum model	Single-corner-frequency ω^{-2}	Single-corner-frequency ω^{-2}
Stress parameter, $\Delta\sigma$ (bars)	80	250
Shear-wave velocity at source depth, β_s (km/s)	3.5	3.7
Density at source depth, ρ_s (gm/cc)	2.8	2.8
Geometric spreading, $Z(R)$	$\begin{cases} R^{-1.0}; R < 40\,km \\ R^{-0.5}; R \geq 40\,km \end{cases}$	$\begin{cases} R^{-1.3}; R < 70\,km \\ R^{+0.2}; 70 \leq R < 140\,km \\ R^{-0.5}; R \geq 140\,km \end{cases}$
Quality factor, Q	$180 f^{0.45}$	$\max(1000, 893 f^{0.32})$
Source duration, T_s (sec)	$1/f_a$	$1/f_a$
Path duration, T_p (sec)	$0.05R$	$\begin{cases} 0; & R \leq 10\,km \\ +0.16R; & 10 < R < 70\,km \\ -0.03R; & 70 < R \leq 130\,km \\ +0.04R; & R > 130\,km \end{cases}$
Site amplification, $A(f)$	Boore and Joyner (1997)	Atkinson and Boore (2006)
Kappa, κ_0 (sec)	0.04	0.005

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

Parameters	WNA	ENA
Source spectrum model	SCPS DCPS	SCPS DCPS
Stress drop (bars)	120–90 (SCPS) 90–60 (DCPS)	105 (0.05),[†] 125 (0.25), 150 (0.40), 180 (0.25), 215 (0.05)
Quality factor	$180f^{0.45}$	$400f^{0.40}$ (0.3),[†] $680f^{0.36}$ (0.4), $1000f^{0.30}$ (0.3)
Kappa	0.04	0.003 (0.3),[†] 0.006 (0.4), 0.012 (0.3)

*WNA, western North America; ENA, eastern North America; SCPS, single-corner point source; DCPS, double-corner point source.
[†]Weighting factors. After Campbell (2003).

Thank You