Update of Hybrid Empirical Ground Motion Model for CEUS/ENA: *A Progress Report*

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The Hybrid Empirical Method (HEM)

- Alternative to Intensity, Stochastic and Theoretical Methods commonly used to derive ground motion relations and engineering estimates of ground motion in regions of sparse strong-motion data
- Applied by adjusting empirical ground motion relations from one region (Host) to represent ground motion characteristics in another region (Target)
- Adjustments are made using seismological models that take into account differences in source, propagation, and site characteristics between the Host and Target regions

History of Hybrid Empirical Method

- 1981: PGA model for CEUS for NRC SEP Project
- 1982: PGA model for Utah for Zonation Conference
- 1987: SA model for Utah for USGS regional study
- 1990: SA model for Palo Verde NPP PSHA study
- 1994: SA model for DOE Rocky Flats PSHA study
- 1994: SA model for CEUS for SSHAC study
- 1997: SA model for DOE Yucca Mtn. PSHA study

History of Hybrid Empirical Method

- 1998: SA model for CEUS for DOE TIP Project
- 2001: Applied to ENA by Atkinson, Abrahamson-Silva
- 2001: SA model for ENA for USGS research grant
- 2002: ENA model used in USGS hazard maps
- 2002: ENA model used in EPRI CEUS Project
- 2003: Publication of method and ENA model in *BSSA*
- 2006: Applied to Norway and Spain by Douglas et al.

General Methodology

- Select empirical ground motion relations for uniform “rock” site condition from suitable Host region
- Select seismological models for Host/Target regions
  - Earthquake source characteristics
  - Crustal structure and attenuation characteristics
  - Local site characteristics
- Use seismological models to estimate ground motion adjustment factors between Host and Target regions
- Apply adjustment factors to empirical ground motion estimates from Host region
- Develop ground motion relations for Target region

Aleatory and Epistemic Uncertainty

- HEM provides means of estimating both aleatory (random) and epistemic (modeling) uncertainty
- Aleatory uncertainty in median ground motion
  - Mean of $\sigma_{\ln y}$ from empirical relations
  - Additional uncertainty (parametric, limited data, regional)
- Epistemic uncertainty in median ground motion
  - $(\sigma_{\mu}^2 + \sigma_F^2)^{1/2}$
  - μ is mean of ln y (median of y) from empirical relations
  - F is median adjustment factor
- Epistemic uncertainty in aleatory standard deviation
  - Standard deviation of $\sigma_{\ln y}$ from empirical relations ($\sigma_{\sigma_{\ln y}}$)
  - Additional uncertainty (parametric, limited relations)

Strengths in Hybrid Empirical Method

- Relies on ground motion relations that are 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* in Stochastic or Theoretical ground-motion estimates rather than absolute values
- Provides explicit estimates of aleatory variability and epistemic uncertainty

Weaknesses in Hybrid Empirical Method

- Requires consistent and reliable seismological models for both Host and Target regions
- Assumes similar near-source ground motion behavior between Host and Target regions
- Has same limitations as empirical ground motion relations from Host region
  - 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)

Application to Eastern North America

- Current application uses four equally weighted empirical ground motion models from WNA for making predictions in Host region:
  - Abrahamson and Silva (1997)
  - Campbell (1997)
  - Sadigh and others (1997)
  - Campbell and Bozorgnia (2003)

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 $R^{-0.5}$; $R \geq 40$ km	R^{-1}; $R < 70$ km R^{0}; $70 \leq R < 130$ km $R^{-0.5}$; $R \geq 130$ 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; $10 \leq R < 70$ km –0.03 R; $70 \leq R < 130$ km 0.04 R; $R \geq 130$ 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**				
	$\kappa = 0.003$ $\Delta\sigma = 150$	**$\kappa = 0.006$**			**$\kappa = 0.012$ $\Delta\sigma = 150$**
		$\Delta\sigma = 105$	**$\Delta\sigma = 150$**	**$\Delta\sigma = 215$**	
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

ENA Median Ground Motion Relation

$$\ln Y = c_1 + f_1(M_w) + f_2(M_w, r_{rup}) + f_3(r_{rup})$$

$$f_1(M_w) = c_2 M_w + c_3 (8.5 - M_w)^2$$

$$f_2(M_w, r_{rup}) = c_4 \ln R + (c_5 + c_6 M_w) r_{rup}$$

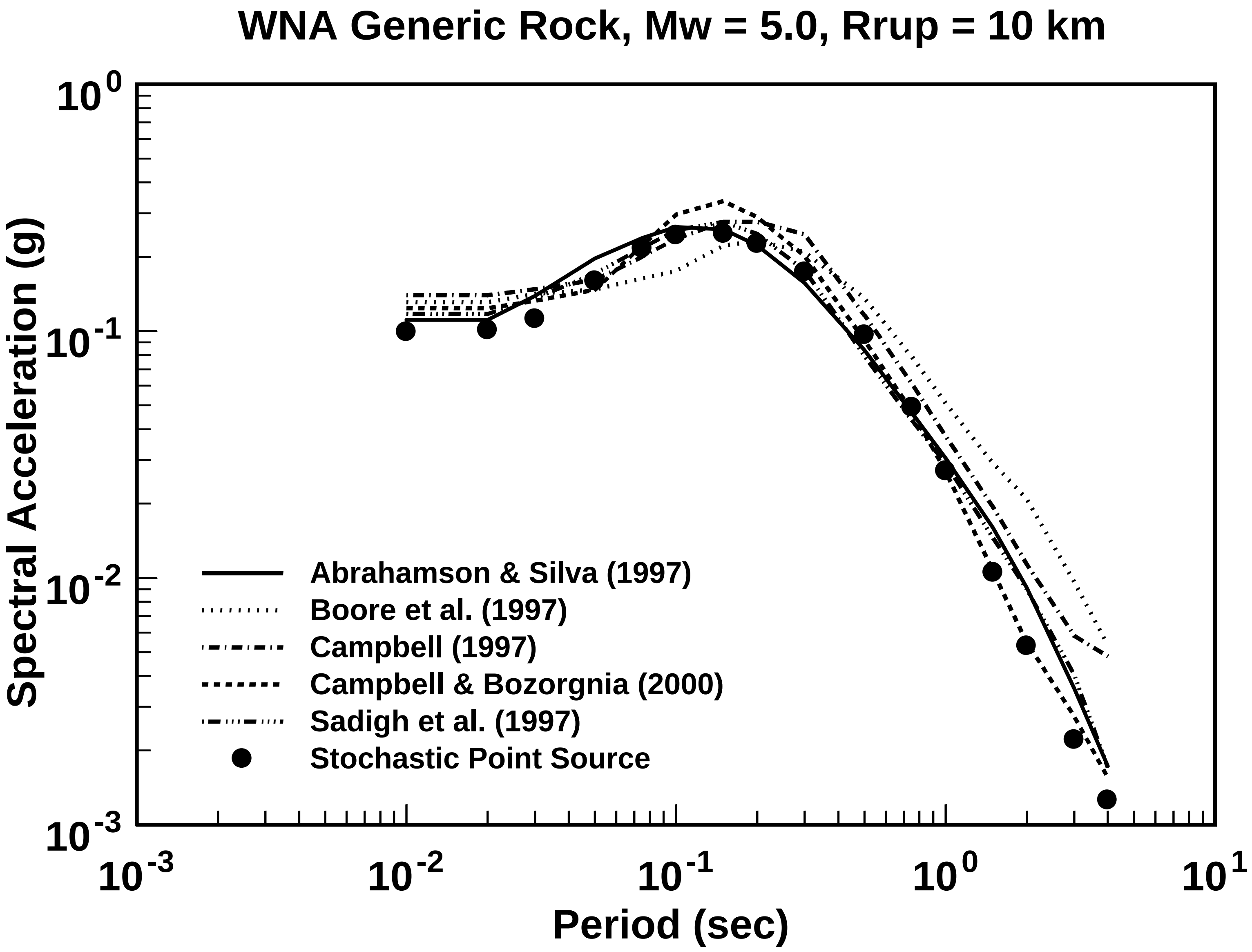
$$R = \sqrt{r_{rup}^2 + [c_7 \exp(c_8 M_w)]^2}$$

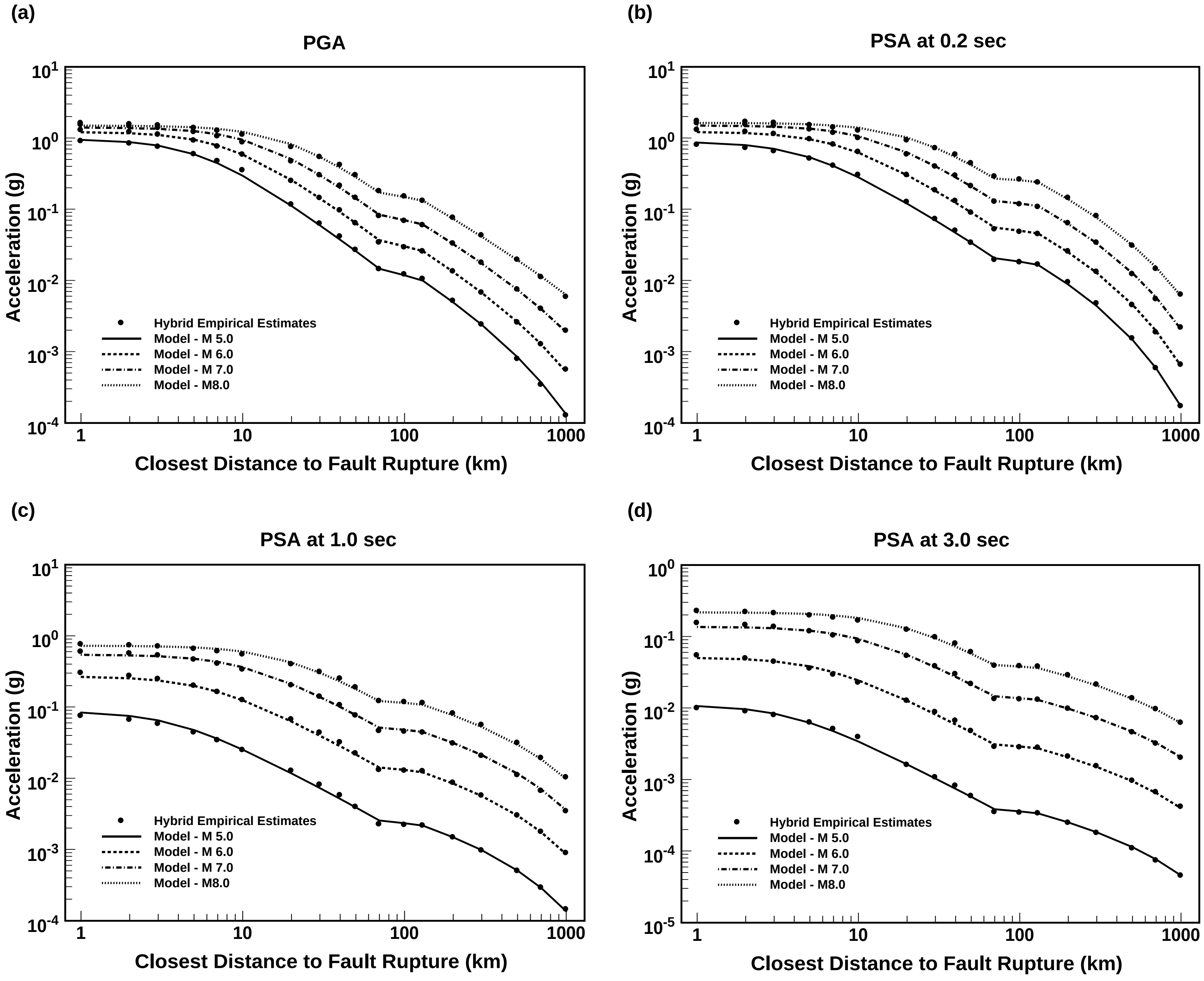
$$f_3(r_{rup}) = \begin{cases} 0 \; ; & r_{rup} \le r_1 \\ c_9 (\ln r_{rup} - \ln r_1) \; ; & r_1 < r_{rup} \le r_2 \\ c_9 (\ln r_{rup} - \ln r_1) + c_{10} (\ln r_{rup} - \ln r_2) \; ; & r_{rup} > r_2 \end{cases}$$

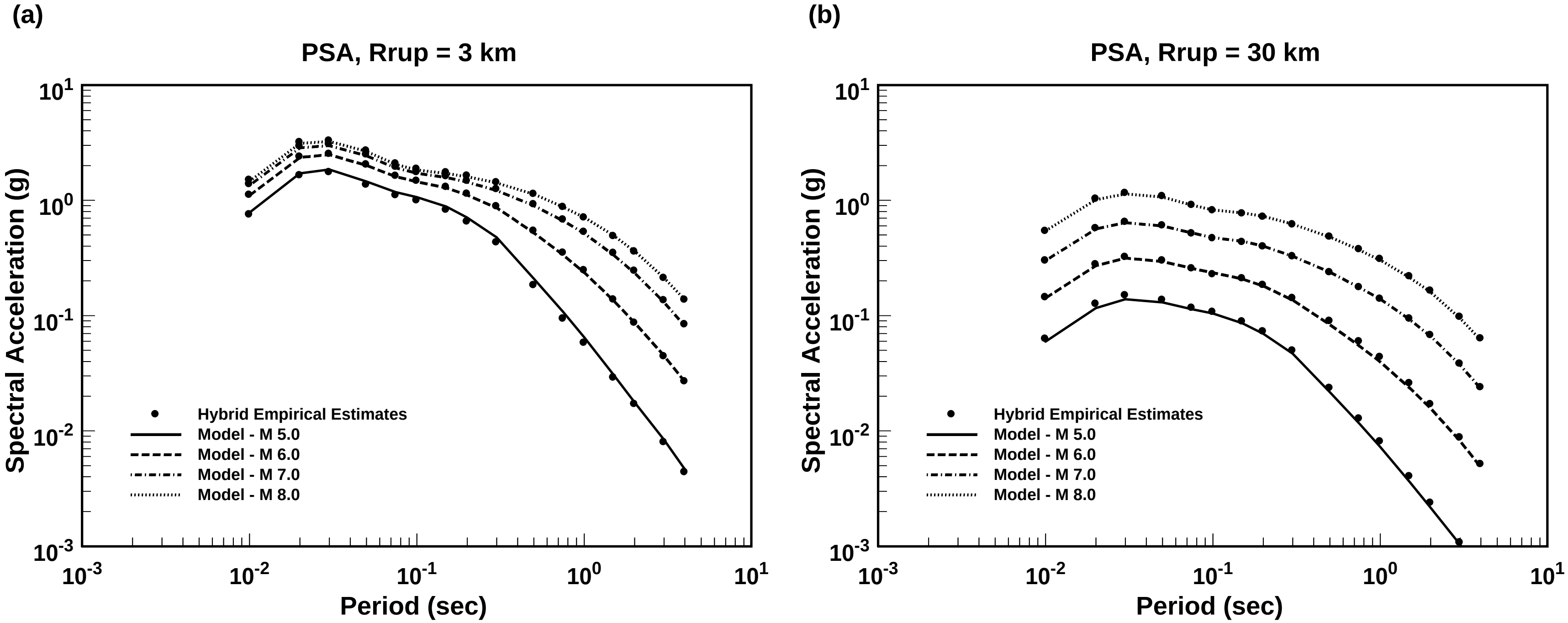
$$r_1 = 70 \text{ km}; \quad r_2 = 130 \text{ k}$$

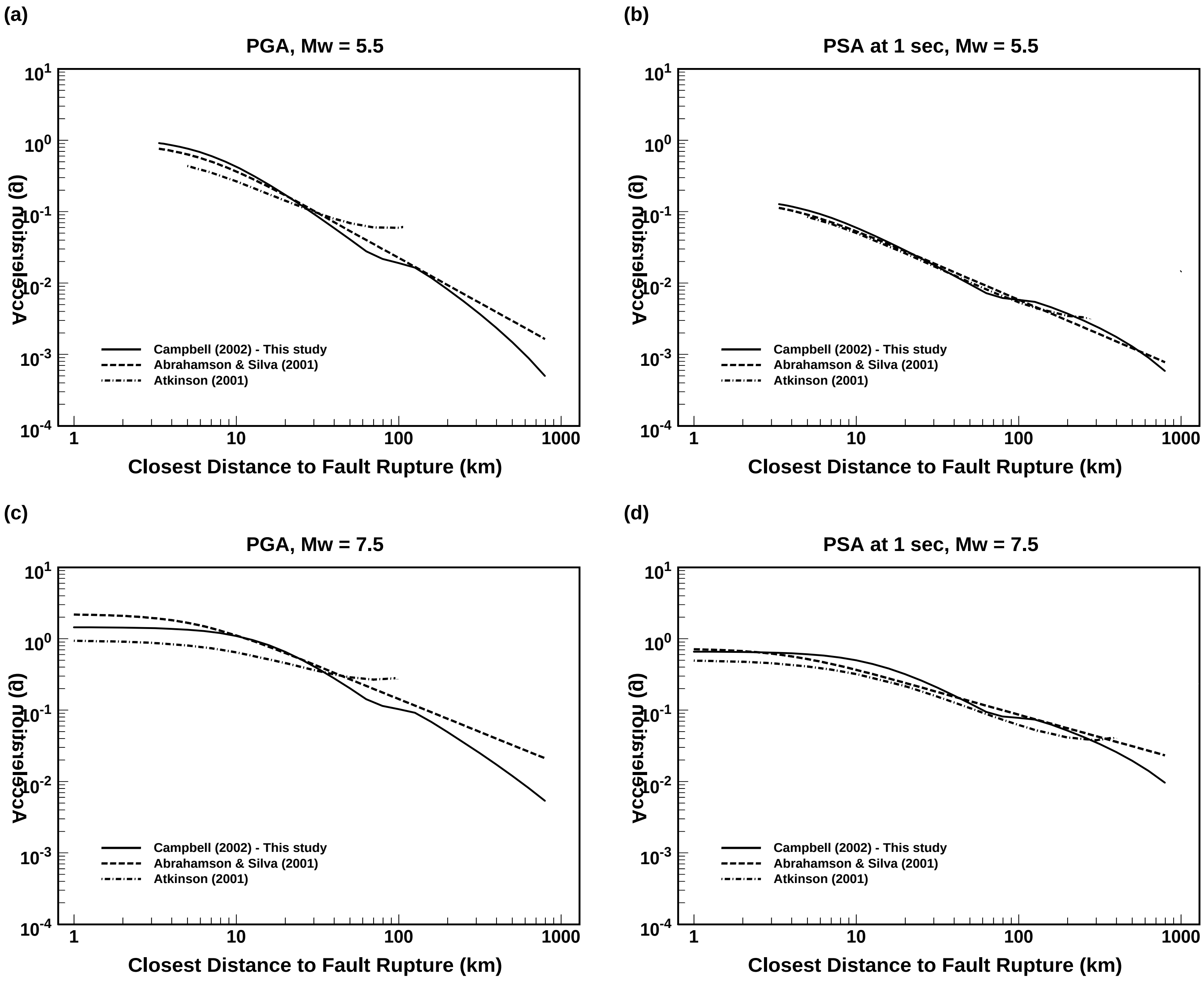
ENA Aleatory Uncertainty Relation

$$\sigma_{\ln Y} = \begin{cases} c_{11} + c_{12}(M_w) & M_w < 7.1 \\ c_{13} & M_w \geq 7.1 \end{cases}$$

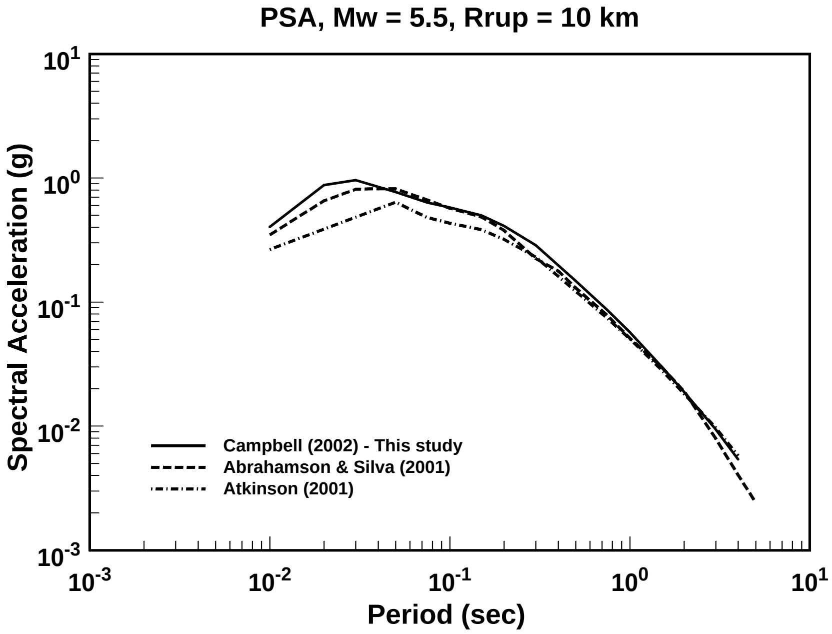

WNA Generic Rock, Mw = 5.0, Rrup = 10 km
Spectral Acceleration (g)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
Period (sec)
Abrahamson & Silva (1997)
Boore et al. (1997)
Campbell (1997)
Campbell & Bozorgnia (2000)
Sadigh et al. (1997)
Stochastic Point Source


(a)
PGA
(b)
PSA at 0.2 sec
(c)
PSA at 1.0 sec
(d)
PSA at 3.0 sec
Acceleration (g)
Closest Distance to Fault Rupture (km)
1
10
100
1000
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Hybrid Empirical Estimates
Model - M 5.0
Model - M 6.0
Model - M 7.0
Model - M8.0


(a)
PSA, Rrup = 3 km
(b)
PSA, Rrup = 30 km
Spectral Acceleration (g)
Period (sec)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
Hybrid Empirical Estimates
Model - M 5.0
Model - M 6.0
Model - M 7.0
Model - M 8.0

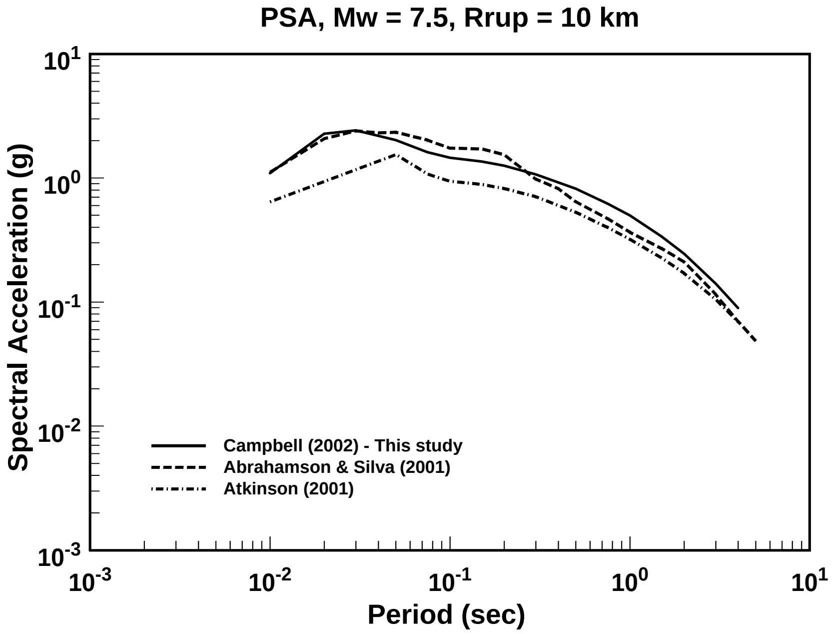

(a)
PGA, Mw = 5.5
(b)
PSA at 1 sec, Mw = 5.5
(c)
PGA, Mw = 7.5
(d)
PSA at 1 sec, Mw = 7.5
Acceleration (g)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
100
1000
Closest Distance to Fault Rupture (km)
Campbell (2002) - This study
Abrahamson & Silva (2001)
Atkinson (2001)

(a)

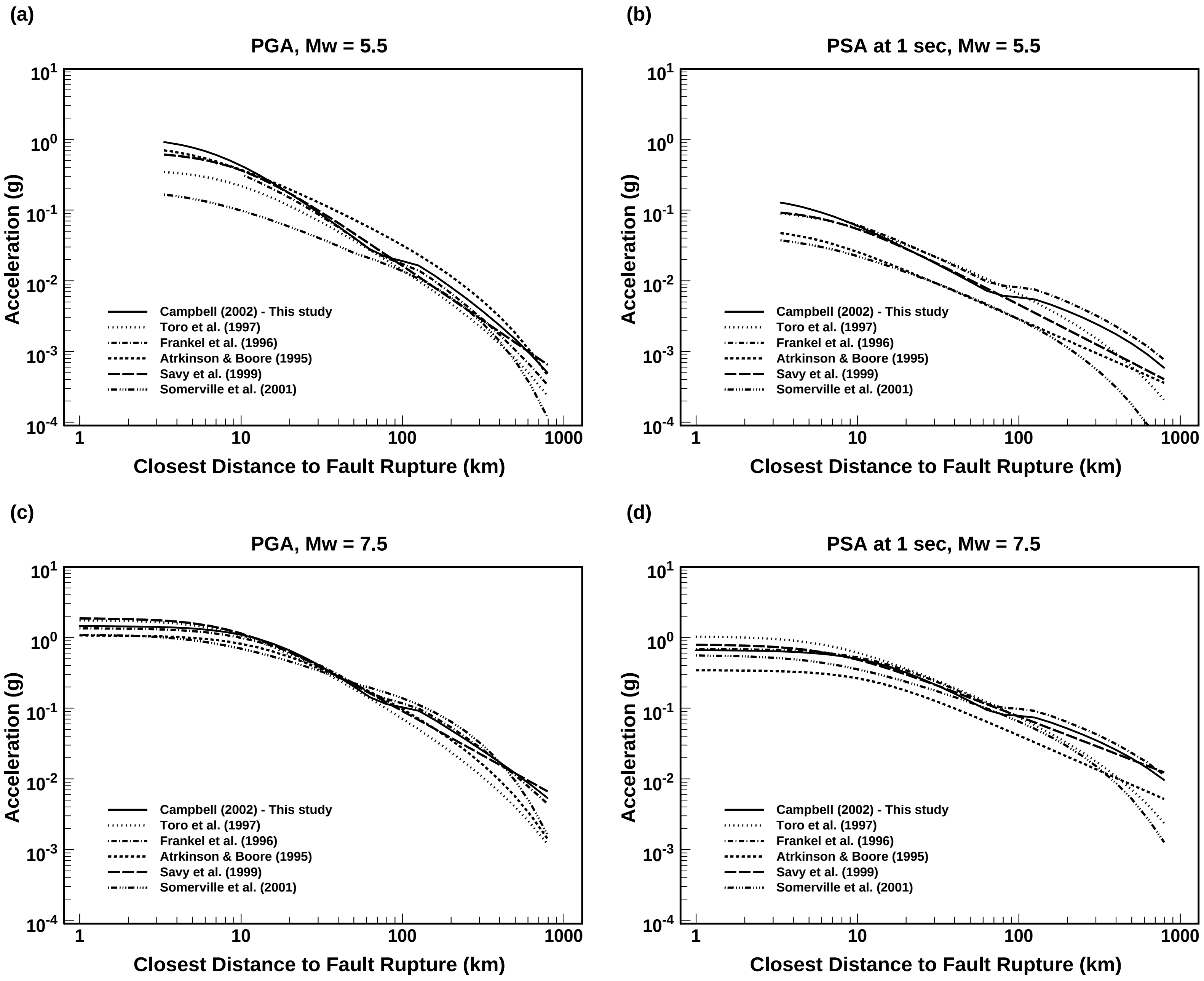


PSA, Mw = 5.5, Rrup = 10 km

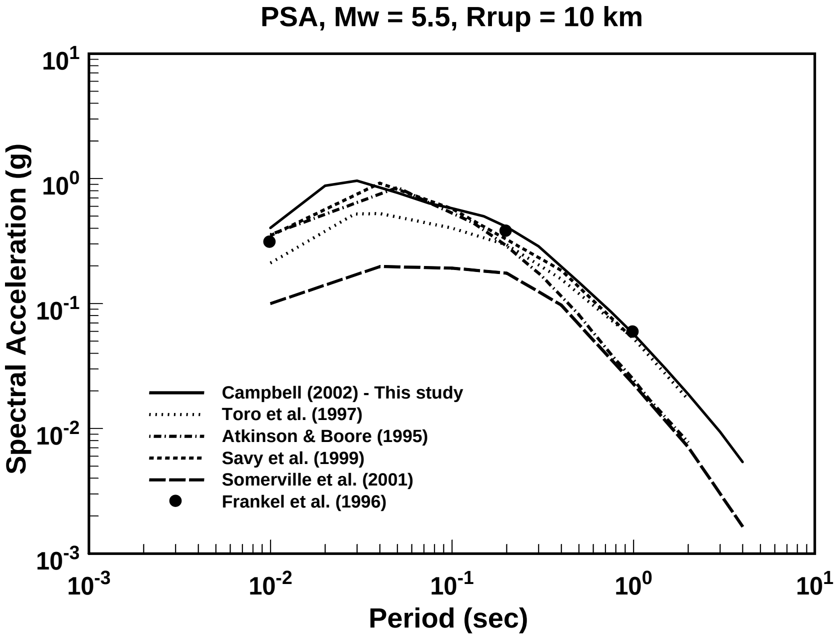
(b)



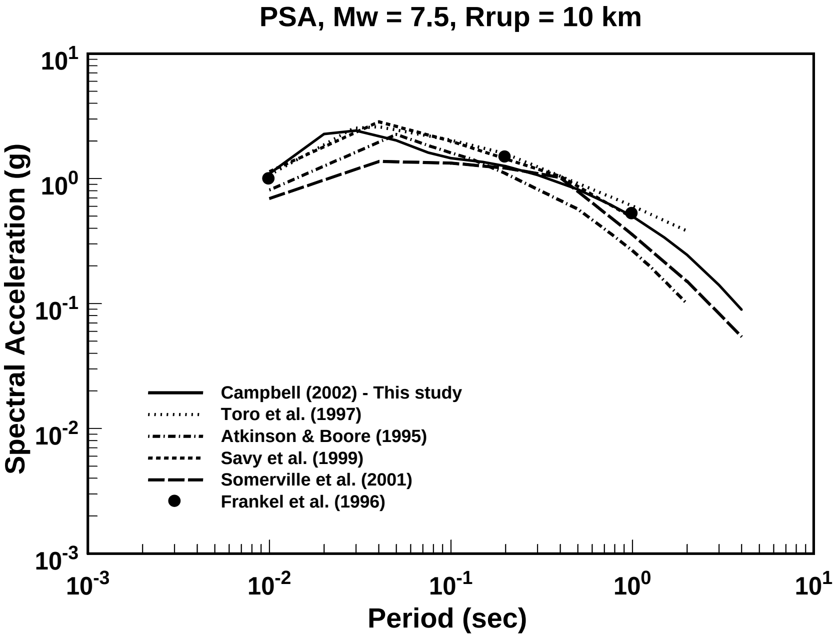
PSA, Mw = 7.5, Rrup = 10 km


(a)
PGA, Mw = 5.5
(b)
PSA at 1 sec, Mw = 5.5
(c)
PGA, Mw = 7.5
(d)
PSA at 1 sec, Mw = 7.5
Acceleration (g)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
100
1000
Closest Distance to Fault Rupture (km)
Campbell (2002) - This study
Toro et al. (1997)
Frankel et al. (1996)
Atrkinson & Boore (1995)
Savy et al. (1999)
Somerville et al. (2001)

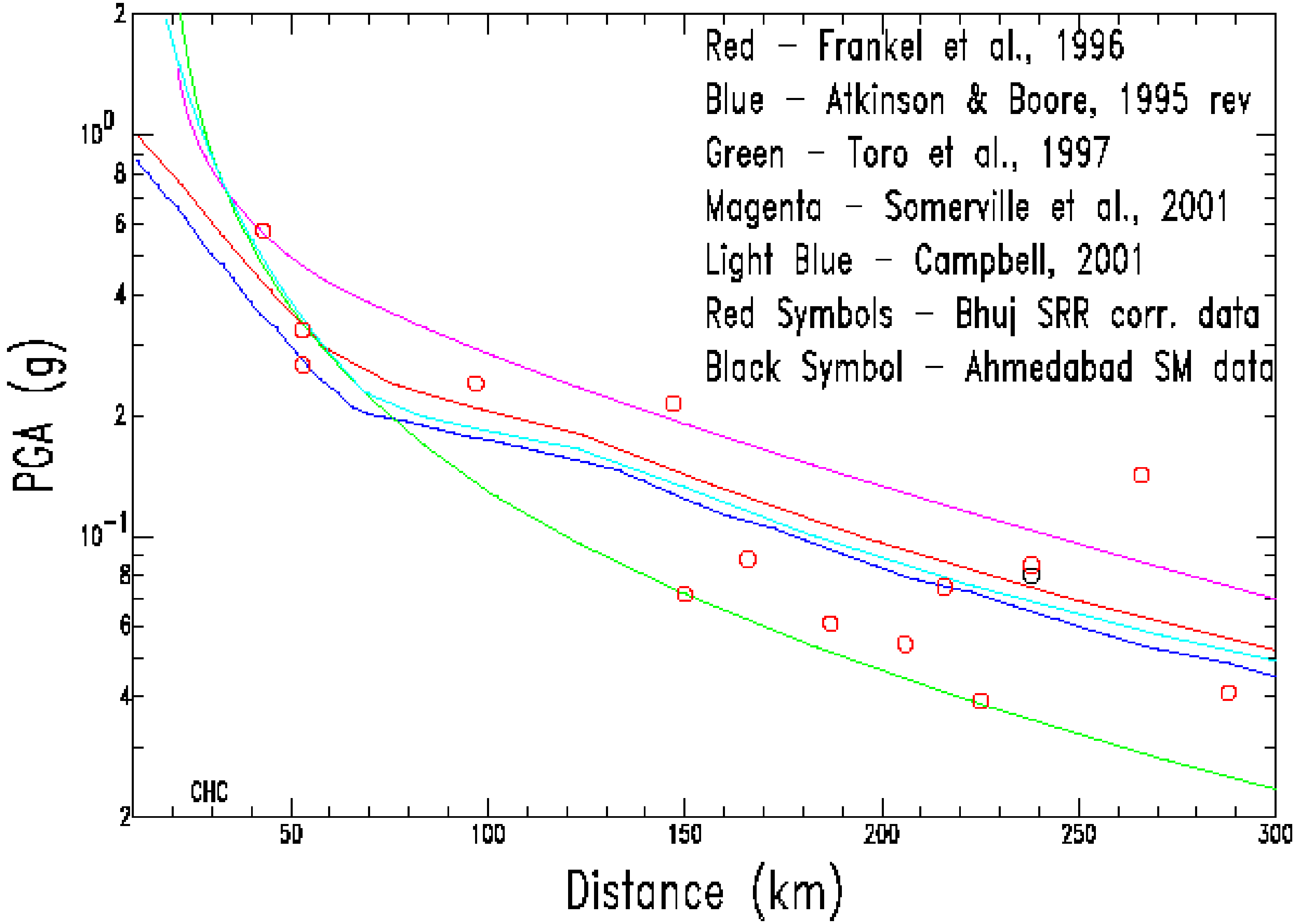
(a)


PSA, Mw = 5.5, Rrup = 10 km
Spectral Acceleration (g)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
Period (sec)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Campbell (2002) - This study
Toro et al. (1997)
Atkinson & Boore (1995)
Savy et al. (1999)
Somerville et al. (2001)
Frankel et al. (1996)

(b)


PSA, Mw = 7.5, Rrup = 10 km
Spectral Acceleration (g)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
Period (sec)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Campbell (2002) - This study
Toro et al. (1997)
Atkinson & Boore (1995)
Savy et al. (1999)
Somerville et al. (2001)
Frankel et al. (1996)

M 7.7 Firm Rock Attenuation Relations



Limitations in Hybrid Empirical Relation

- Inherits weaknesses of Hybrid Empirical Method
- Assumes same (Brune) source spectrum in both Host and Target regions, whereas there could be non-systematic differences between regions
- Assumes same geometric attenuation at all magnitudes, whereas it is constrained only for small earthquakes (i.e., point sources)
- Reviews have suggested the use of a different set of empirical ground motion relations
- Assumes no epistemic uncertainty in Stochastic ground motion estimates in Host region

Advantages in Hybrid Empirical Relation

- Inherits strengths of Hybrid Empirical Method
- Provides a third independent method for estimating ground motion in ENA
- Contributes to a more robust estimate of epistemic uncertainty
- Uses a fault-distance measure rather than a point-source distance measure
- Specifically designed to provide estimates of near-source ground motion from large earthquakes

General Conclusions

- Hybrid Empirical Method (HEM) is a viable alternative to Stochastic, Theoretical and Intensity Methods for estimating ground motion in regions of sparse strong-motion data, such as ENA and Australia
- Example application of HEM to ENA gives reasonable near-source ground motion amplitudes without requiring the somewhat arbitrary adjustments to hypocentral depth required for point-source models
- Additional studies are needed to test sensitivity of HEM to assumptions used in ENA relation
- Limitations notwithstanding, the HEM ground motion relation is a valuable alternative to existing ENA ground motion relations

Proposed Revisions for 2005–2006 NEHRP

- Update empirical ground motion models for WNA
  - Same models used for NSHMP update
  - Next Generation Attenuation (NGA) models
  - 2002 models, if continued to be used by USGS
  - Two models kept separate to facilitate USGS weighting
- Update seismological models for WNA
  - Frank Scherbaum has agreed to apply his method published in April 2006 BSSA titled *The Estimation of Minimum-Misfit Stochastic Models from Empirical Ground-Motion Prediction Equations* to identify seismological models that are consistent with the NGA empirical models
  - Other models that might become available

Proposed Revisions for 2005–2006 NEHRP

- Update seismological models for ENA
  - Use revised geometrical and anelastic attenuation parameters developed by Atkinson (2004)
  - Use revised Brune stress parameter and site factors developed by Atkinson & Boore (submitted, 2006)
- Two vs. one-corner source spectra for WNA and ENA
  - Two-corner source spectra are used to mimic finite-faulting effects of large earthquakes (Atkinson & Silva, 2000; Atkinson & Boore, 2006)
  - If use of seismological models is restricted to small earthquakes, one-corner source spectra will be adequate for calculating ENA/WNA adjustment factors
  - WNA empirical ground motion models will be used to add finite-faulting effects to the ENA hybrid empirical model

Proposed Revisions for 2005–2006 NEHRP

- Validate using weak and strong ground-motion recordings from ENA
  - Use updated ENA ground-motion database of Atkinson & Boore (2006) to validate and/or calibrate ENA hybrid empirical model in magnitude range of $M_w \geq 4.0$
- Develop epistemic uncertainty model
  - Previous model gave a table of representative values of epistemic standard deviations
  - New model will use more robust estimates of epistemic uncertainty to develop a model for epistemic standard deviations

Expected Impact of Revisions

- Use of NGA (2006) empirical ground motion models
  - Reduce short-period ground-motion predictions for $M_w > 6.5–7.0$ due to more widespread modeling of magnitude saturation effects
  - Reduce ground-motion predictions at all periods due to elimination of bias in definition of reference soil (NGA models use V_{S30} to model shallow site conditions)
  - Increase probabilistic estimates of ground-motion predictions at large magnitudes due to larger aleatory uncertainty
  - Reduce probabilistic estimates of ground-motion predictions at small magnitudes due to smaller aleatory uncertainty
  - Increase probabilistic estimates of ground-motion predictions due to use of more robust epistemic uncertainty (depends on whether such uncertainty is propagated through the analysis)

Expected Impact of Revisions

- Use of Scherbaum (2006) seismological parameters for WNA
  - Unknown (awaiting availability of NGA models)
- Use of Atkinson (2004) and Atkinson & Boore (2006) seismological parameters for ENA
  - Reduce short-period ground-motion predictions due to larger kappa (site attenuation)
  - Reduce short-period ground-motion predictions due to greater near-source geometric attenuation
  - Reduce short-period ground-motion predictions due to smaller Brune stress parameter
  - Increase ground-motion predictions at all periods due to larger site amplification factors