Ground Motion Simulation Using the Hybrid Empirical Method: Application, Insights and Issues

Kenneth W. Campbell
EQECAT Inc.
Beaverton, Oregon, USA

NGA-East SSHAC Workshop 2:
Proponent Discussions and Remaining Critical Issues and Data Needs
Berkeley, California, USA
October 11–13, 2011

The Hybrid Empirical Method (HEM)

- Alternative to Intensity, Stochastic and Theoretical based methods often used to derive GMPEs and engineering estimates of ground motion in regions of sparse strong-motion data
- Applied by adjusting empirical GMPEs from one region (Host) to use in another region (Target) which is typically located in a different tectonic environment
- Adjustments are made using stochastic simulation based on seismological models that take into account differences in source, propagation (path), and generic site characteristics between the Host and Target regions

History

- 1981: PGA model for ENA for DOE SEP Project
- 1982: PGA model for Utah for USGS microzonation
- 1987: PSA model for Utah for USGS regional hazard
- 1990: PSA model for Palo Verde NPP PSHA study
- 1994: PSA model for DOE Rocky Flats PSHA study
- 1994: PSA model for ENA for original SSHAC study
- 1997: PSA model for DOE Yucca Mtn. PSHA study
- 1998: PSA model for ENA for DOE TIP Project
- 2001: Formalized HEM with USGS research grant

History

- 2001: Applied to ENA by Atkinson
- 2001: Applied to ENA by Abrahamson and Silva
- 2002: 2001 ENA model used in USGS hazard maps
- 2002: 2001 ENA model used in EPRI CEUS Project
- 2003: Publication of method / ENA model in *BSSA*
- 2005: Applied to ENA by Tavakoli and Pezeshk
- 2005: Applied to U.S. Pacific Northwest by Atkinson
- 2005: Applied to Central Europe by Scherbaum et al.
- 2006: Applied to Norway and Spain by Douglas et al

History

- 2007: Updated ENA model using CB08 NGA GMPE
- 2008: ENA Reference Empirical model by Atkinson
- 2008: 2003 ENA model used in USGS hazard maps
- 2010: Hawaii Reference Empirical model by Atkinson
- 2011: ENA model from NGA GMPEs by Pezeshk et al
- 2011: Site adjustments for Europe by Van Houtte et al
- 2011: Site adjustments for PEGASOS refin. Project
- 2012: Being considered for South Africa PSHA project

General Methodology

- Select and evaluate empirical GMPEs for a uniform (preferably stiff) site condition for Host region
- Select seismological models for Host & Target regions
  - Earthquake source characteristics
  - Path and propagation characteristics
  - Local site characteristics
- Use seismological models and stochastic simulation to estimate adjustment factors between Host and Target regions
- Apply adjustment factors to Host region estimates
- Develop GMPE for Target region

Potential Strengths

- Relies on GMPEs that are empirically constrained by recordings at small distances and large magnitudes of greatest engineering interest
- Incorporates empirically based near-source magnitude and attenuation scaling characteristics
- Uses *relative differences* rather than absolute values of Stochastic ground motion estimates
- Provides explicit estimates of aleatory variability and epistemic uncertainty
- Simple and transparent
- Provides credible results compared to other methods

Potential Weaknesses

- Requires consistent and reliable seismological models for both Host and Target regions
- Assumes Stochastic simulation method is appropriate for estimating relative regional adjustment factors
- Assumes similar near-source ground motion behavior between Host and Target regions
- Has same limitations as empirical GMPEs
  - Limited or no near-source strong-motion recordings from very large earthquakes (improved in NGA models)
  - Typically valid only to distances of around 100 km (can be extrapolated using Stochastic model in Target region; somewhat improved in NGA models)

Example:
Application to Eastern North America
(Campbell 2001, 2003)

Models Used in Analysis

- Four equally weighted empirical GMPEs from WNA for estimating ground motion in Host region:
  - Abrahamson and Silva (1997)
  - Campbell (1997)
  - Sadigh and others (1997)
  - Campbell and Bozorgnia (2003)
- Seismological model for ENA:
  - Atkinson and Boore (1995)
- Seismological model for WNA:
  - Atkinson and Silva (1997, 2000)

Seismological Models

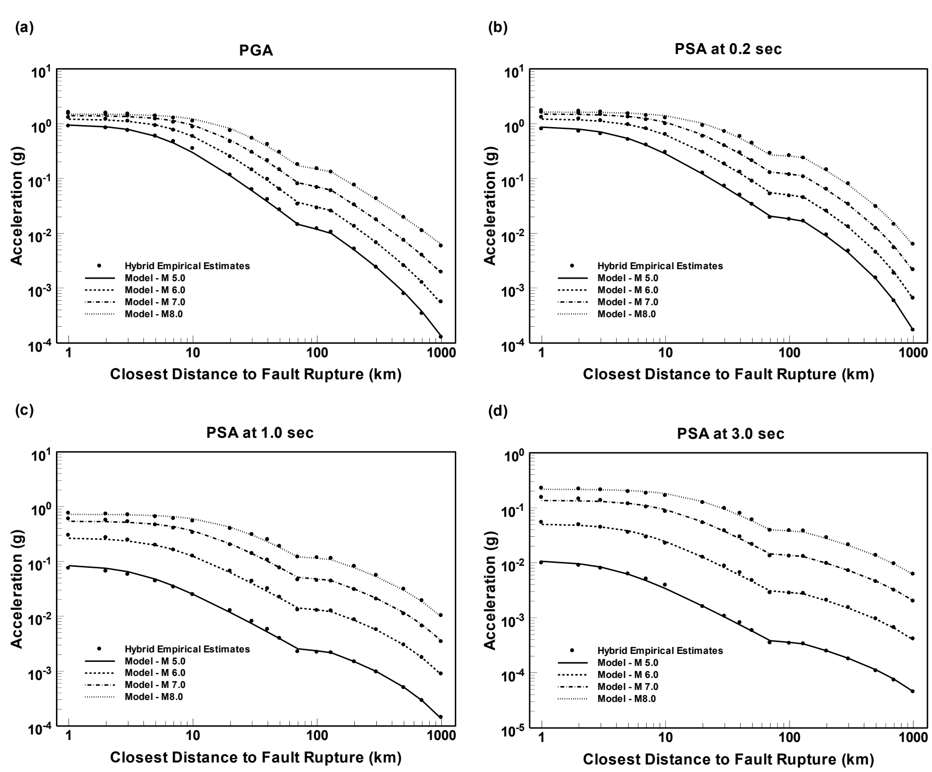
Seismological Parameter	Host Region–California	Target Region–ENA
Source spectrum	Brune ω^2 point source	Brune ω^2 point source
$\Delta\sigma$ (bars)	100	150 ($\sigma_{\ln \Delta\sigma} = 0.18$)
β (km/s), ρ (g/cc)	3.5, 2.8	3.8, 2.8
Geometric attenuation	R^{-1}; R < 40 km $R^{-0.5}$; R ≥ 40 km	R^{-1}; R < 70 km R^{0}; 70 ≤ R < 130 km $R^{-0.5}$; R ≥ 130 km
Crustal attenuation (Q)	$180\ f^{0.45}$	$400\ f^{0.4}$; $680\ f^{0.36}$; $1000\ f^{0.3}$
Source duration (sec)	$1/f_0$	$1/f_0$
Path duration (distance proportionality)	0.05 R	0; R < 10 km 0.16 R; 10 ≤ R < 70 km –0.03 R; 70 ≤ R < 130 km 0.04 R; R ≥ 130 km
Kappa (κ, sec)	0.04	0.003; 0.006; 0.012
Site amplification method	Joyner ¼–wavelength	Joyner ¼–wavelength
Local site profile	WNA rock (V_{30}=620 m/s)	ENA rock (V_{30}=2,800 m/s)

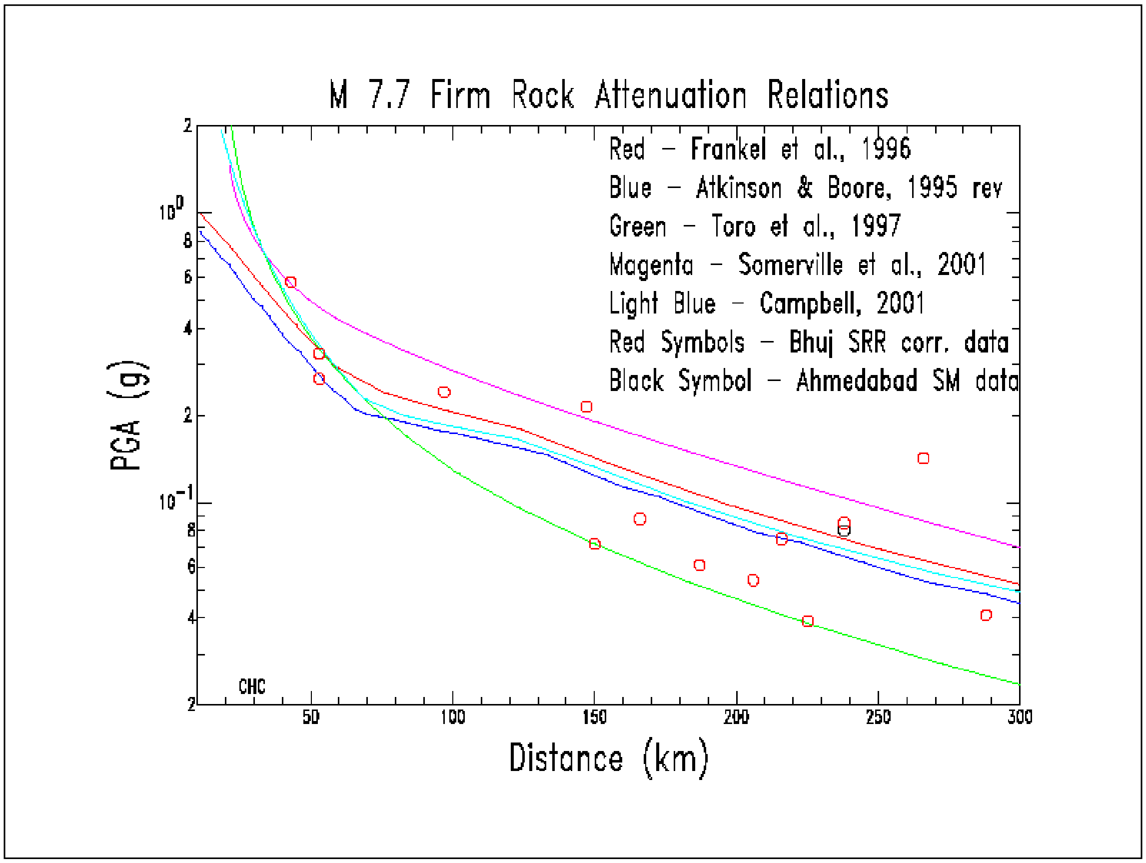
Site Amplification Models

Host Region–California			Target Region–ENA		
Freq. (Hz)	$\kappa = 0$ (sec)	$\kappa = 0.04$ (sec)	Freq. (Hz)	$\kappa = 0$ (sec)	$\kappa = 0.006$ (sec)
0.0	1.00	1.00	0.0	1.00	1.00
0.1	1.10	1.09	0.1	1.02	1.02
0.2	1.18	1.16	0.2	1.03	1.03
0.5	1.42	1.33	0.5	1.07	1.06
0.8	1.58	1.42	0.9	1.09	1.07
1.3	1.74	1.49	1.3	1.11	1.08
3.2	2.25	1.51	3.0	1.13	1.07
6.0	2.58	1.21	5.3	1.14	1.03
17.0	3.13	0.39	14.0	1.15	0.88
61.0	4.00	0.00	60.0	1.15	0.37
100.0	4.40	0.00	100.0	1.15	0.17

Adjustment Factors: M_W 6.5, R = 10 km

Period (sec)	Adjustment Factor				
	κ = 0.003	κ = 0.006			κ = 0.012
	Δσ = 150	Δσ = 105	Δσ = 150	Δσ = 215	Δσ = 150
PGA	3.0	1.7	2.3	3.0	1.6
0.02	7.7	3.8	5.0	6.7	2.5
0.05	4.1	2.6	3.5	4.6	2.4
0.10	1.9	1.3	1.8	2.3	1.5
0.20	1.2	0.89	1.2	1.6	1.1
0.50	1.0	0.77	1.0	1.3	0.96
1.0	1.0	0.78	0.99	1.3	0.98
2.0	0.98	0.80	0.98	1.2	0.97
4.0	0.92	0.81	0.92	1.0	0.92

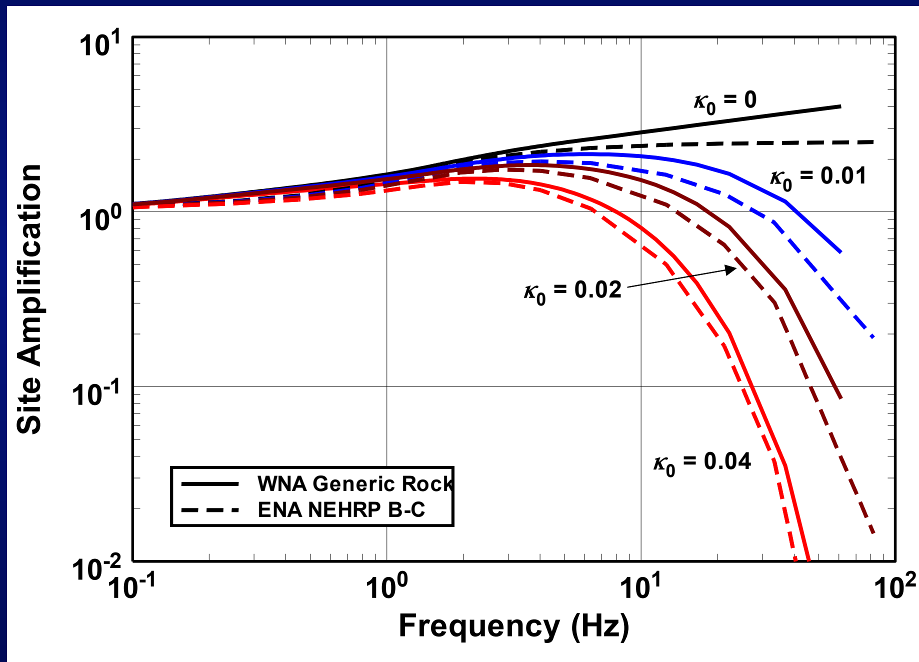




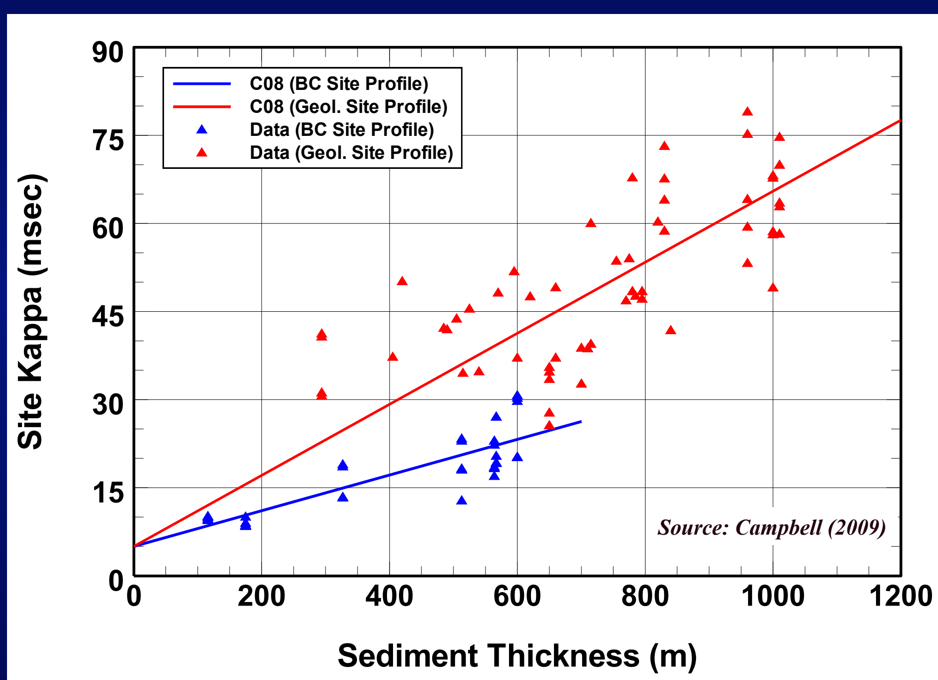
Some Issues and Insights

- Relative differences in Host and Target seismological models (need to use consistent models/methods)
  - Type of source (i.e., point vs. finite source)
  - Source spectral shape (i.e., one vs. two corner)
  - Stress drop (stress parameter) (constant vs. M dependent)
  - Near-source geometrical attenuation (i.e., R^{-1} vs. $R^{-1.3}$)
  - Mid-source geometrical attenuation (i.e., bi vs. trilinear)
  - Anelastic attenuation (i.e., constant vs. freq. dependent Q)
  - Crustal model and site kappa (i.e., depth, V_S gradient, Q)
- Small-magnitude scaling bias in empirical GMPEs
  - Magnitude scaling
  - Distance scaling

Impact of Kappa on FAS Site Amplification



Impact of Profile Depth on Kappa



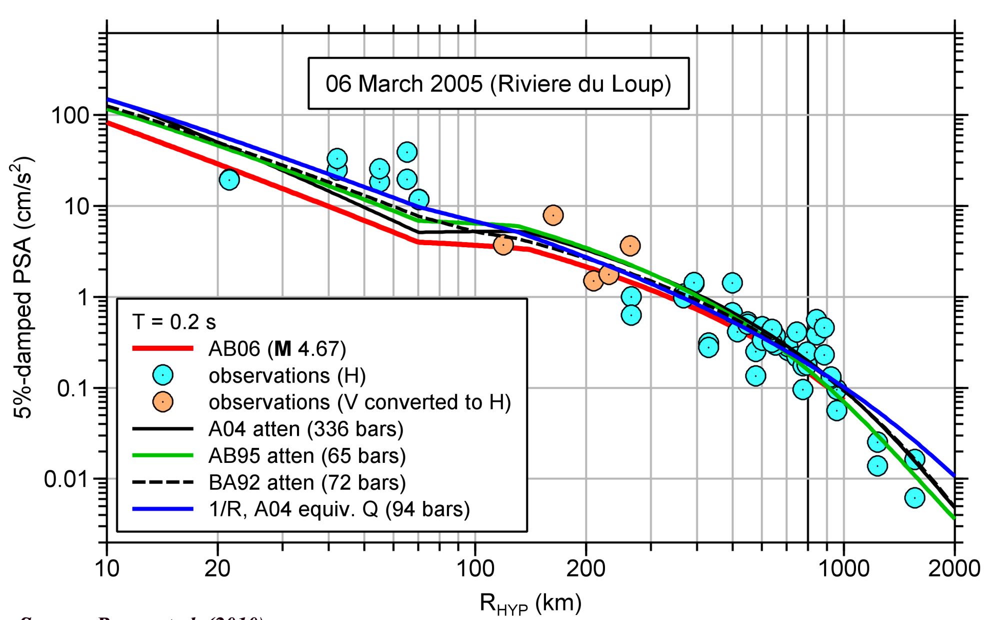
Impact of Kappa on PSA Site Amplification

Source	Profile Depth (m)	Short-Period Factor (0.1–0.5 sec)	Long-Period Factor (0.4–2.0 sec)
NEHRP (BSSC, 2004)[a]	—	1.37	1.63
USGS (Frankel *et al.*, 1996)[b]	175	1.53	1.34
This study (κ_0 = 0.01 sec)[a]	175	1.52 (1.38, 1.67)	1.38 (1.25, 1.52)
This study (κ_0 = 0.02 sec)[a]	175	1.32 (1.20, 1.45)	1.32 (1.20, 1.45)
This study (κ_0 = 0.01 sec)[b]	175	1.53 (1.39, 1.68)	1.33 (1.21, 1.46)
This study (κ_0 = 0.02 sec)[b]	175	1.32 (1.20, 1.45)	1.38 (1.25, 1.52)

[a] Based on range of periods
[b] Based on single period of 0.2 sec (short period) and 1.0 sec (long period)

Source: Campbell (2009)

Impact of ENA Geometrical Attenuation



Source: Boore et al. (2010)

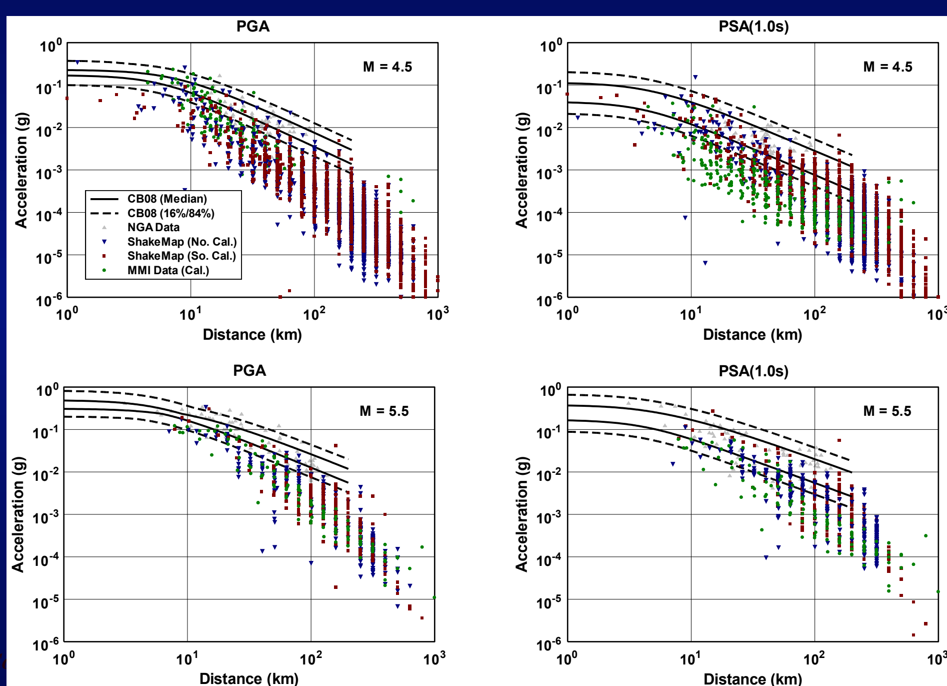
Impact of ENA Attenuation on Stress Drop

Attenuation Model	Stress Drop (Without Saguenay)			Stress Drop (With Saguenay)		
	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range
A04	172	0.19	107–336	235	0.41	107–2161
AB95	42	0.18	23–78	57	0.39	23–467
BA92	44	0.18	23–81	60	0.41	23–603
1/R	61	0.16	38–108	82	0.38	38–650

Source: Boore et al. (2010)

Source: Boore et al. (2010)

Impact of WNA GMPE Small Magnitude Bias



Conclusions

- Hybrid Empirical Method is a viable and credible alternative to Stochastic and Theoretical Methods
- Hybrid Empirical simulation methodology is sensitive to the following models and parameters:
  - Form and scaling characteristics of Host empirical GMPEs
  - Seismological source characterization (e.g., stress drop)
  - Seismological path and propagation characterization (e.g., geometrical and anelastic attenuation)
  - Seismological site characterization (e.g., velocity profile, depth of sediments, site attenuation (i.e., kappa))
- A calibrated seismological model depends on the inter-dependence of all models and parameters:
  - Changing one or two parameters can invalidate the method
  - Correlation between parameters must be taken into account