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CENTER FOR GEOTECHNICAL PRACTICE AND RESEARCH

Ground Motion Predictive (Attenuation) Equations

by

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1 INTRODUCTION

The objective of this report is to provide a single resource for recent ground motion prediction equations (GMPEs) for various tectonic settings and/or regions of the world. Included herein are GMPEs for peak and spectral ground motion values for: (chapter 2) shallow active tectonic regimes; (3) shallow stable continental tectonic regimes; (4) subduction zones; and (5) specific geographical regions of the world. At the beginning of each of these sections, tables are provided showing a summary of the input and output parameters used in each model and a figure graphically describing the fault geometry parameters used. Also included in this report are relationships for Arias intensity, strong ground motion duration, equivalent number of stress and strain cycles, characteristic periods, and response spectra damping correction factors. The GMPEs in this report are presented using consistent format (e.g., consistent units and symbols), and thus they may differ slightly in form from the equations as originally published.

For each GMPE, citations of the original publications in which the GMPE appeared, as well as any additional relevant sources, are listed first. Then, a brief abstract describes the applicability and limitations of the GMPE. Next, the input parameters needed for the model are listed, followed by the model itself and tables containing the regression coefficients. Calibration plots are provided so that the user can verify codes of the GMPEs. If available, plots are shown of the magnitude and site-to-source distances of the ground motion database used to develop the model. Finally, MATLAB scripts are provided for each GMPE. The scripts can be copy-pasted directly into an .m file with the same name as the function given in the code (e.g., use "AS_1997.m" for GMPE 2.1). Also, Microsoft Excel spreadsheets are provided for each GMPE. Both the MATLAB scripts and the Excel spreadsheets are written in consistent format for all models to facilitate their use.

The authors spent significant effort verifying the GMPE MATLAB scripts and Excel spreadsheets that are in this report. (Note, the authors are using the word "verify" to mean that the models are coded/implemented as intended by the developer. This is in contrast to "validating" the models, which means that the models actually yield valid ground motion predictions; validation of the models is left to the developers and/or users.) Towards the verification end, the authors attempted to replicate every plot in the papers/reports in which the GMPEs were proposed. If discrepancies were found, which was quite often, the authors first scrutinized their coding of the model and modified it accordingly. If the discrepancies still existed, which again was quite often, the authors then contacted the GMPE developers for input. For the most part, the discrepancies were the result of: insufficient/incorrect information given in the GMPE paper/report to replicate a plot, ambiguity in the description of the models in the GMPE papers/reports, and typographical errors in the GMPE papers/reports, as well as errors in the authors coding. The compilation of verified codes of GMPEs is the most significant valuable of this report. However, as of May 27, 2011 the following issues still remain with a few of the GMPEs:

- Abrahamson and Silva (1997): Vertical component high at large periods compared to original publication (cannot duplicate Figures 10 and 11 in A&S97).
- Chiou and Youngs (2008): Cannot duplicate Figure 21 in C&Y08.

- Grazier and Kalkan (2009): Cannot duplicate basin effect curves in Figure 11a in G&K09.
- McVerry et al. (2006): Cannot duplicate PGA plots for both crustal and subduction zone models.
- Somerville et al. (2009): Cannot duplicate plots in the original publication.

The authors will continue to try to resolve these issues.

Finally, this report is intended to be a "living" document; new models will be added periodically. Accordingly, if you find any errors in the coding or presentation of the GMPEs, please let the authors know and they will make the needed corrections. The authors hope that this report provides a useful resource and would appreciate any comments or suggestions that you may have to improve it.

2 SHALLOW ACTIVE TECTONIC REGIONS

The attenuation relations in this section apply to shallow active tectonic regions such as the western United States. They do not apply to subduction zones.

Table 2-1. List of parameters used in this section by each relationship. Definitions below.

Input Parameter	AS97	BJF97	C97	SCEMY97	SJLBMF99	F00	CB03	AS08	BA08	CB08	CY08	I08	GK09
T	●	●	●	●	●	●	●	●	●	●	●	●	●
M	●	●	●	●	●	●	●	●	●	●	●	●	●
C	●		●				●						
δ							●	●		●	●		
λ								●		●	●		
W								●					
Z_{TOR}								●		●	●		
F	●	●	●	●			●		●			●	●
F_{AS}								●			●		
F_{HW}	●							●					
R_{rup}	●			●				●		●	●	●	●
R_{jb}		●			●	●	●	●	●	●	●		
R_{seis}			●				●						
R_x								●			●		
$Z_{1.0}$								●			●		
$Z_{2.5}$										●			
D			●										
V_{S30}		●				●		●	●	●	●	●	●
E								●			●		
S	●		●	●	●		●						
D_1													●
SMM									●				
sig_{type}						●	●						
arb		●			●					●			

T – Period (sec), PGA, PGV or PGD
M – Moment magnitude
C – Component indicator
δ – Dip angle (degrees)
λ – Rake angle (degrees)
W – Down-dip rupture width (km)
Z_{TOR} – Depth to top of rupture plane (km)
F – Fault type indicator
F_{AS} – Aftershock indicator
F_{HW} – Hanging wall indicator
R_{rup} – Closest distance to rupture plane (km)
R_{jb} – Joyner-Boore distance (i.e. closest horizontal distance to surface projection of fault rupture plane) (km)
R_{seis} – Closest distance between the site and the rupture plane in the zone of seismogenic rupture (km) (same as R_{rup} except ignore any part of the rupture plane that is not in the seismogenic zone)
R_x – Horizontal distance from the top of the rupture plane, measured perpendicular to the fault strike (km)
$Z_{1.0}$ – Depth to the 1.0 km/s shear-wave velocity horizon (m)
$Z_{2.5}$ – Depth to the 2.5 km/s shear-wave velocity horizon (km)
D – Depth to basement rock (km)
V_{S30} – Shear wave velocity (m/s) averaged over top 30 m
E – Estimated/Measured V_{S30} indicator (1 for estimated, 0 for measured)
S – Soil type indicator
D_1 – Basin effect indicator
SMM – Small-to-moderate magnitude adjustment
sig_{type} – Indicator for desired error dependancy
arb – Error type indicator (i.e. geometric mean or arbitrary)

Table 2-2. List of parameters provided by relationships in this section. Definitions below.

Output Parameter	AS97	BJF97	C97	SCEMY97	SJLBMF99	F00	CB03	AS08	BA08	CB08	CY08	I08	GK09
PSA	•	•	•	•	•	•	•	•	•	•	•	•	•
PGA	•	•	•	•	•	•	•	•	•	•	•	•	•
PGV			•		•			•	•	•	•		
PGD										•			

PSA – 5%-damped pseudo-spectral acceleration (g)
PGA – Peak ground acceleration (g)
PGV – Peak ground velocity (cm/s)
PGD – Peak ground displacement (cm)

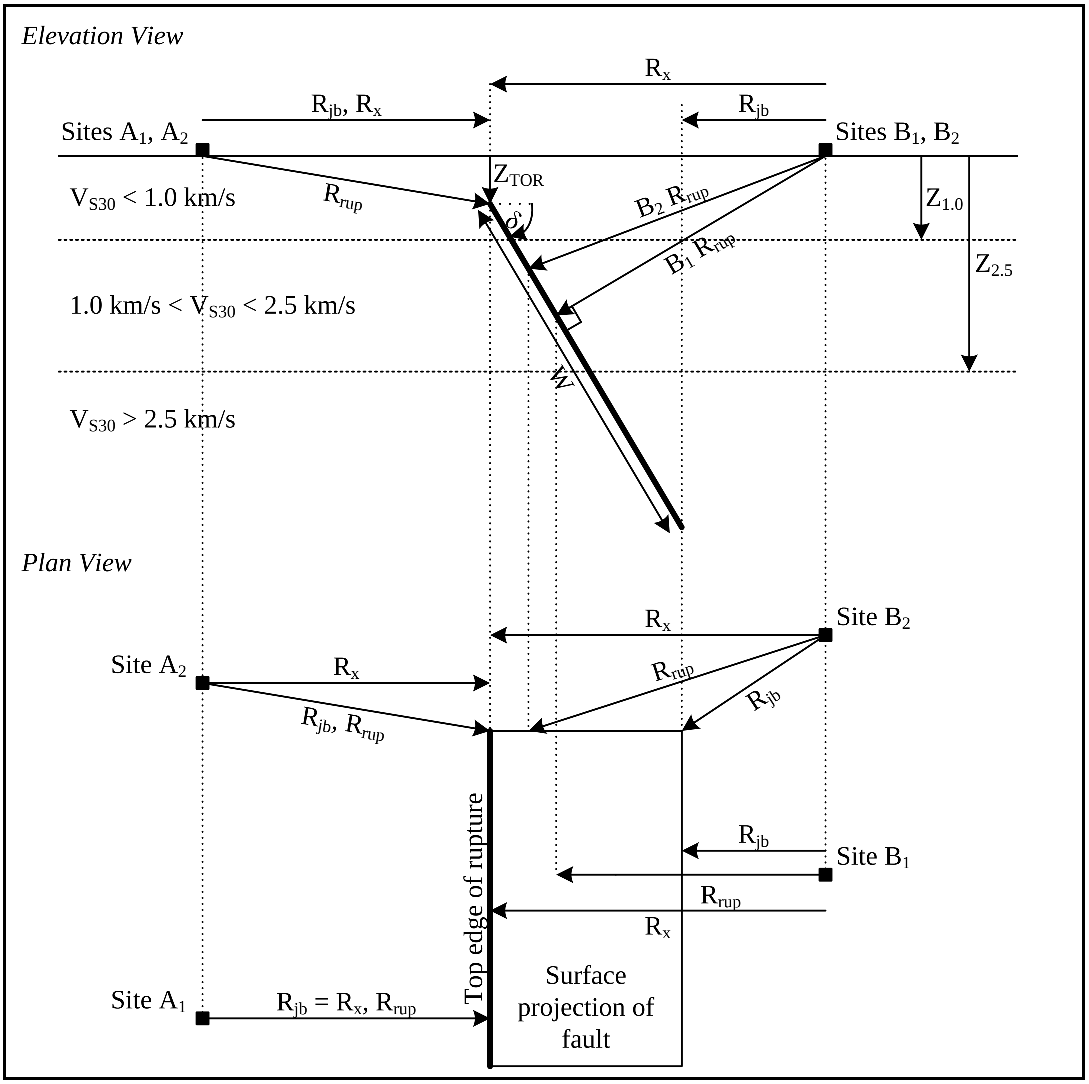


Figure 2-1. Fault geometry graphical definitions.

2.1 Abrahamson and Silva – 1997

2.1.1 Reference

Abrahamson, N. A., and W. Silva (1997). Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes, *Seismological Research Letters* **68**, 94-127.

2.1.2 Abstract

Using strong ground motions from 655 recordings from 58 earthquakes, empirical ground-motion models for the average horizontal and vertical components were developed. The model predicts 5%-damped spectral values (in g) for periods ranging from 0.01 to 5 s. Based on the bounds of the earthquakes in the database, this model is most applicable for earthquakes between M4.5 and M7.5 and distances up to 200 km. (Note: Despite attempts to address the issue, the vertical plots from this code do not match the paper for vertical motions at high periods.)

2.1.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0.01 or 0 for PGA
- **M** – Moment magnitude
- C – Component: 1 for vertical motion, 0 for horizontal
- F – Fault type: 1 for reverse fault, 0.5 for reverse/oblique, 0 otherwise
- F_{HW} – 1 for site over hanging wall, 0 otherwise
- R_{rup} – Closest distance to rupture plane (km)
- S – Soil type: 0 for rock or shallow soil, 1 for deep soil

$$\ln(Sa) = f_1(M, R_{rup}) + F\, f_3(M) + \mathrm{F}_{HW} f_4(M, R_{rup}) + S f_5(\widehat{pga}_{rock})$$

where:

$$f_1(M, R_{rup}) = a_1 + a_{12}(8.5 - M)^n + [a_3 + a_{13}(M - m_1)]\ln R + \begin{cases} a_2(M - m_1) & for\ M \le m_1 \\ a_4(M - m_1) & for\ M > m_1 \end{cases}$$

where:

$$R = \sqrt{{R_{rup}}^2 + {c_4}^2}$$

$$f_3(M) = \begin{cases} a_5 & for\ M \le 5.8 \\ a_5 + \dfrac{a_6 - a_5}{m_1 - 5.8}(M - 5.8) & for\ 5.8 < M < m_1 \\ a_6 & for\ M \ge m_1 \end{cases}$$

$$f_4(M) = f_{HW}(M) f_{HW}(R_{rup})$$

where:

$$f_{\mathrm{HW}}(M) = \begin{cases} 0 & for\ M \leq 5.5 \\ M - 5.5 & for\ 5.5 < M < 6.5 \\ 1 & for\ M \geq 6.5 \end{cases}$$

$$f_{\mathrm{HW}}(R_{rup}) = \begin{cases} 0 & for\ R_{rup} < 4 \\ a_9 \dfrac{R_{rup} - 4}{4} & for\ 4 < R_{rup} < 8 \\ a_9 & for\ 8 < R_{rup} < 18 \\ a_9 \left(1 - \dfrac{R_{rup} - 18}{7}\right) & for\ 18 < R_{rup} < 25 \\ 0 & for\ 25 > R_{rup} \end{cases}$$

$$f_5 = a_{10} + a_{11} \ln(pga_{rock} + c_5)$$

where:

pga_{rock} = median predicted PGA on rock in g (use T = 0.01, S = 0)

Standard Error

$$\sigma_{total}(M) = \begin{cases} b_5 & for\ M \leq 5.0 \\ b_5 - b_6(M - 5) & for\ 5.0 < M < 7.0 \\ b_5 - 2b_6 & for\ M \geq 7.0 \end{cases}$$

Coefficients

Table 2-3. Period-independent coefficients for horizontal component.

a_2	a_4	a_{13}	m_1	c_5	n
0.512	-0.144	0.17	6.4	0.03	2

Table 2-4. Period-dependent coefficients for horizontal component.

T (sec)	c_4	a_1	a_3	a_5	a_6	a_9	a_{10}	a_{11}	a_{12}	b_5	b_6
5.0	3.50	-1.460	-0.7250	0.400	-0.200	0.000	0.664	0.040	-0.2150	0.89	0.087
4.0	3.50	-1.130	-0.7250	0.400	-0.200	0.039	0.640	0.040	-0.1956	0.88	0.092
3.0	3.50	-0.690	-0.7250	0.400	-0.156	0.089	0.630	0.040	-0.1726	0.87	0.097
2.0	3.50	-0.150	-0.7250	0.400	-0.094	0.160	0.610	0.040	-0.1400	0.85	0.105
1.5	3.55	0.260	-0.7721	0.438	-0.049	0.210	0.600	0.040	-0.1200	0.84	0.110
1.0	3.70	0.828	-0.8383	0.490	0.013	0.281	0.423	0.000	-0.1020	0.83	0.118
0.85	3.81	1.020	-0.8648	0.512	0.038	0.309	0.370	-0.028	-0.0927	0.82	0.121
0.75	3.90	1.160	-0.8852	0.528	0.057	0.331	0.320	-0.050	-0.0862	0.81	0.123
0.60	4.12	1.428	-0.9218	0.557	0.091	0.370	0.194	-0.089	-0.0740	0.81	0.127
0.50	4.30	1.615	-0.9515	0.581	0.119	0.370	0.085	-0.121	-0.0625	0.80	0.130
0.46	4.38	1.717	-0.9652	0.592	0.132	0.370	0.020	-0.136	-0.0594	0.80	0.132
0.40	4.52	1.860	-0.9880	0.610	0.154	0.370	-0.065	-0.160	-0.0518	0.79	0.135
0.36	4.62	1.955	-1.0052	0.610	0.170	0.370	-0.123	-0.173	-0.0460	0.79	0.135
0.30	4.80	2.114	-1.0350	0.610	0.198	0.370	-0.219	-0.195	-0.0360	0.78	0.135
0.24	4.97	2.293	-1.0790	0.610	0.232	0.370	-0.350	-0.223	-0.0238	0.77	0.135
0.20	5.10	2.406	-1.1150	0.610	0.260	0.370	-0.445	-0.245	-0.0138	0.77	0.135
0.17	5.19	2.430	-1.1350	0.610	0.260	0.370	-0.522	-0.265	-0.0040	0.76	0.135
0.15	5.27	2.407	-1.1450	0.610	0.260	0.370	-0.577	-0.280	0.0050	0.75	0.135
0.12	5.39	2.272	-1.1450	0.610	0.260	0.370	-0.591	-0.280	0.0180	0.75	0.135
0.10	5.50	2.160	-1.1450	0.610	0.260	0.370	-0.598	-0.280	0.0280	0.74	0.135
0.090	5.54	2.100	-1.1450	0.610	0.260	0.370	-0.609	-0.280	0.0300	0.74	0.135
0.075	5.58	2.037	-1.1450	0.610	0.260	0.370	-0.628	-0.280	0.0300	0.73	0.135
0.060	5.60	1.940	-1.1450	0.610	0.260	0.370	-0.665	-0.280	0.0300	0.72	0.135
0.050	5.60	1.870	-1.1450	0.610	0.260	0.370	-0.620	-0.267	0.0280	0.71	0.135
0.040	5.60	1.780	-1.1450	0.610	0.260	0.370	-0.555	-0.251	0.0245	0.71	0.135
0.030	5.60	1.690	-1.1450	0.610	0.260	0.370	-0.470	-0.230	0.0143	0.70	0.135
0.020	5.60	1.640	-1.1450	0.610	0.260	0.370	-0.417	-0.230	0.0000	0.70	0.135
0.010	5.60	1.640	-1.1450	0.610	0.260	0.370	-0.417	-0.230	0.0000	0.70	0.135

Table 2-5. Period-independent coefficients for vertical component.

a_2	a_4	a_{13}	m_1	c_5	n
0.909	0.275	0.06	6.4	0.3	3

Table 2-6. Period-dependent coefficients for vertical component.

T (sec)	c_4	a_1	a_3	a_5	a_6	a_9	a_{10}	a_{11}	a_{12}	b_5	b_6
5.0	2.50	-2.053	-0.7200	0.260	-0.100	0.240	0.040	-0.220	-0.0670	0.78	0.050
4.0	2.50	-1.857	-0.7200	0.260	-0.100	0.240	0.040	-0.220	-0.0565	0.75	0.050
3.0	2.50	-1.581	-0.7200	0.260	-0.100	0.240	0.040	-0.220	-0.0431	0.72	0.050
2.0	2.50	-1.224	-0.7200	0.260	-0.008	0.240	0.040	-0.220	-0.0240	0.69	0.050
1.5	2.50	-0.966	-0.7285	0.260	0.058	0.240	0.025	-0.220	-0.0180	0.69	0.050
1.0	2.50	-0.602	-0.7404	0.260	0.150	0.240	0.004	-0.220	-0.0115	0.69	0.050
0.85	2.50	-0.469	-0.7451	0.309	0.150	0.273	-0.004	-0.220	-0.0097	0.69	0.050
0.75	2.50	-0.344	-0.7488	0.348	0.150	0.299	-0.010	-0.220	-0.0083	0.69	0.050
0.60	2.85	-0.087	-0.7896	0.416	0.150	0.345	-0.022	-0.220	-0.0068	0.69	0.050
0.50	3.26	0.145	-0.8291	0.471	0.150	0.383	-0.031	-0.220	-0.0060	0.69	0.050
0.46	3.45	0.271	-0.8472	0.497	0.150	0.400	-0.035	-0.220	-0.0056	0.69	0.050
0.40	3.77	0.478	-0.8776	0.539	0.150	0.428	-0.043	-0.220	-0.0050	0.69	0.050
0.36	4.01	0.617	-0.9004	0.571	0.150	0.450	-0.048	-0.220	-0.0047	0.69	0.050
0.30	4.42	0.878	-0.9400	0.580	0.150	0.488	-0.057	-0.220	-0.0042	0.69	0.050
0.24	4.93	1.312	-1.0274	0.580	0.109	0.533	-0.069	-0.220	-0.0035	0.69	0.050
0.20	5.35	1.648	-1.0987	0.580	0.076	0.571	-0.078	-0.220	-0.0030	0.69	0.050
0.17	5.72	1.960	-1.1623	0.580	0.047	0.604	-0.087	-0.220	-0.0025	0.70	0.056
0.15	6.00	2.170	-1.2113	0.580	0.024	0.630	-0.093	-0.220	-0.0022	0.72	0.063
0.12	6.00	2.480	-1.2986	0.580	-0.017	0.630	-0.104	-0.220	-0.0015	0.74	0.075
0.10	6.00	2.700	-1.3700	0.580	-0.050	0.630	-0.114	-0.220	-0.0010	0.76	0.085
0.090	6.00	2.730	-1.3700	0.567	-0.050	0.630	-0.119	-0.220	-0.0009	0.76	0.085
0.075	6.00	2.750	-1.3700	0.545	-0.050	0.630	-0.129	-0.220	-0.0007	0.76	0.085
0.060	6.00	2.710	-1.3700	0.518	-0.050	0.630	-0.140	-0.220	-0.0004	0.76	0.085
0.050	6.00	2.620	-1.3700	0.496	-0.050	0.630	-0.140	-0.220	-0.0002	0.76	0.085
0.040	6.00	2.420	-1.3700	0.469	-0.050	0.630	-0.140	-0.220	0.0000	0.76	0.085
0.030	6.00	2.100	-1.3168	0.432	-0.050	0.630	-0.140	-0.220	0.0000	0.76	0.085
0.020	6.00	1.642	-1.2520	0.390	-0.050	0.630	-0.140	-0.220	0.0000	0.76	0.085
0.010	6.00	1.642	-1.2520	0.390	-0.050	0.630	-0.140	-0.220	0.0000	0.76	0.085

2.1.4 Calibration Plots

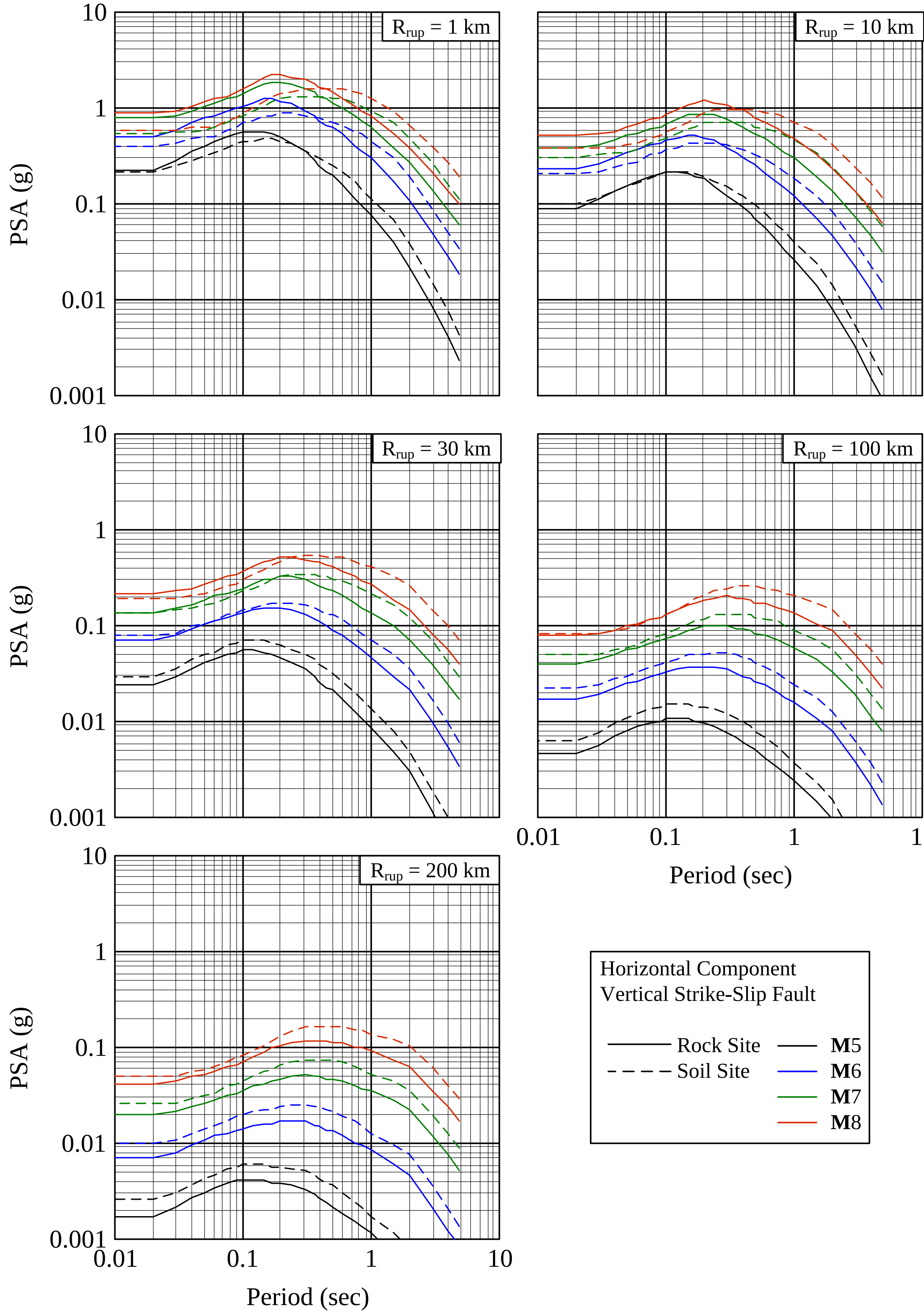


Figure 2-2. Horizontal component of PSA as a function of period for a strike-slip fault, various magnitudes, distances and site conditions.

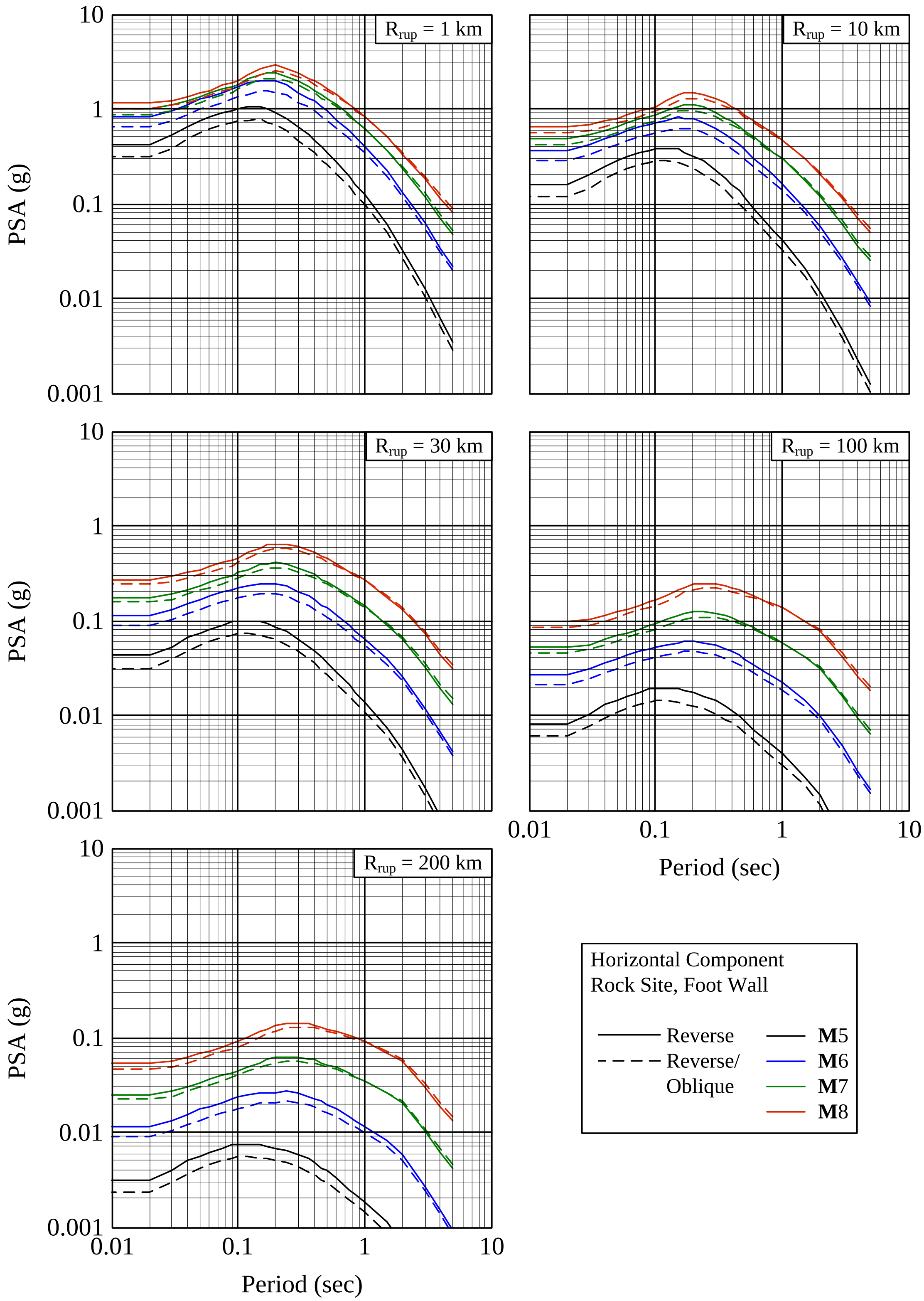


Figure 2-3. Horizontal component of PSA as a function of period on the foot wall at a rock site for various magnitudes, distances and fault types.

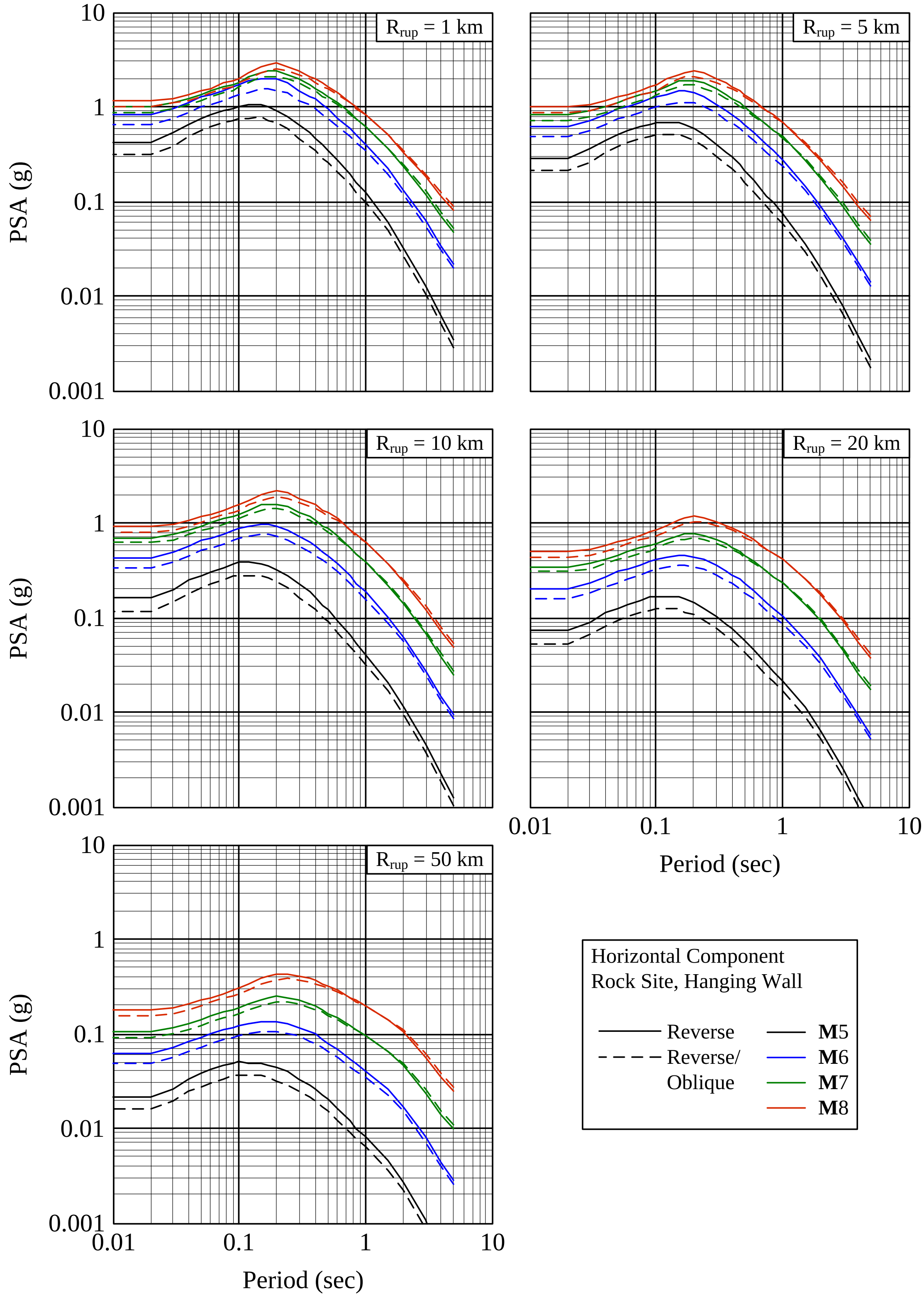


Figure 2-4. Horizontal component of PSA as a function of period on the hanging wall of a rock site for various magnitudes, distances and fault types. Note that at distances larger than 25 km, PSA is equivalent for hanging wall and foot wall sites.

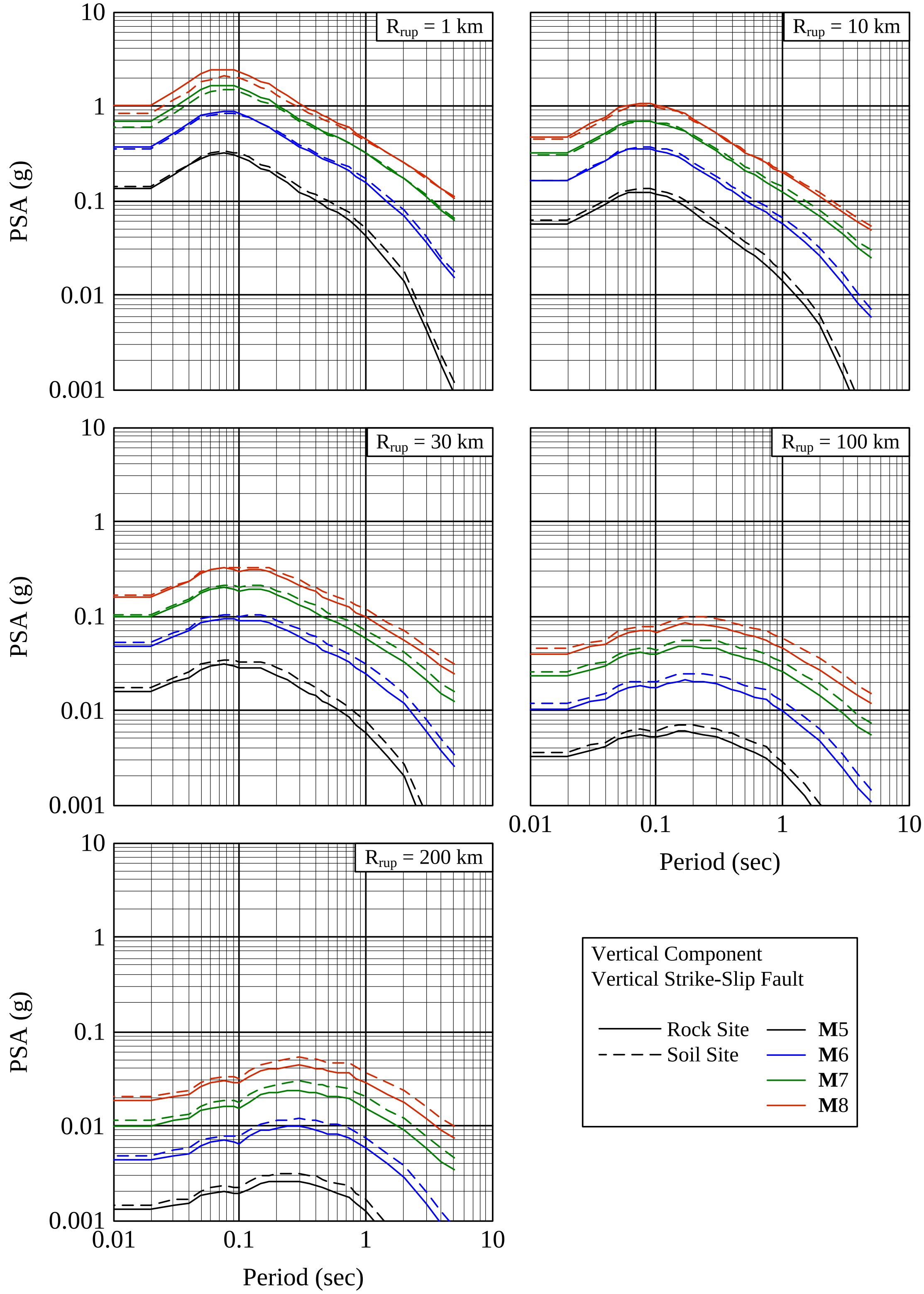


Figure 2-5. Vertical component of PSA as a function of period for a strike-slip fault, various magnitudes, distances and site conditions.

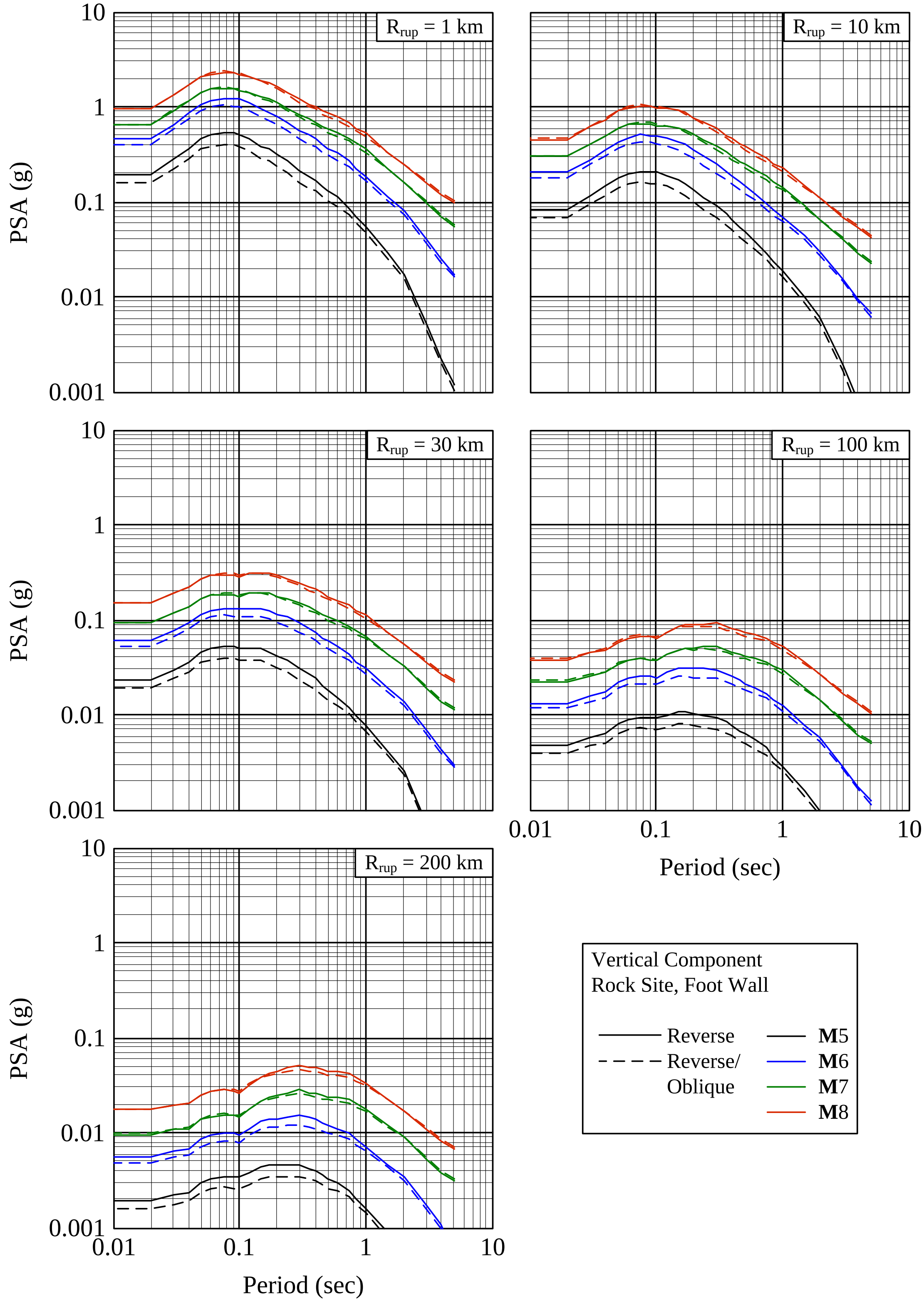


Figure 2-6. Vertical component of PSA as a function of period on the foot wall at a rock site for various magnitudes, distances and fault types.

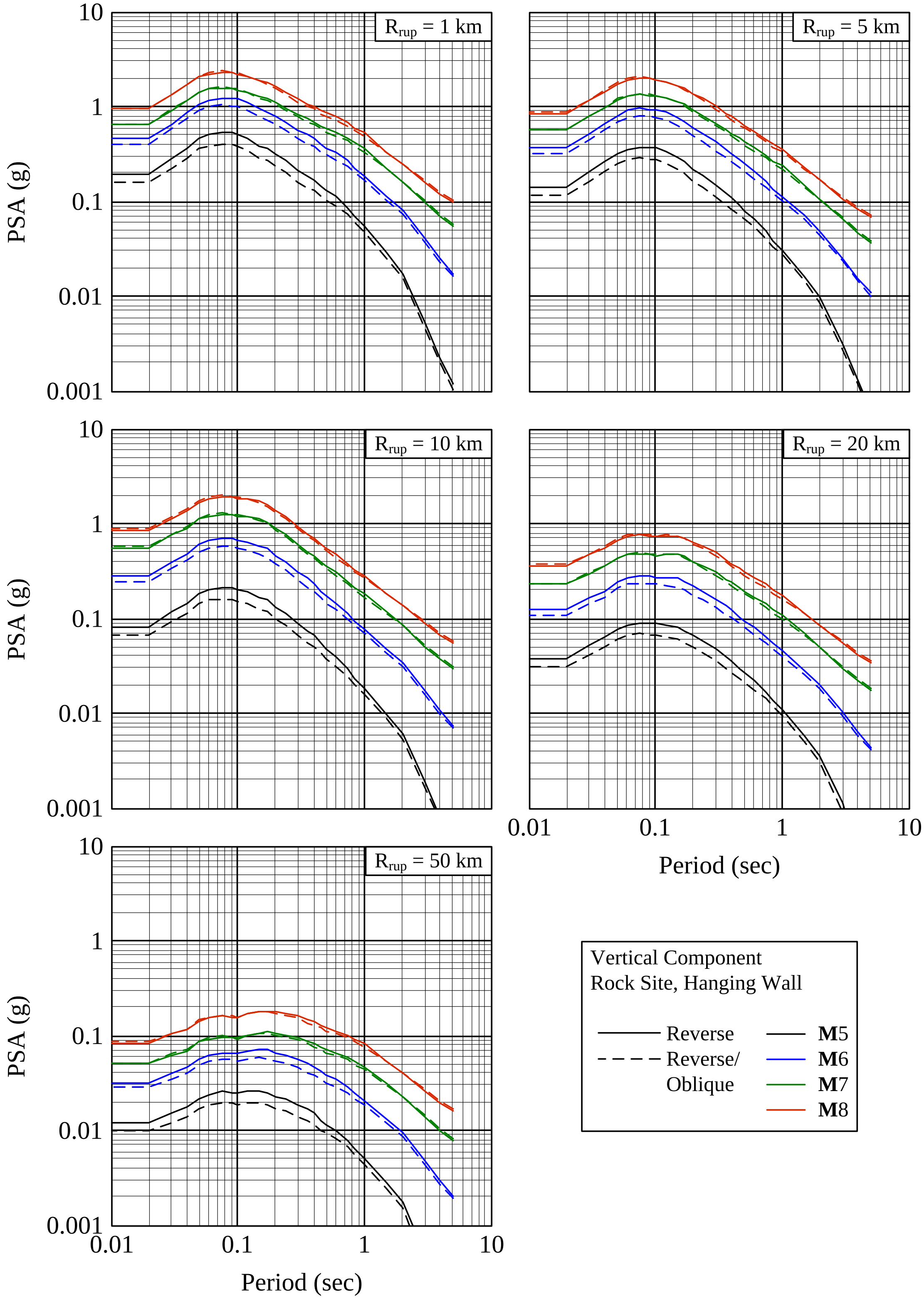


Figure 2-7. Vertical component of PSA as a function of period on the hanging wall of a rock site for various magnitudes, distances and fault types. Note that at distances larger than 25 km, PSA is equivalent for hanging wall and foot wall sites.

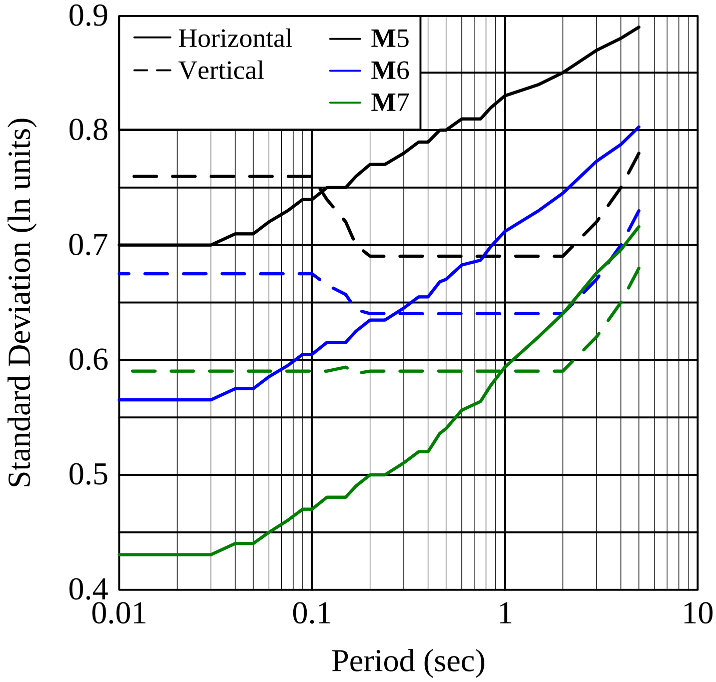


Figure 2-8. Standard deviation as a function of period for vertical and horizontal components and various magnitudes. Note that standard deviation at a specific period is only dependant on magnitude.

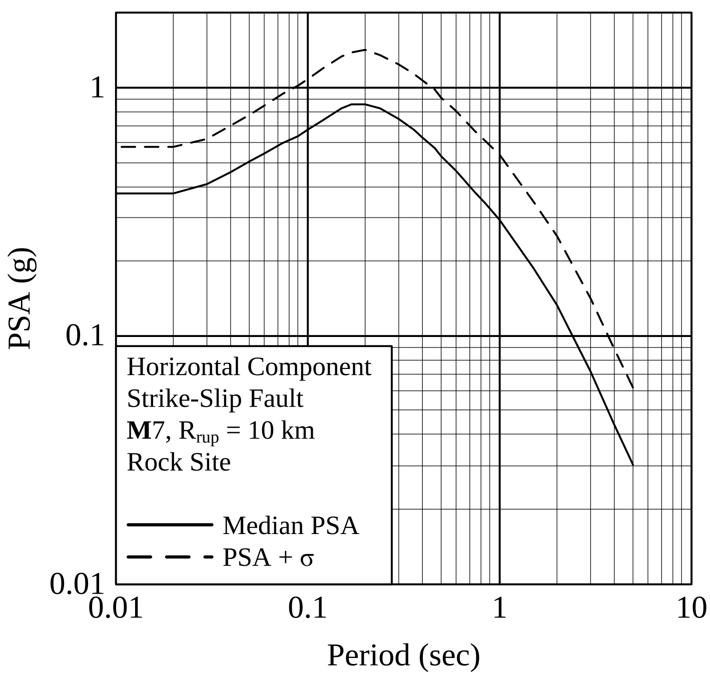


Figure 2-9. Example of application of median PSA plus one standard deviation.

2.1.5 Database

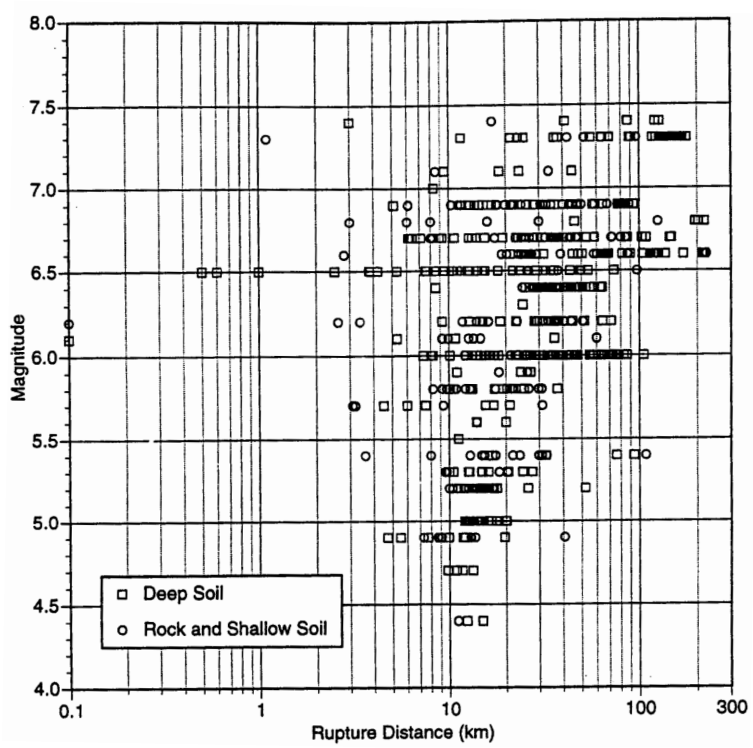


Figure 2-10. Distribution of data for 1.0 sec period for the horizontal component.

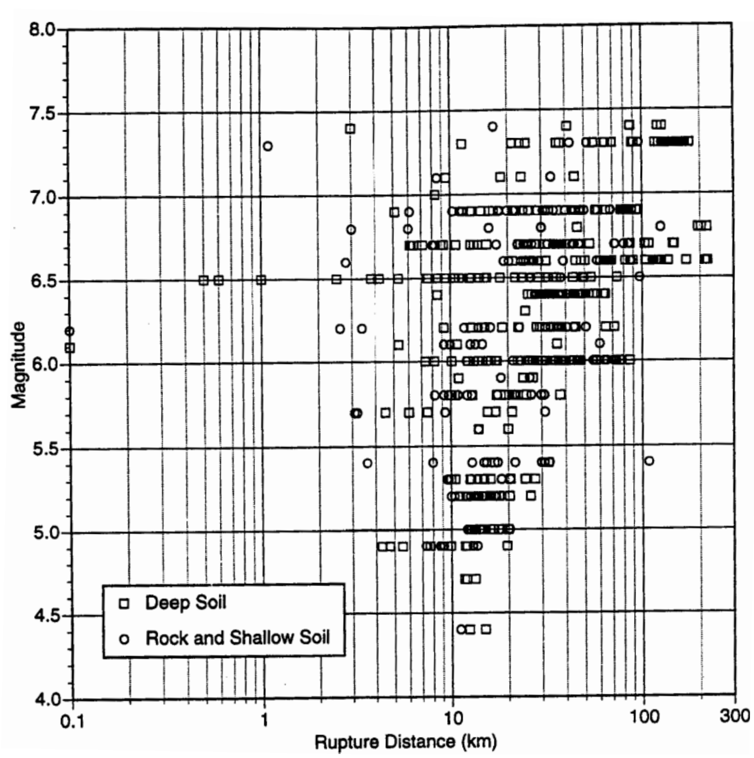


Figure 2-11. Distribution of data for 1.0 sec period for the vertical component.

2.1.6 MATLAB Code

```
% by Kathryn A. Gunberg 3/3/2008
% Virginia Tech
% kgunberg@vt.edu
%
% Abrahamson & Silva attenuation equation, 1997
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0.01 or 0 for PGA
% M         = Magnitude
% C         = Component: 1 for vertical, 0 for horizontal
% F         = Fault type: 1 for reverse, 0.5 for reverse/oblique, 0 otherwise
% Fhw       = 1 for site over hanging wall, 0 otherwise
% Rrup      = Closest distance to rupture plane (km)
% S         = Soil type: 0 for rock or shallow soil, 1 for deep soil
% ------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = AS_1997(T, M, C, F, Fhw, Rrup, S)
% Coefficients
m1  = 6.4;
period  =  [5       4       3       2       1.5     1       0.85    0.75    0.6     ...
            0.5     0.46    0.4     0.36    0.30    0.24    0.20    0.17    0.15    ...
            0.12    0.10    0.09    0.075   0.06    0.05    0.04    0.03    0.02    0.01];
if C==0
    a2  =   0.512;
    a4  =   -0.144;
    a13 =   0.17;
    c5  =   0.03;
    n   =   2;
    c4  =  [3.50    3.50    3.50    3.50    3.55    3.70    3.81    3.90    4.12    ...
            4.30    4.38    4.52    4.62    4.80    4.97    5.10    5.19    5.27    ...
            5.39    5.50    5.54    5.58    5.60    5.60    5.60    5.60    5.60    5.60];
    a1  =  [-1.460  -1.130  -0.690  -0.150  0.260   0.828   1.020   1.160   1.428   ...
            1.615   1.717   1.860   1.955   2.114   2.293   2.406   2.430   2.407   ...
            2.272   2.160   2.100   2.037   1.940   1.870   1.780   1.690   1.640   1.640];
    a3  =  [-0.7250 -0.7250 -0.7250 -0.7250 -0.7721 -0.8383 -0.8648 -0.8852 -0.9218 ...
            -0.9515 -0.9652 -0.9880 -1.0052 -1.0350 -1.0790 -1.1150 -1.1350 -1.1450 ...
            -1.1450 -1.1450 -1.1450 -1.1450 -1.1450 -1.1450 -1.1450 -1.1450 -1.1450 -1.1450];
    a5  =  [0.400   0.400   0.400   0.400   0.438   0.490   0.512   0.528   0.557   ...
            0.581   0.592   0.610   0.610   0.610   0.610   0.610   0.610   0.610   ...
            0.610   0.610   0.610   0.610   0.610   0.610   0.610   0.610   0.610   0.610];
    a6  =  [-0.200  -0.200  -0.156  -0.094  -0.049  0.013   0.038   0.057   0.091   ...
            0.119   0.132   0.154   0.170   0.198   0.232   0.260   0.260   0.260   ...
            0.260   0.260   0.260   0.260   0.260   0.260   0.260   0.260   0.260   0.260];
    a9  =  [0.000   0.039   0.089   0.160   0.210   0.281   0.309   0.331   0.370   ...
            0.370   0.370   0.370   0.370   0.370   0.370   0.370   0.370   0.370   ...
            0.370   0.370   0.370   0.370   0.370   0.370   0.370   0.370   0.370   0.370];
    a10 =  [0.664   0.640   0.630   0.610   0.600   0.423   0.370   0.320   0.194   ...
            0.085   0.020   -0.065  -0.123  -0.219  -0.350  -0.445  -0.522  -0.577  ...
            -0.591  -0.598  -0.609  -0.628  -0.665  -0.620  -0.555  -0.470  -0.417  -0.417];
    a11 =  [0.040   0.040   0.040   0.040   0.040   0.000   -0.028  -0.050  -0.089  ...
            -0.121  -0.136  -0.160  -0.173  -0.195  -0.223  -0.245  -0.265  -0.280  ...
            -0.280  -0.280  -0.280  -0.280  -0.280  -0.267  -0.251  -0.230  -0.230  -0.230];
    a12 =  [-0.2150 -0.1956 -0.1726 -0.1400 -0.1200 -0.1020 -0.0927 -0.0862 -0.0740 ...
            -0.0625 -0.0594 -0.0518 -0.0460 -0.0360 -0.0238 -0.0138 -0.0040 0.0050  ...
            0.0180  0.0280  0.0300  0.0300  0.0300  0.0280  0.0245  0.0143  0.0000  0.0000];
    b5  =  [0.89    0.88    0.87    0.85    0.84    0.83    0.82    0.81    0.81    ...
            0.80    0.80    0.79    0.79    0.78    0.77    0.77    0.76    0.75    ...
            0.75    0.74    0.74    0.73    0.72    0.71    0.71    0.70    0.70    0.70];
    b6  =  [0.087   0.092   0.097   0.105   0.110   0.118   0.121   0.123   0.127   ...
            0.130   0.132   0.135   0.135   0.135   0.135   0.135   0.135   0.135   ...
            0.135   0.135   0.135   0.135   0.135   0.135   0.135   0.135   0.135   0.135];
else
    a2  =   0.909;
```

```
    a4  =   0.275;
    a13 =   0.06;
    c5  =   0.3;
    n   =   3;
    c4  =  [2.50    2.50    2.50    2.50    2.50    2.50    2.50    2.50    2.85    ...
            3.26    3.45    3.77    4.01    4.42    4.93    5.35    5.72    6.00    ...
            6.00    6.00    6.00    6.00    6.00    6.00    6.00    6.00    6.00    6.00];
    a1  =  [-2.053  -1.857  -1.581  -1.224  -0.966  -0.602  -0.469  -0.344  -0.087  ...
            0.145   0.271   0.478   0.617   0.878   1.312   1.648   1.960   2.170   ...
            2.480   2.700   2.730   2.750   2.710   2.620   2.420   2.100   1.642   1.642];
    a3  =  [-0.7200 -0.7200 -0.7200 -0.7200 -0.7285 -0.7404 -0.7451 -0.7488 -0.7896 ...
            -0.8291 -0.8472 -0.8776 -0.9004 -0.9400 -1.0274 -1.0987 -1.1623 -1.2113 ...
            -1.2986 -1.3700 -1.3700 -1.3700 -1.3700 -1.3700 -1.3700 -1.3168 -1.2520 -1.2520];
    a5  =  [0.260   0.260   0.260   0.260   0.260   0.260   0.309   0.348   0.416   ...
            0.471   0.497   0.539   0.571   0.580   0.580   0.580   0.580   0.580   ...
            0.580   0.580   0.567   0.545   0.518   0.496   0.469   0.432   0.390   0.390];
    a6  =  [-0.100  -0.100  -0.100  -0.008  0.058   0.150   0.150   0.150   0.150   ...
            0.150   0.150   0.150   0.150   0.150   0.109   0.076   0.047   0.024   ...
            -0.017  -0.050  -0.050  -0.050  -0.050  -0.050  -0.050  -0.050  -0.050  -0.050];
    a9  =  [0.240   0.240   0.240   0.240   0.240   0.240   0.273   0.299   0.345   ...
            0.383   0.400   0.428   0.450   0.488   0.533   0.571   0.604   0.630   ...
            0.630   0.630   0.630   0.630   0.630   0.630   0.630   0.630   0.630   0.630];
    a10 =  [0.040   0.040   0.040   0.040   0.025   0.004   -0.004  -0.010  -0.022  ...
            -0.031  -0.035  -0.043  -0.048  -0.057  -0.069  -0.078  -0.087  -0.093  ...
            -0.104  -0.114  -0.119  -0.129  -0.140  -0.140  -0.140  -0.140  -0.140  -0.140];
    a11 =  [-0.220  -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  ...
            -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  ...
            -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  -0.220  -0.220];
    a12 =  [-0.0670 -0.0565 -0.0431 -0.0240 -0.0180 -0.0115 -0.0097 -0.0083 -0.0068 ...
            -0.0060 -0.0056 -0.0050 -0.0047 -0.0042 -0.0035 -0.0030 -0.0025 -0.0022 ...
            -0.0015 -0.0010 -0.0009 -0.0007 -0.0004 -0.0002 0.0000  0.0000  0.0000  0.0000];
    b5  =  [0.78    0.75    0.72    0.69    0.69    0.69    0.69    0.69    0.69    ...
            0.69    0.69    0.69    0.69    0.69    0.69    0.69    0.70    0.72    ...
            0.74    0.76    0.76    0.76    0.76    0.76    0.76    0.76    0.76    0.76];
    b6  =  [0.050   0.050   0.050   0.050   0.050   0.050   0.050   0.050   0.050   ...
            0.050   0.050   0.050   0.050   0.050   0.050   0.050   0.056   0.063   ...
            0.075   0.085   0.085   0.085   0.085   0.085   0.085   0.085   0.085   0.085];
end
% interpolate between periods if neccesary
if T == 0
    T = min(period);
end
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = AS_1997(T_low, M, C, F, Fhw, Rrup, S);
    [sa_hi,  sigma_hi]  = AS_1997(T_hi,  M, C, F, Fhw, Rrup, S);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    R = sqrt(Rrup^2+c4(i)^2);
    if M <= m1
        f1 = a1(i) + a2*(M-m1) + a12(i)*(8.5-M)^n + (a3(i)+a13*(M-m1))*log(R);
    else
        f1 = a1(i) + a4*(M-m1) + a12(i)*(8.5-M)^n + (a3(i)+a13*(M-m1))*log(R);
    end
    if M <= 5.8
        f3 = a5(i);
    elseif M < m1
        f3 = a5(i) + (a6(i)-a5(i))/(m1-5.8)*(M-5.8);
    else
        f3 = a6(i);
    end
    if M <= 5.5
        fHWm = 0;
    elseif M < 6.5
        fHWm = M-5.5;
```

```
    else
        fHWm = 1;
    end
    if Rrup < 4
        fHWr = 0;
    elseif Rrup < 8
        fHWr = a9(i)*(Rrup-4)/4;
    elseif Rrup < 18
        fHWr = a9(i);
    elseif Rrup < 25
        fHWr = a9(i)*(1-(Rrup-18)/7);
    else
        fHWr = 0;
    end
    f4 = fHWm * fHWr;
    if S == 0
        f5 = 0;
    else
        [pgarock sigmarock] = AS_1997(0.01, M, C, F, Fhw, Rrup, 0);
        f5 = a10(i) + a11(i)*log(pgarock + c5);
    end
    Sa = exp(f1 + F*f3 + Fhw*f4 + f5);
    if M <= 5.0
        sigma = b5(i);
    elseif M < 7.0
        sigma = b5(i) - b6(i)*(M-5);
    else
        sigma = b5(i) - 2*b6(i);
    end
end
```

2.2 Boore, Joyner and Fumal – 1997

2.2.1 References

Boore, D. M., W. B. Joyner, and T. E. Fumal (1997). Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work, *Seismological Research Letters* **68**, 128-153.

Boore, D. M. (2005). Erratum: Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work, *Seismological Research Letters* **76**(3), 368-369.

2.2.2 Abstract

Using strong ground motions from shallow, western North American earthquakes, an empirical ground-motion model for the average horizontal component was developed. The model predicts peak ground acceleration (PGA, in g) and 5%-damped spectral values (in g) for periods ranging from 0.1 to 2 s. The model is applicable for earthquakes between M5.5 and M7.5, distances up to 80 km and average shear wave velocities of the top 30 m between 100 and 1500 m/s.

2.2.3 Attenuation Relationship

The spectral acceleration is a function of:

T	– Period (sec), use 0 for PGA
M	– Moment magnitude
F	– Fault type: 0 for unspecified, 1 for strike-slip fault, 2 for reverse
R_{jb}	– Joyner-Boore distance (km)
V_{S30}	– Shear wave velocity (m/s) averaged over top 30 m
arb	– Error: 0 for error from geometric mean of horizontal components, 1 for arbitrary

$$\ln(Sa) = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5\ln(r) + b_V\ln\left(\frac{V_{S30}}{V_A}\right)$$

where:

$$r = \sqrt{{R_{jb}}^2 + h^2}$$

$$b_1 = \begin{cases} b_{1SS} & for\ F = 1 \\ b_{1RV} & for\ F = 2 \\ b_{1ALL} & for\ F = 0 \end{cases}$$

Standard Error

$$\sigma = \begin{cases} \sigma_{\ln Y} & for\ arbitrary\ component \\ \sqrt{{\sigma_1}^2 + {\sigma_e}^2} & for\ average\ component \end{cases}$$

Coefficients

Table 2-7. Coefficients for attenuation model.

T (sec)	b_{1SS}	b_{1RV}	b_{1ALL}	b_2	b_3	b_5	b_V	V_A	h	σ_1	σ_C	σ_r	σ_e	$\sigma_{\ln Y}$
0.00	-0.313	-0.117	-0.242	0.527	0.000	-0.778	-0.371	1396	5.57	0.431	0.160	0.460	0.184	0.495
0.10	1.006	1.087	1.059	0.753	-0.226	-0.934	-0.212	1112	6.27	0.440	0.134	0.460	0.000	0.460
0.11	1.072	1.164	1.130	0.732	-0.230	-0.937	-0.211	1291	6.65	0.437	0.141	0.459	0.000	0.459
0.12	1.109	1.215	1.174	0.721	-0.233	-0.939	-0.215	1452	6.91	0.437	0.148	0.462	0.000	0.462
0.13	1.128	1.246	1.200	0.711	-0.233	-0.939	-0.221	1596	7.08	0.435	0.153	0.461	0.000	0.461
0.14	1.135	1.261	1.208	0.707	-0.230	-0.938	-0.228	1718	7.18	0.435	0.158	0.463	0.000	0.463
0.15	1.128	1.264	1.204	0.702	-0.228	-0.937	-0.238	1820	7.23	0.435	0.163	0.464	0.000	0.464
0.16	1.112	1.257	1.192	0.702	-0.226	-0.935	-0.248	1910	7.24	0.435	0.166	0.466	0.000	0.466
0.17	1.090	1.242	1.173	0.702	-0.221	-0.933	-0.258	1977	7.21	0.435	0.169	0.467	0.000	0.467
0.18	1.063	1.222	1.151	0.705	-0.216	-0.930	-0.270	2037	7.16	0.435	0.173	0.468	0.002	0.468
0.19	1.032	1.198	1.122	0.709	-0.212	-0.927	-0.281	2080	7.10	0.435	0.176	0.469	0.005	0.469
0.20	0.999	1.170	1.089	0.711	-0.207	-0.924	-0.292	2118	7.02	0.435	0.177	0.470	0.009	0.470
0.22	0.925	1.104	1.019	0.721	-0.198	-0.918	-0.315	2158	6.83	0.437	0.182	0.474	0.016	0.474
0.24	0.847	1.033	0.941	0.732	-0.189	-0.912	-0.338	2178	6.62	0.437	0.185	0.475	0.025	0.475
0.26	0.764	0.958	0.861	0.744	-0.180	-0.906	-0.360	2173	6.39	0.437	0.189	0.476	0.032	0.477
0.28	0.681	0.881	0.780	0.758	-0.168	-0.899	-0.381	2158	6.17	0.440	0.192	0.480	0.039	0.482
0.30	0.598	0.803	0.700	0.769	-0.161	-0.893	-0.401	2133	5.94	0.440	0.195	0.481	0.048	0.484
0.32	0.518	0.725	0.619	0.783	-0.152	-0.888	-0.420	2104	5.72	0.442	0.197	0.484	0.055	0.487
0.34	0.439	0.648	0.540	0.794	-0.143	-0.882	-0.438	2070	5.50	0.444	0.199	0.486	0.064	0.491
0.36	0.361	0.570	0.462	0.806	-0.136	-0.877	-0.456	2032	5.30	0.444	0.200	0.487	0.071	0.492
0.38	0.286	0.495	0.385	0.820	-0.127	-0.872	-0.472	1995	5.10	0.447	0.202	0.491	0.078	0.497
0.40	0.212	0.423	0.311	0.831	-0.120	-0.867	-0.487	1954	4.91	0.447	0.204	0.491	0.085	0.499
0.42	0.140	0.352	0.239	0.840	-0.113	-0.862	-0.502	1919	4.74	0.449	0.205	0.494	0.092	0.502
0.44	0.073	0.282	0.169	0.852	-0.108	-0.858	-0.516	1884	4.57	0.449	0.206	0.494	0.099	0.504
0.46	0.005	0.217	0.102	0.863	-0.101	-0.854	-0.529	1849	4.41	0.451	0.209	0.497	0.104	0.508
0.48	-0.058	0.151	0.036	0.873	-0.097	-0.850	-0.541	1816	4.26	0.451	0.210	0.497	0.111	0.510
0.50	-0.122	0.087	-0.025	0.884	-0.090	-0.846	-0.553	1782	4.13	0.454	0.211	0.501	0.115	0.514
0.55	-0.268	-0.063	-0.176	0.907	-0.078	-0.837	-0.579	1710	3.82	0.456	0.214	0.504	0.129	0.520
0.60	-0.401	-0.203	-0.314	0.928	-0.069	-0.830	-0.602	1644	3.57	0.458	0.216	0.507	0.143	0.526
0.65	-0.523	-0.331	-0.440	0.946	-0.060	-0.823	-0.622	1592	3.36	0.461	0.218	0.510	0.154	0.533
0.70	-0.634	-0.452	-0.555	0.962	-0.053	-0.818	-0.639	1545	3.20	0.463	0.220	0.513	0.166	0.539
0.75	-0.737	-0.562	-0.661	0.979	-0.046	-0.813	-0.653	1507	3.07	0.465	0.221	0.515	0.175	0.544
0.80	-0.829	-0.666	-0.760	0.992	-0.041	-0.809	-0.666	1476	2.98	0.467	0.223	0.517	0.184	0.549
0.85	-0.915	-0.761	-0.851	1.006	-0.037	-0.805	-0.676	1452	2.92	0.467	0.226	0.519	0.191	0.553
0.90	-0.993	-0.848	-0.933	1.018	-0.035	-0.802	-0.685	1432	2.89	0.470	0.228	0.522	0.200	0.559
0.95	-1.066	-0.932	-1.010	1.027	-0.032	-0.800	-0.692	1416	2.88	0.472	0.230	0.525	0.207	0.564
1.0	-1.133	-1.009	-1.080	1.036	-0.032	-0.798	-0.698	1406	2.90	0.474	0.230	0.527	0.214	0.569
1.1	-1.249	-1.145	-1.208	1.052	-0.030	-0.795	-0.706	1396	2.99	0.477	0.233	0.531	0.226	0.577
1.2	-1.345	-1.265	-1.315	1.064	-0.032	-0.794	-0.710	1400	3.14	0.479	0.236	0.534	0.235	0.583
1.3	-1.428	-1.370	-1.407	1.073	-0.035	-0.793	-0.711	1416	3.36	0.481	0.239	0.537	0.244	0.590
1.4	-1.495	-1.460	-1.483	1.080	-0.039	-0.794	-0.709	1442	3.62	0.484	0.241	0.541	0.251	0.596
1.5	-1.552	-1.538	-1.550	1.085	-0.044	-0.796	-0.704	1479	3.92	0.486	0.244	0.544	0.256	0.601
1.6	-1.598	-1.608	-1.605	1.087	-0.051	-0.798	-0.697	1524	4.26	0.488	0.246	0.547	0.262	0.606
1.7	-1.634	-1.668	-1.652	1.089	-0.058	-0.801	-0.689	1581	4.62	0.490	0.249	0.550	0.267	0.611
1.8	-1.663	-1.718	-1.689	1.087	-0.067	-0.804	-0.679	1644	5.01	0.493	0.251	0.553	0.269	0.615
1.9	-1.685	-1.763	-1.720	1.087	-0.074	-0.808	-0.667	1714	5.42	0.493	0.254	0.555	0.274	0.619
2.0	-1.699	-1.801	-1.743	1.085	-0.085	-0.812	-0.655	1795	5.85	0.495	0.256	0.557	0.276	0.622

2.2.4 Calibration Plots

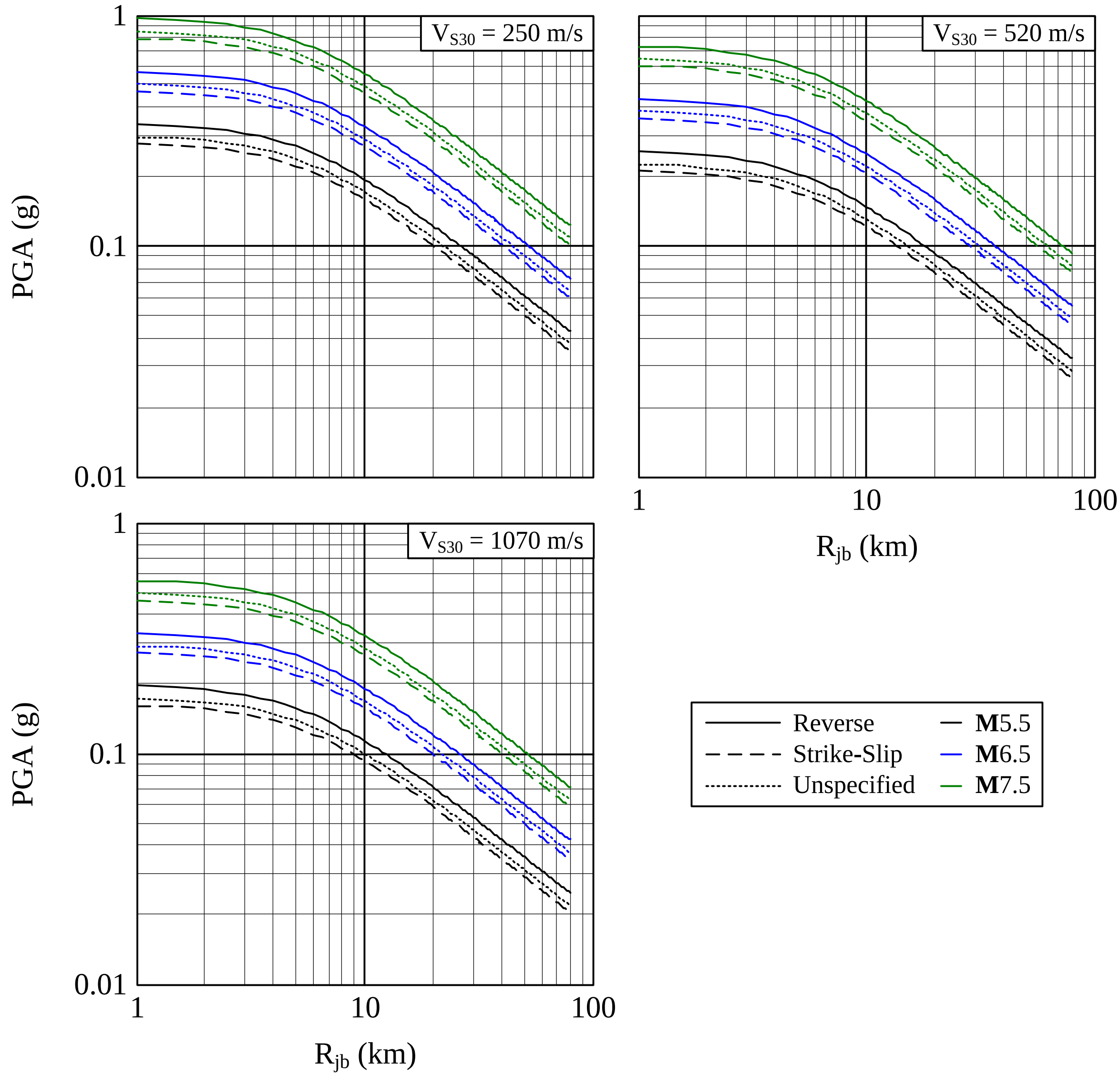


Figure 2-12. Predicted peak ground acceleration for various shear wave velocities, magnitudes and fault types as a function of distance.

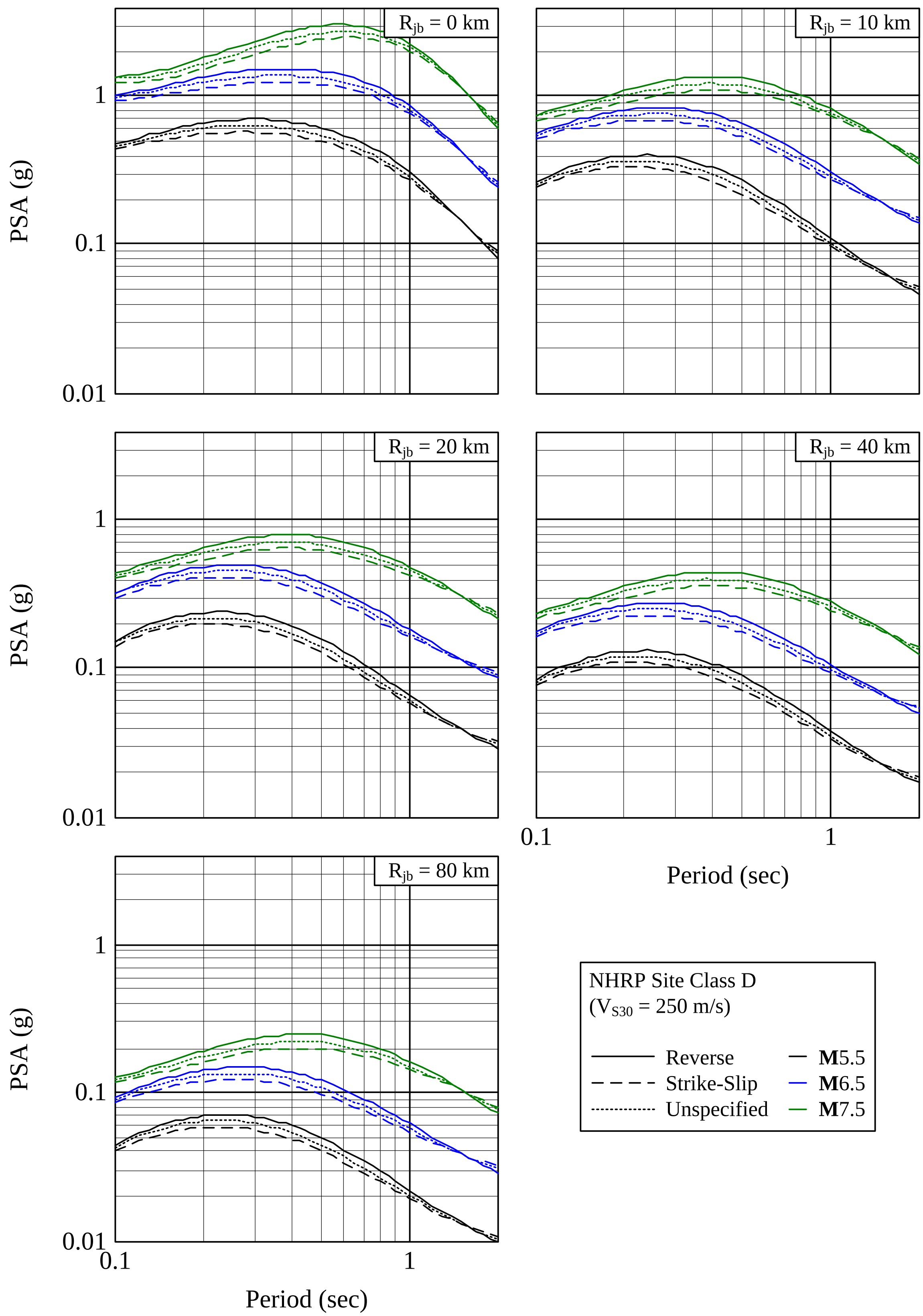


Figure 2-13. Predicted spectral acceleration for various distances, magnitudes and fault types as a function of period for NEHRP site class D conditions (V_{S30} = 250 m/s).

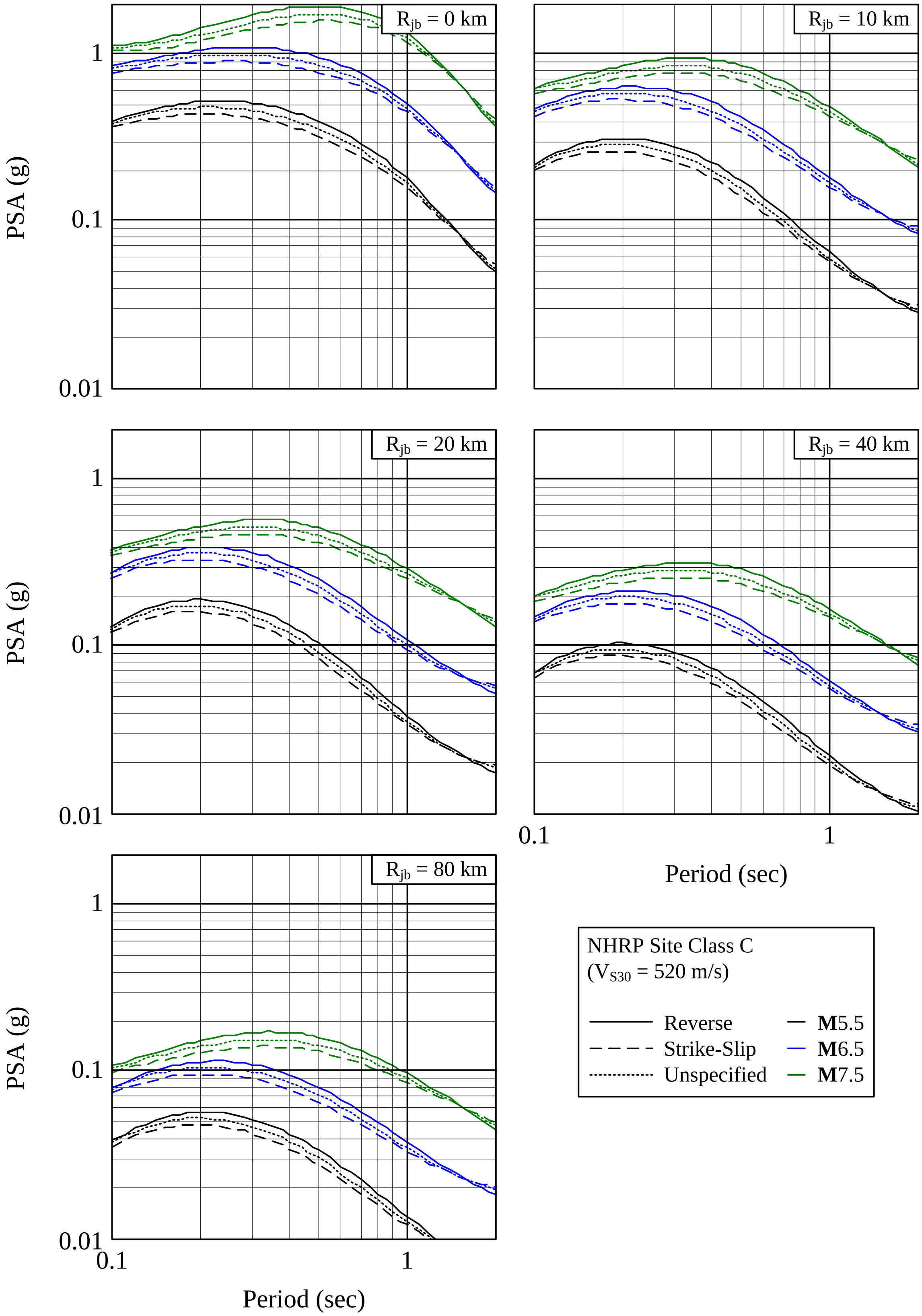


Figure 2-14. Predicted spectral acceleration for various distances, magnitudes and fault types as a function of period for NEHRP site class C conditions (V_{S30} = 520 m/s).

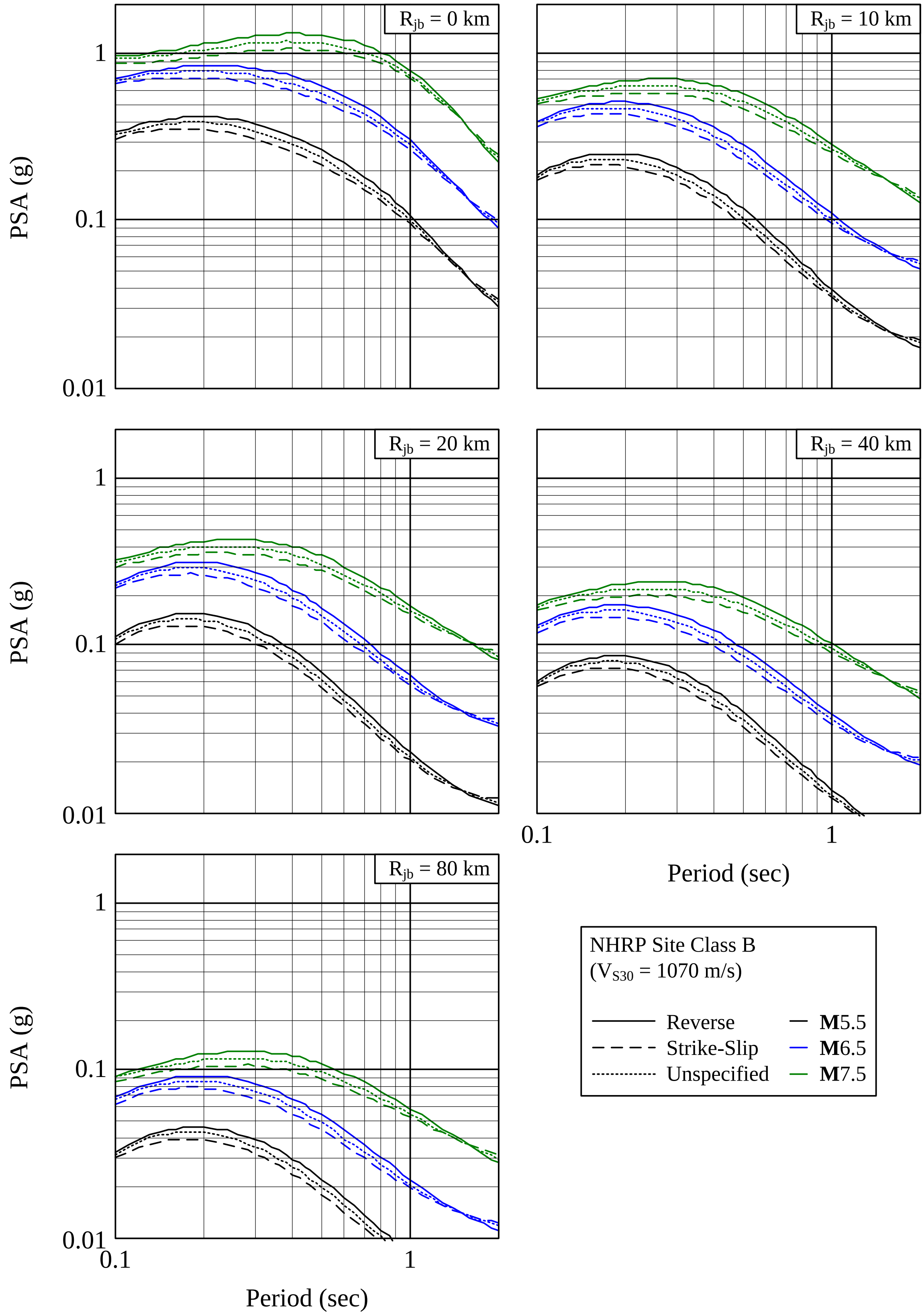


Figure 2-15. Predicted spectral acceleration for various distances, magnitudes and fault types as a function of period for NEHRP site class B conditions (V_{S30} = 1070 m/s).

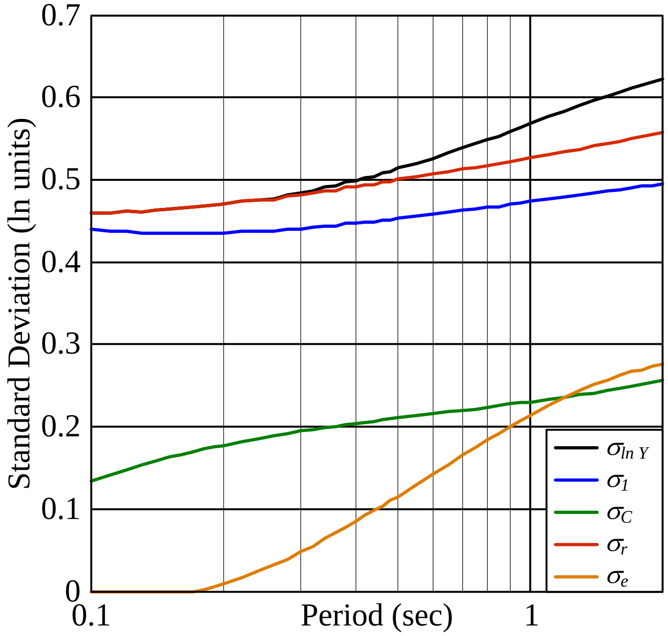


Figure 2-16. Standard deviations (with erratum).

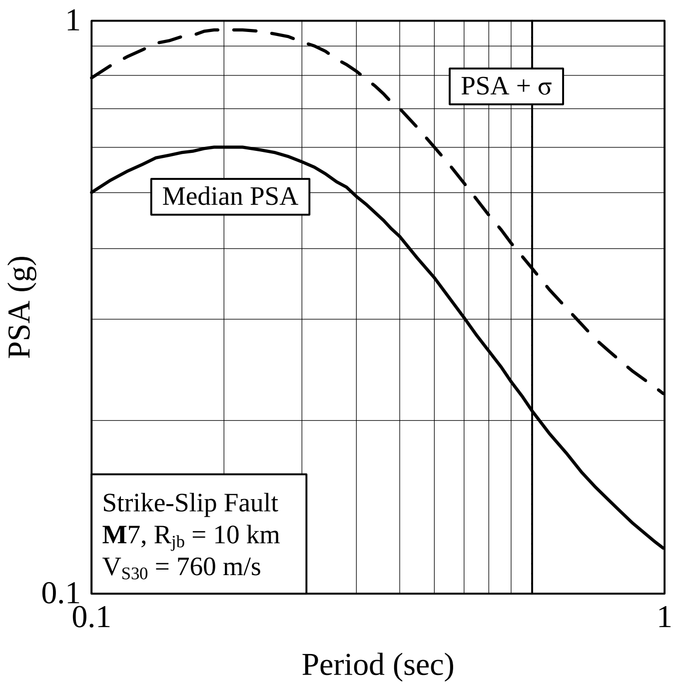


Figure 2-17. Example of application of median PSA plus one standard deviation.

2.2.5 Database

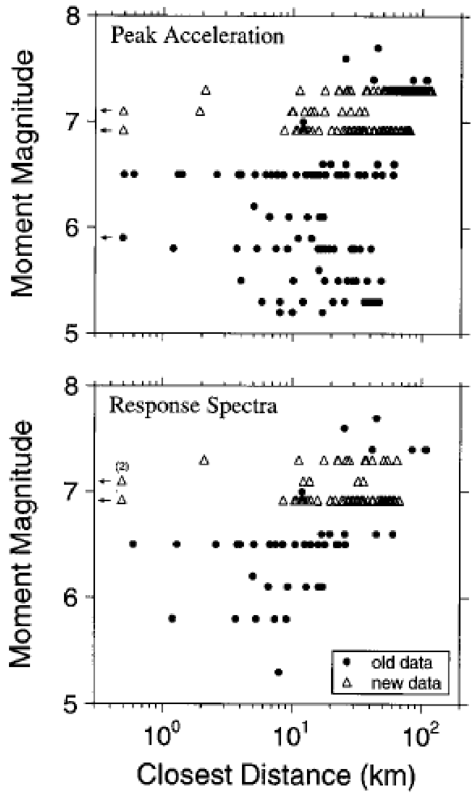


Figure 2-18. The distribution of the data in magnitude and distance (each point represents a recording). The data points labeled old data are ones that were also used in Joyner and Boore, 1981 and 1982. The top frame is for the peak acceleration dataset, and the bottom is for the response spectral data set.

2.2.6 MATLAB Code

```
% by Jack Baker, 2/1/05
% Stanford University
% bakerjw@stanford.edu
%
% edited by Kathryn A. Gunberg 3/2/09
%
% Boore Joyner and Fumal attenuation model (1997 Seismological Research
% Letters, Vol 68, No 1, p154).
%
% This script includes standard deviations for either
% arbitrary or average components of ground motion See Baker, JW, and
% Cornell, CA (2006). "Which spectral acceleration are you using?"
% Earthquake Spectra, 22(2), 293-312.
%
% This script has also been modified to correct an error in the original
% publication. See Boore, DM (2005). "Erratum: Equations for Estimating
% Horizontal Response Spectra and Peak Acceleration from Western North
% American Earthquakes: A Summary of Recent Work." Seismological Research
% Letters, 76(3), 368-369.
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T             = Period (0.1 to 2s or 0 for PGA)
% M             = Moment Magnitude
% F             = Fault type: 0 for unspecified, 1 for strike-slip fault
%                 2 for reverse-slip fault
% Rjb           = Joyner-Boore distance (km)
% Vs            = Shear wave velocity averaged over top 30 m (m/s)
%                 (use 310 for soil, 620 for rock)
% arb           = Error type: 1 for arbitrary, 0 for average
% -------------------------------------------------------------------------
% Output
% Sa            = median spectral acceleration prediction (g)
% sigma         = logarithmic standard deviation of spectral acceleration
%                 prediction FOR AN ARBITRARY OR AVERAGE COMPONENT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa, sigma] = BJF_1997(T, M, F, Rjb, Vs, arb)
period  =  [0       0.1     0.11    0.12    0.13    0.14    0.15    0.16    0.17    ...
    0.18    0.19    0.2     0.22    0.24    0.26    0.28    0.3     0.32    0.34    ...
    0.36    0.38    0.4     0.42    0.44    0.46    0.48    0.5     0.55    0.6     ...
    0.65    0.7     0.75    0.8     0.85    0.9     0.95    1       1.1     1.2     ...
    1.3     1.4     1.5     1.6     1.7     1.8     1.9     2];
if F == 1
    B1  =  [-0.313  1.006   1.072   1.109   1.128   1.135   1.128   1.112   1.09    ...
    1.063   1.032   0.999   0.925   0.847   0.764   0.681   0.598   0.518   0.439   ...
    0.361   0.286   0.212   0.14    0.073   0.005   -0.058  -0.122  -0.268  -0.401  ...
    -0.523  -0.634  -0.737  -0.829  -0.915  -0.993  -1.066  -1.133  -1.249  -1.345  ...
    -1.428  -1.495  -1.552  -1.598  -1.634  -1.663  -1.685  -1.699 ];
elseif F == 2
    B1  =  [-0.117  1.087   1.164   1.215   1.246   1.261   1.264   1.257   1.242   ...
    1.222   1.198   1.17    1.104   1.033   0.958   0.881   0.803   0.725   0.648   ...
    0.57    0.495   0.423   0.352   0.282   0.217   0.151   0.087   -0.063  -0.203  ...
    -0.331  -0.452  -0.562  -0.666  -0.761  -0.848  -0.932  -1.009  -1.145  -1.265  ...
    -1.37   -1.46   -1.538  -1.608  -1.668  -1.718  -1.763  -1.801 ];
else
    B1  =  [-0.242  1.059   1.13    1.174   1.2     1.208   1.204   1.192   1.173   ...
    1.151   1.122   1.089   1.019   0.941   0.861   0.78    0.7     0.619   0.54    ...
    0.462   0.385   0.311   0.239   0.169   0.102   0.036   -0.025  -0.176  -0.314  ...
    -0.44   -0.555  -0.661  -0.76   -0.851  -0.933  -1.01   -1.08   -1.208  -1.315  ...
    -1.407  -1.483  -1.55   -1.605  -1.652  -1.689  -1.72   -1.743 ];
end
B2      =  [0.527   0.753   0.732   0.721   0.711   0.707   0.702   0.702   0.702   ...
    0.705   0.709   0.711   0.721   0.732   0.744   0.758   0.769   0.783   0.794   ...
    0.806   0.82    0.831   0.84    0.852   0.863   0.873   0.884   0.907   0.928   ...
    0.946   0.962   0.979   0.992   1.006   1.018   1.027   1.036   1.052   1.064   ...
    1.073   1.08    1.085   1.087   1.089   1.087   1.087   1.085 ];
B3      =  [0       -0.226  -0.23   -0.233  -0.233  -0.23   -0.228  -0.226  -0.221  ...
```

```
    -0.216  -0.212  -0.207  -0.198  -0.189  -0.18   -0.168  -0.161  -0.152  -0.143  ...
    -0.136  -0.127  -0.12   -0.113  -0.108  -0.101  -0.097  -0.09   -0.078  -0.069  ...
    -0.06   -0.053  -0.046  -0.041  -0.037  -0.035  -0.032  -0.032  -0.03   -0.032  ...
    -0.035  -0.039  -0.044  -0.051  -0.058  -0.067  -0.074  -0.085 ];
B5      =  [-0.778  -0.934  -0.937  -0.939  -0.939  -0.938  -0.937  -0.935  -0.933  ...
    -0.93   -0.927  -0.924  -0.918  -0.912  -0.906  -0.899  -0.893  -0.888  -0.882  ...
    -0.877  -0.872  -0.867  -0.862  -0.858  -0.854  -0.85   -0.846  -0.837  -0.83   ...
    -0.823  -0.818  -0.813  -0.809  -0.805  -0.802  -0.8    -0.798  -0.795  -0.794  ...
    -0.793  -0.794  -0.796  -0.798  -0.801  -0.804  -0.808  -0.812 ];
Bv      =  [-0.371  -0.212  -0.211  -0.215  -0.221  -0.228  -0.238  -0.248  -0.258  ...
    -0.27   -0.281  -0.292  -0.315  -0.338  -0.36   -0.381  -0.401  -0.42   -0.438  ...
    -0.456  -0.472  -0.487  -0.502  -0.516  -0.529  -0.541  -0.553  -0.579  -0.602  ...
    -0.622  -0.639  -0.653  -0.666  -0.676  -0.685  -0.692  -0.698  -0.706  -0.71   ...
    -0.711  -0.709  -0.704  -0.697  -0.689  -0.679  -0.667  -0.655 ];
Va      =  [1396    1112    1291    1452    1596    1718    1820    1910    1977    ...
    2037    2080    2118    2158    2178    2173    2158    2133    2104    2070    ...
    2032    1995    1954    1919    1884    1849    1816    1782    1710    1644    ...
    1592    1545    1507    1476    1452    1432    1416    1406    1396    1400    ...
    1416    1442    1479    1524    1581    1644    1714    1795 ];
h       =  [5.57    6.27    6.65    6.91    7.08    7.18    7.23    7.24    7.21    ...
    7.16    7.1     7.02    6.83    6.62    6.39    6.17    5.94    5.72    5.5     ...
    5.3     5.1     4.91    4.74    4.57    4.41    4.26    4.13    3.82    3.57    ...
    3.36    3.2     3.07    2.98    2.92    2.89    2.88    2.9     2.99    3.14    ...
    3.36    3.62    3.92    4.26    4.62    5.01    5.42    5.85 ];
sigma1  =  [0.431   0.44    0.437   0.437   0.435   0.435   0.435   0.435   0.435   ...
    0.435   0.435   0.435   0.437   0.437   0.437   0.44    0.44    0.442   0.444   ...
    0.444   0.447   0.447   0.449   0.449   0.451   0.451   0.454   0.456   0.458   ...
    0.461   0.463   0.465   0.467   0.467   0.47    0.472   0.474   0.477   0.479   ...
    0.481   0.484   0.486   0.488   0.49    0.493   0.493   0.495 ];
sigmac  =  [0.160   0.134   0.141   0.148   0.153   0.158   0.163   0.166   0.169   ...
    0.173   0.176   0.177   0.182   0.185   0.189   0.192   0.195   0.197   0.199   ...
    0.200   0.202   0.204   0.205   0.206   0.209   0.210   0.211   0.214   0.216   ...
    0.218   0.220   0.221   0.223   0.226   0.228   0.230   0.230   0.233   0.236   ...
    0.239   0.241   0.244   0.246   0.249   0.251   0.254   0.256];
sigmar  =  [0.460   0.460   0.459   0.462   0.461   0.463   0.464   0.466   0.467   ...
    0.468   0.469   0.470   0.474   0.475   0.476   0.480   0.481   0.484   0.486   ...
    0.487   0.491   0.491   0.494   0.494   0.497   0.497   0.501   0.504   0.507   ...
    0.510   0.513   0.515   0.517   0.519   0.522   0.525   0.527   0.531   0.534   ...
    0.537   0.541   0.544   0.547   0.550   0.553   0.555   0.557];
sigmae  =  [0.184   0       0       0       0       0       0       0       0       ...
    0.002   0.005   0.009   0.016   0.025   0.032   0.039   0.048   0.055   0.064   ...
    0.071   0.078   0.085   0.092   0.099   0.104   0.111   0.115   0.129   0.143   ...
    0.154   0.166   0.175   0.184   0.191   0.2     0.207   0.214   0.226   0.235   ...
    0.244   0.251   0.256   0.262   0.267   0.269   0.274   0.276 ];
sigmalny = [0.495   0.460   0.459   0.462   0.461   0.463   0.464   0.466   0.467   ...
    0.468   0.469   0.470   0.474   0.475   0.477   0.482   0.484   0.487   0.491   ...
    0.492   0.497   0.499   0.502   0.504   0.508   0.510   0.514   0.520   0.526   ...
    0.533   0.539   0.544   0.549   0.553   0.559   0.564   0.569   0.577   0.583   ...
    0.590   0.596   0.601   0.606   0.611   0.615   0.619   0.622];
% interpolate between periods if neccesary
if (length(find(period == T)) == 0)
    index_low = sum(period<T);
    T_low = period(index_low);
    T_hi = period(index_low+1);
    [sa_low, sigma_low] = BJF_1997(T_low, M, F, Rjb, Vs, arb);
    [sa_hi, sigma_hi]   = BJF_1997(T_hi,  M, F, Rjb, Vs, arb);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(period == T);
    r = sqrt(Rjb^2 + h(i)^2);
    Sa = exp(B1(i) + B2(i)*(M-6) + B3(i)*(M-6)^2 + B5(i)*log(r) + Bv(i)*log(Vs / Va(i)));
    if (arb) % arbitrary component sigma
        sigma = sigmalny(i);
    else     % average component sigma
        sigma = sqrt(sigma1(i)^2 + sigmae(i)^2);
    end
end
```

2.3 Campbell – 1997

2.3.1 Reference

Campbell, K. W. (1997). Empirical Near-Source Attenuation Relationships for Horizontal and Vertical Components of Peak Ground Acceleration, Peak Ground Velocity, and Pseudo-Absolute Acceleration Response Spectra, *Seismological Research Letters* **68**, 154-179.

Campbell, K. W. (2000). ERRATUM: Empirical Near-Source Attenuation Relationships for Horizontal and Vertical Components of Peak Ground Acceleration, Peak Ground Velocity, and Pseudo-Absolute Acceleration Response Spectra, *Seismological Research Letters* **71**, 352-354.

Campbell, K. W. (2001). ERRATUM: Empirical Near-Source Attenuation Relationships for Horizontal and Vertical Components of Peak Ground Acceleration, Peak Ground Velocity, and Pseudo-Absolute Acceleration Response Spectra, *Seismological Research Letters* **72**, 474.

2.3.2 Abstract

Using strong ground motions from shallow active tectonic regions in western North American and around the globe, an empirical ground-motion model for the average horizontal and vertical components were developed. The model predicts peak ground acceleration (PGA, in g), peak ground velocity (PGV, in cm/s), and 5%-damped spectral values (in g) for periods ranging from 0.5 to 4.0 s. The model is applicable for earthquakes between M5.0 and M8.0, distances between 3 km and 60 km for PGA, distances from 3 km to 30 km for PGV and PSA for magnitudes less than 6.25 and 3 km to 50 km for magnitudes greater than 6.25.

2.3.3 Attenuation Relationship

The spectral acceleration is a function of:

T – Period (sec), use 0 for PGA, -1 for PGV
M – Moment magnitude
C – Component: 0 for horizontal component, 1 for vertical
F – Fault type: 1 for reverse fault, 0.5 for normal, 0 for strike-slip
R_{seis} – Closest distance between the site and the rupture plane in the zone of seismogenic rupture (km)
D – Depth to basement rock (km)
S – Soil type: 0 for alluvium/firm soil, 1 for soft rock, 2 for hard rock
sig_{type} – 1 for sigma as a function of **M**, 0 for sigma as a function of PGA

For the equations below, A, V, and SA correspond to the predicted PGA, PGV and PSA respectively. The subscripts, H and V correspond to the horizontal and vertical components.

$$\begin{aligned}\ln(A_H) = &-3.512 + 0.904M - 1.328\ln\sqrt{{R_{seis}}^2 + [0.149e^{0.647M}]^2} \\ &+ [1.125 - 0.112\ln(R_{seis}) - 0.0957M]F + [0.440 - 0.171\ln(R_{seis})]S_{SR} \\ &+ [0.405 - 0.222\ln(R_{seis})]S_{HR} + f_A(D)\end{aligned}$$

$$\ln(V_H) = \ln(A_H) + 0.26 + 0.29M - 1.44\ln[R_{seis} + 0.0203e^{0.958M}] \\ + 1.89\ln[R_{seis} + 0.361e^{0.576M}] + (0.0001 - 0.000565M)R_{seis} - 0.12F \\ - 0.15S_{SR} - 0.30S_{HR} + 0.75\tanh(0.51D)\,(1 - S_{HR}) + f_V(D)$$

$$\ln(SA_H) = \ln(A_H) + c_1 + c_2\tanh[c_3(M - 4.7)] + (c_4 + c_5M)R_{seis} + 0.5c_6S_{SR} + c_6S_{HR} \\ + c_7\tanh(c_8D)\,(1 - S_{HR}) + f_{SA}(D)$$

$$\ln(A_V) = \ln(A_H) - 1.58 - 0.10M - 1.5\ln[R_{seis} + 0.079e^{0.661M}] \\ + 1.89\ln[R_{seis} + 0.361e^{0.576M}] - 0.11F$$

$$\ln(V_V) = \ln(V_H) - 2.15 + 0.07M - 1.24\ln[R_{seis} + 0.00394e^{1.17M}] \\ + 1.44\ln[R_{seis} + 0.0203e^{0.958M}] + 0.10F \\ + [0.46\tanh(2.68D) - 0.53\tanh(0.47D)](1 - S_{HR})$$

$$\ln(SA_V) = \ln(SA_H) + c_1 - 0.10M + c_2\tanh[0.71(M - 4.7)] + c_3\tanh[0.66(M - 4.7)] \\ - 1.5\ln[R_{seis} + 0.079e^{0.661M}] + 1.89\ln[R_{seis} + 0.361e^{0.576M}] - 0.11F \\ + [c_4\tanh(0.51D) + c_5\tanh(0.57D)](1 - S_{HR})$$

where:

$$\mathrm{S_{SR}} = \begin{cases} 1 & for\ S = 1 \\ 0 & otherwise \end{cases} \qquad \mathrm{S_{HR}} = \begin{cases} 1 & for\ S = 2 \\ 0 & otherwise \end{cases}$$

$$f_A(D) = \begin{cases} 0 & for\ D \geq 1\ km \\ \{[0.405 - 0.222\ln(R_{seis})] - [0.440 - 0.171\ln(R_{seis})]S_{SR}\} & \\ \qquad \times (1 - D)(1 - S_{HR}) & for\ D < 1\ km \end{cases}$$

$$f_V(D) = \begin{cases} 0 & for\ D \geq 1\ km \\ -0.30(1 - D)(1 - 0.5S_{SR})(1 - S_{HR}) & for\ D < 1\ km \end{cases}$$

$$f_{SA}(D) = \begin{cases} 0 & for\ D \geq 1\ km \\ c_6(1 - D)(1 - 0.5S_{SR})(1 - S_{HR}) & for\ D < 1\ km \end{cases}$$

Standard Error

$$\sigma_{A_H}(A_H) = \begin{cases} 0.55 & for\ A_H < 0.068\ g \\ 0.173 - 0.140\ln(A_H) & for\ 0.068\ g \leq A_H \leq 0.21\ g \\ 0.39 & for\ A_H > 0.21\ g \end{cases}$$

OR

$$\sigma_{A_H}(M) = \begin{cases} 0.889 - 0.0691M & for\ M < 7.4 \\ 0.38 & for\ M \geq 7.4 \end{cases}$$

$$\sigma_{V_H} = \sqrt{{\sigma_{A_H}}^2 + 0.06^2}$$

$$\sigma_{SA_H} = \sqrt{{\sigma_{A_H}}^2 + 0.27^2}$$

$$\sigma_{A_V} = \sqrt{{\sigma_{A_H}}^2 + 0.36^2}$$

$$\sigma_{V_V} = \sqrt{{\sigma_{V_H}}^2 + 0.30^2} = \sqrt{{\sigma_{A_H}}^2 + 0.06^2 + 0.30^2}$$

$$\sigma_{SA_V} = \sqrt{{\sigma_{SA_H}}^2 + 0.39^2} = \sqrt{{\sigma_{A_H}}^2 + 0.27^2 + 0.39^2}$$

Coefficients

Table 2-8. Coefficients for horizontal component.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
0.050	0.05	0.00	0.00	-0.0011	0.000055	0.20	0.00	0.00
0.075	0.27	0.00	0.00	-0.0024	0.000095	0.22	0.00	0.00
0.10	0.48	0.00	0.00	-0.0024	0.000007	0.14	0.00	0.00
0.15	0.72	0.00	0.00	-0.0010	-0.000270	-0.02	0.00	0.00
0.20	0.79	0.00	0.00	0.0011	-0.000530	-0.18	0.00	0.00
0.30	0.77	0.00	0.00	0.0035	-0.000720	-0.40	0.00	0.00
0.50	-0.28	0.74	0.66	0.0068	-0.001000	-0.42	0.25	0.62
0.75	-1.08	1.23	0.66	0.0077	-0.001000	-0.44	0.37	0.62
1.0	-1.79	1.59	0.66	0.0085	-0.001000	-0.38	0.57	0.62
1.5	-2.65	1.98	0.66	0.0094	-0.001000	-0.32	0.72	0.62
2.0	-3.28	2.23	0.66	0.0100	-0.001000	-0.36	0.83	0.62
3.0	-4.07	2.39	0.66	0.0108	-0.001000	-0.22	0.86	0.62
4.0	-4.26	2.03	0.66	0.0112	-0.001000	-0.30	1.05	0.62

Table 2-9. Coefficients for vertical component.

T (sec)	c_1	c_2	c_3	c_4	c_5
0.050	-1.32	0.00	0.00	0.00	0.00
0.075	-1.21	0.00	0.00	0.00	0.00
0.10	-1.29	0.00	0.00	0.00	0.00
0.15	-1.57	0.00	0.00	0.00	0.00
0.20	-1.73	0.00	0.00	0.00	0.00
0.30	-1.98	0.00	0.00	0.00	0.00
0.50	-2.03	0.46	-0.74	0.00	0.00
0.75	-1.79	0.67	-1.23	0.00	0.00
1.0	-1.82	1.13	-1.59	0.18	-0.18
1.5	-1.81	1.52	-1.98	0.57	-0.49
2.0	-1.65	1.65	-2.23	0.61	-0.63
3.0	-1.31	1.28	-2.39	1.07	-0.84
4.0	-1.35	1.15	-2.03	1.26	-1.17

2.3.4 Calibration Plots

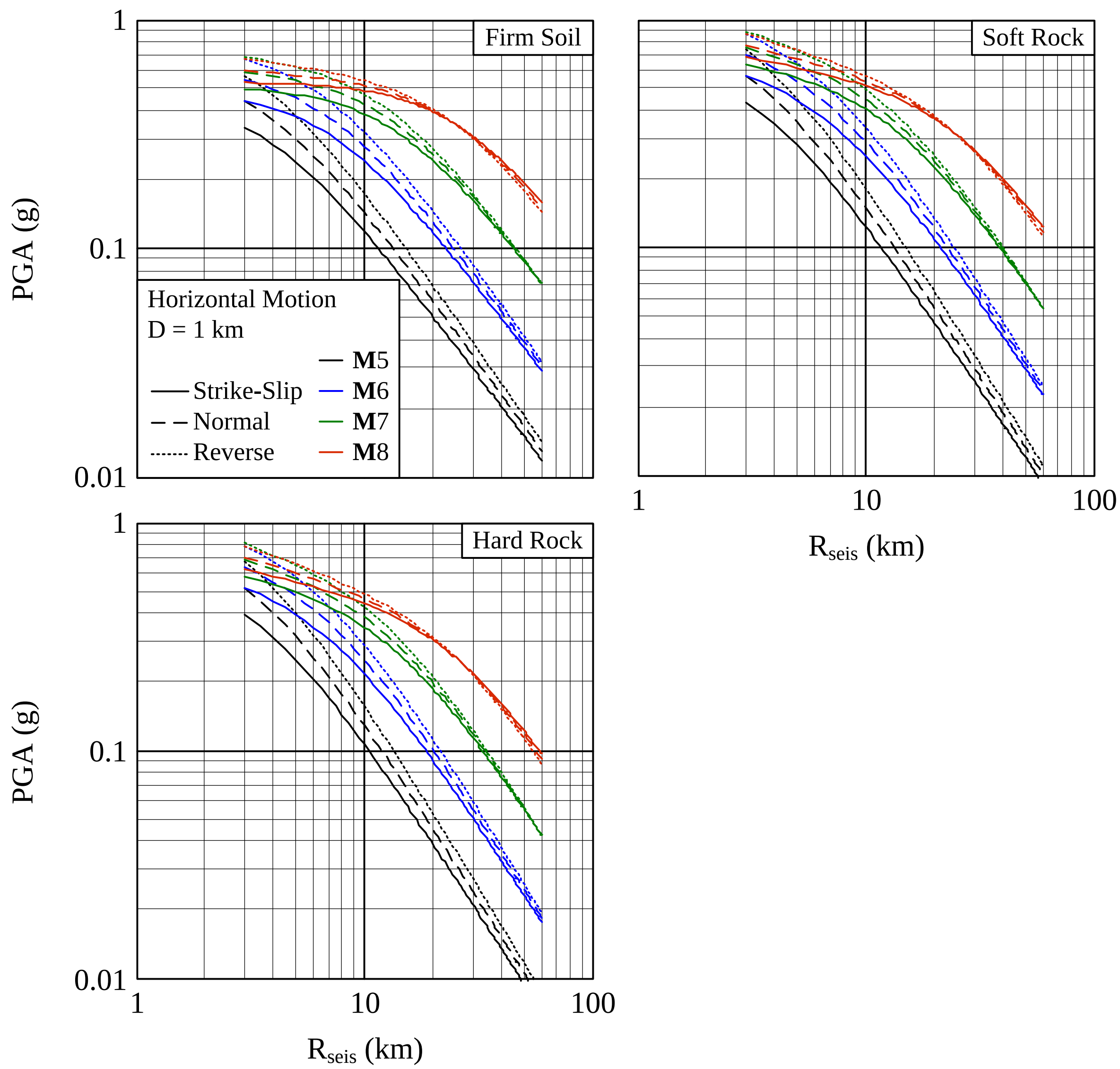


Figure 2-19. PGA as a function of distance for conditions shown.

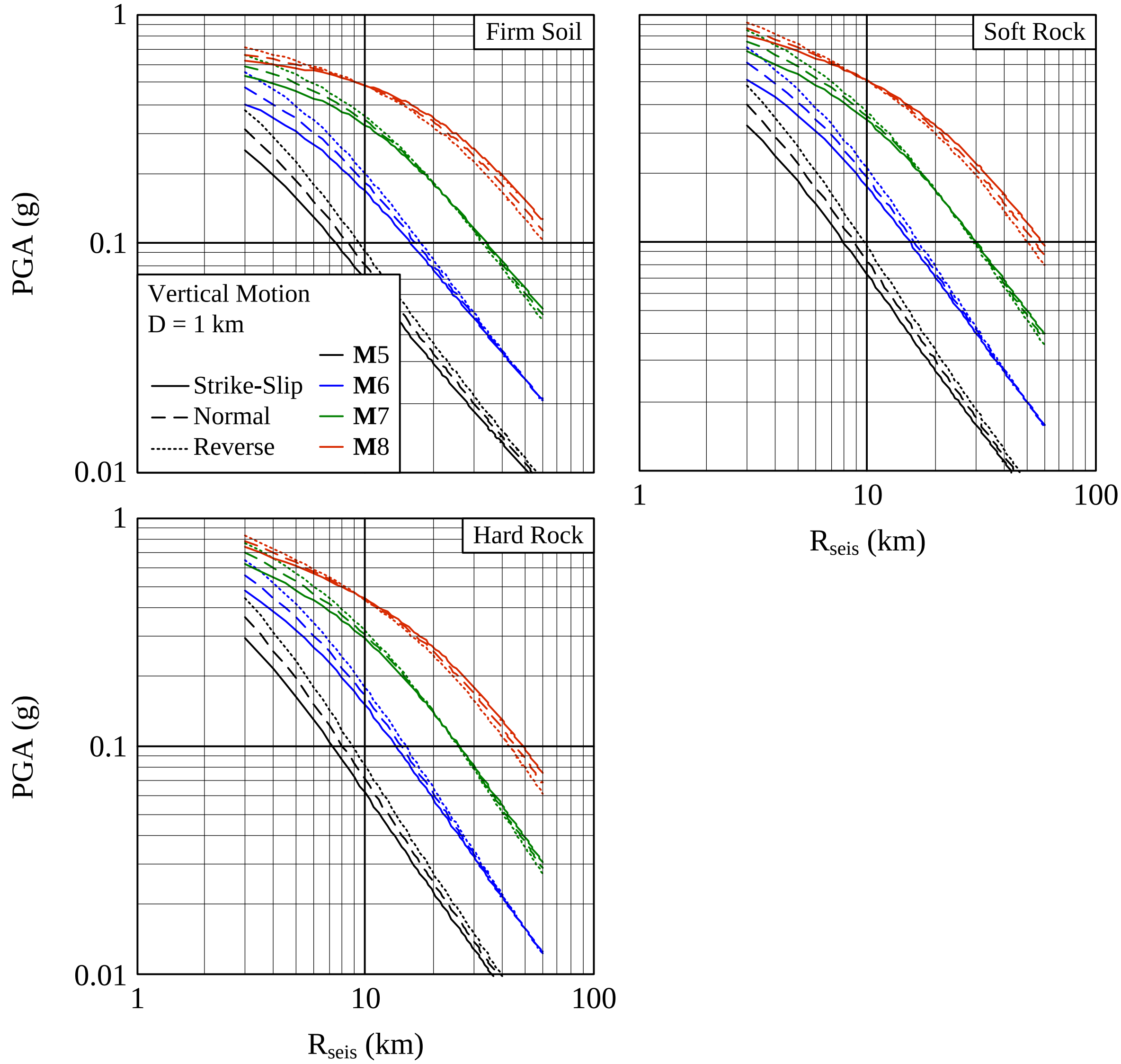


Figure 2-20. PGA as a function of distance for conditions shown.

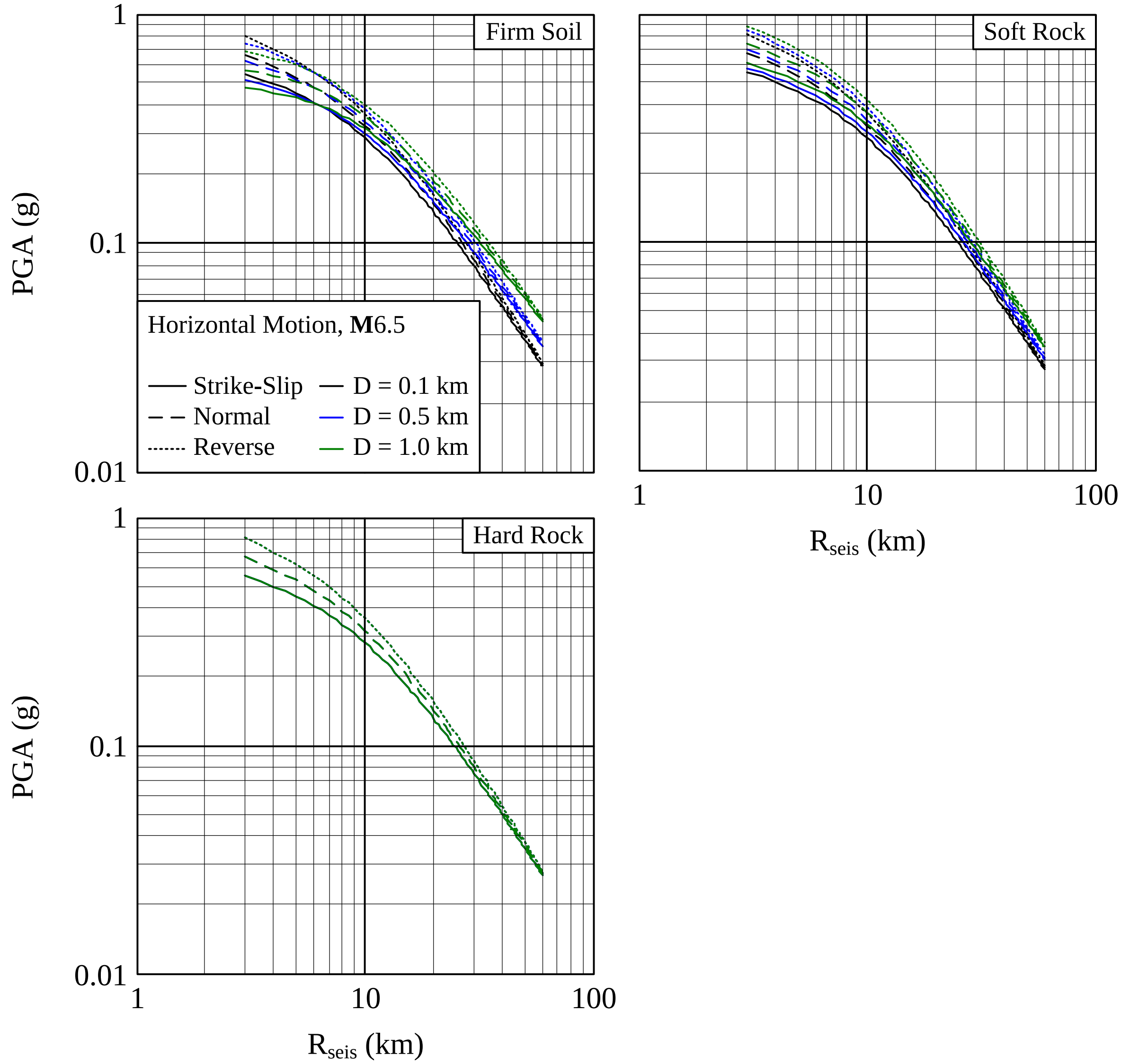


Figure 2-21. PGA as a function of distance for conditions shown.

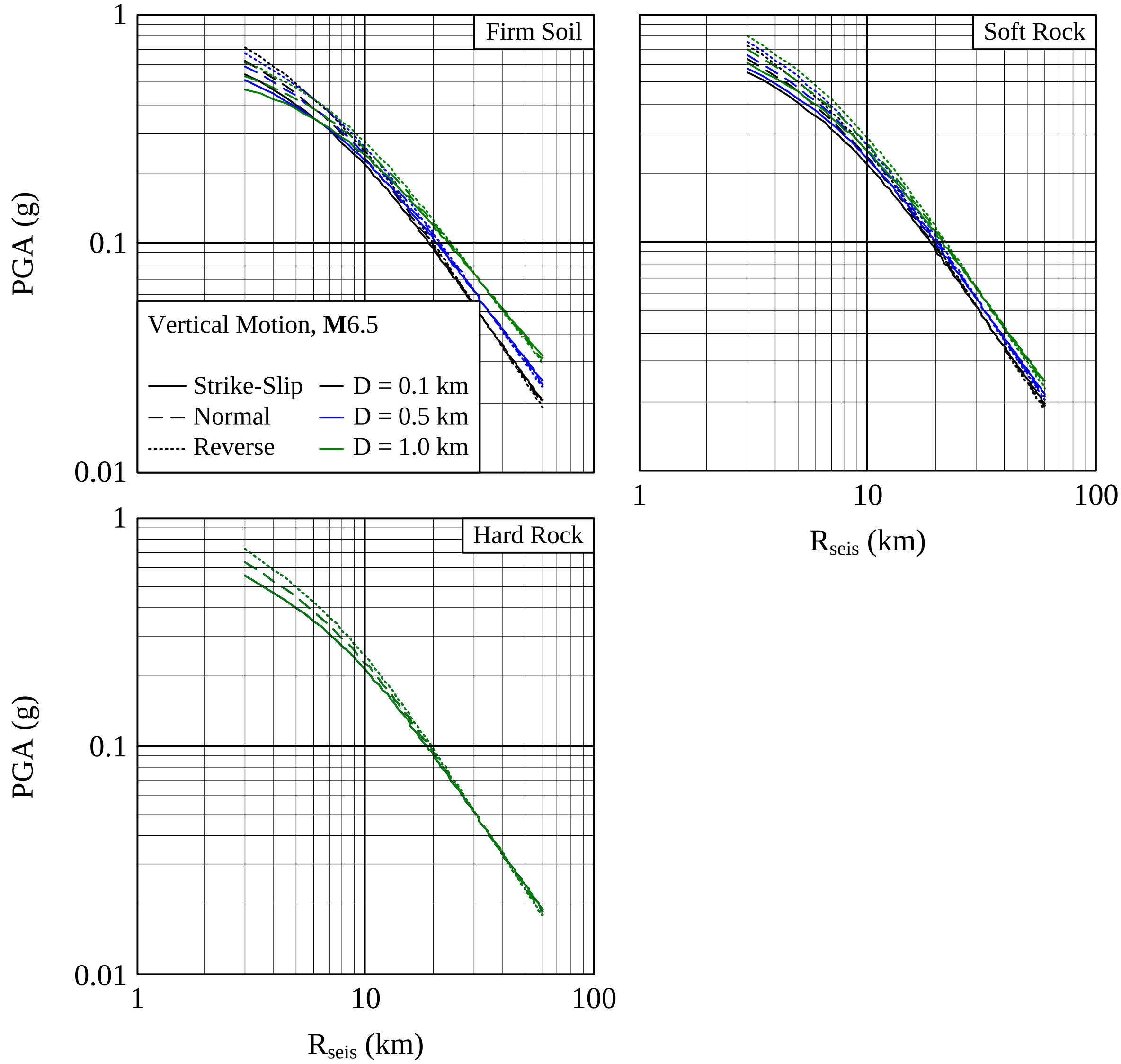


Figure 2-22. PGA as a function of distance for conditions shown.

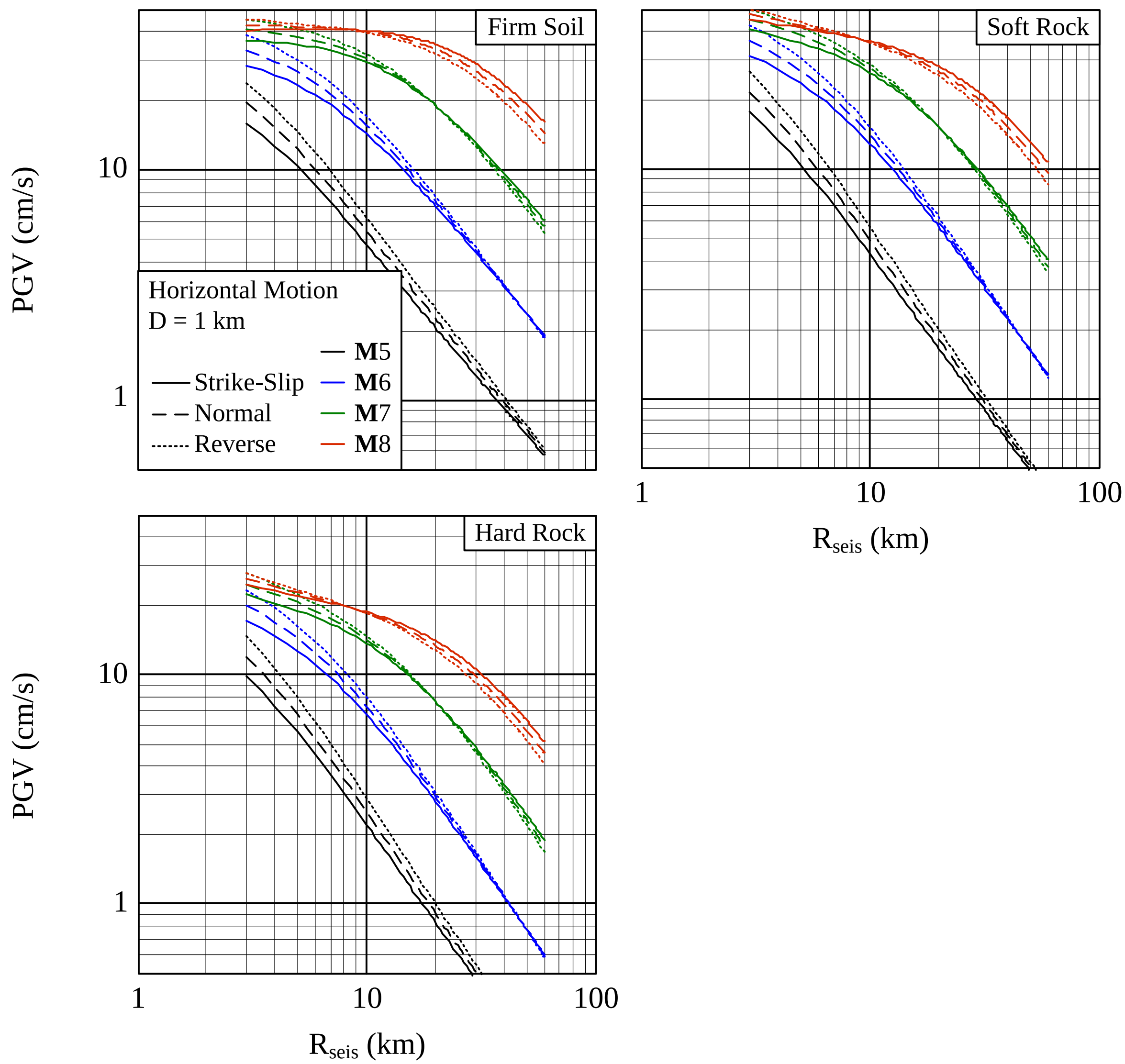


Figure 2-23. PGV as a function of distance for conditions shown.

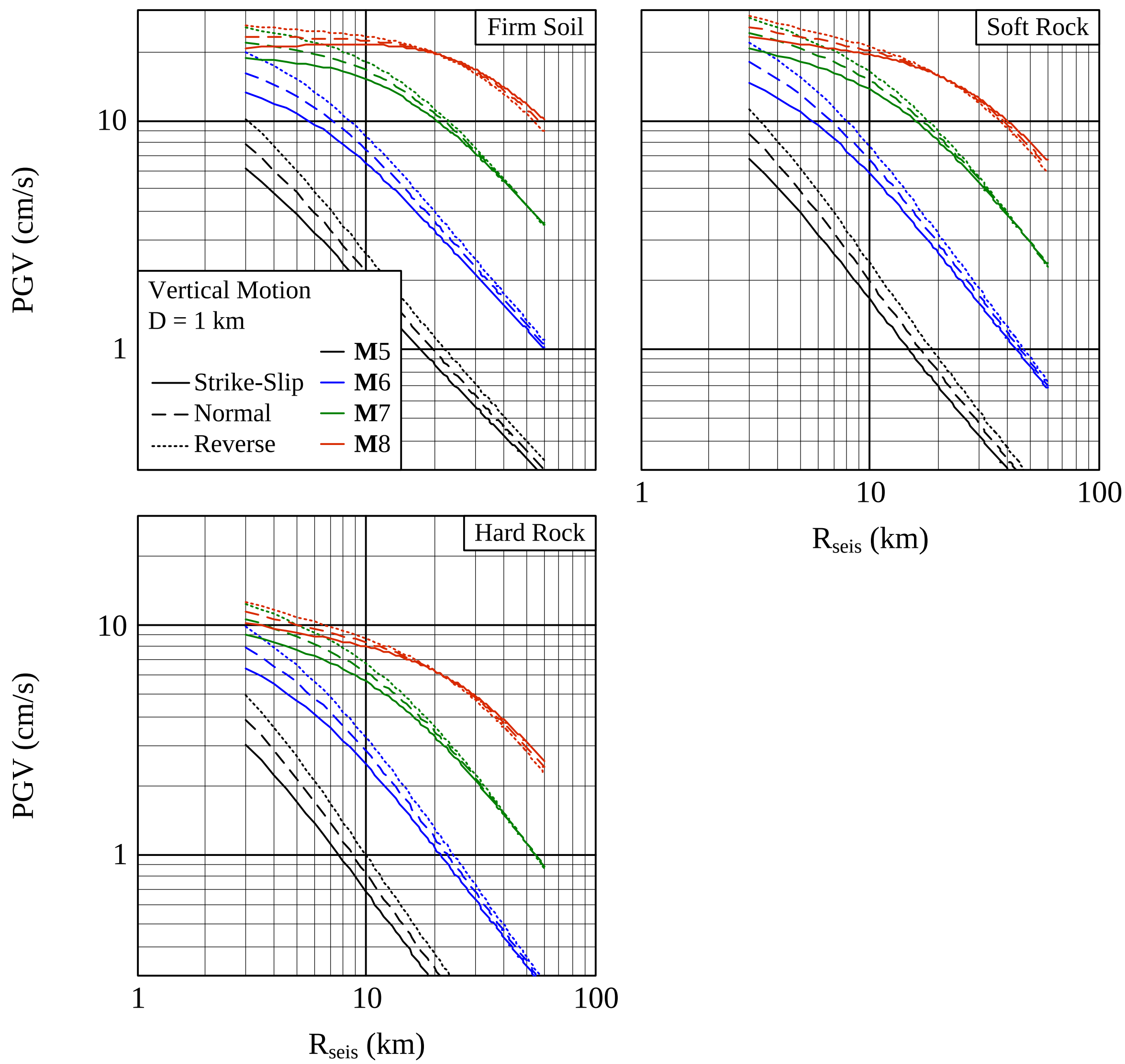


Figure 2-24. PGV as a function of distance for conditions shown.

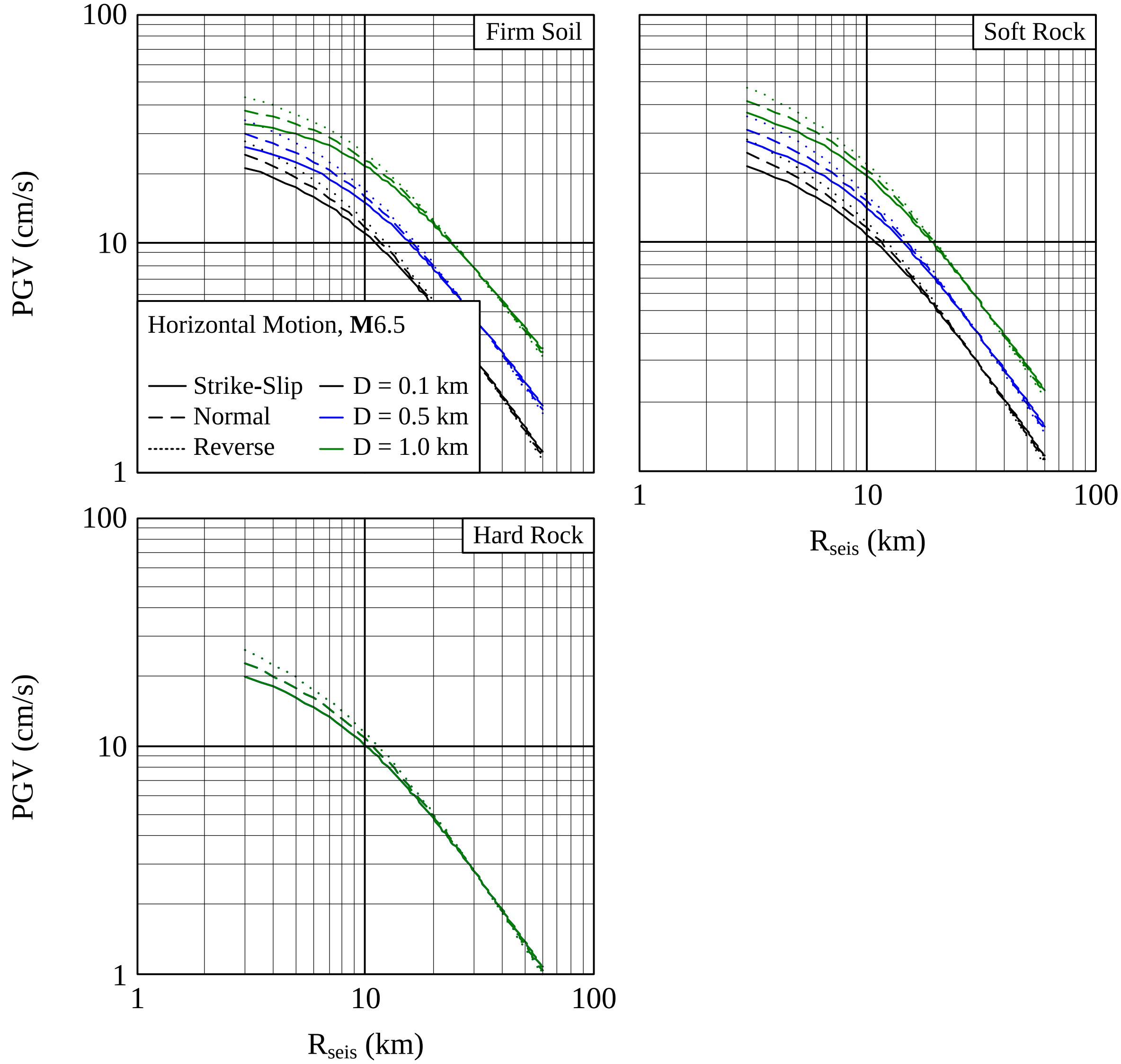


Figure 2-25. PGV as a function of distance for conditions shown.

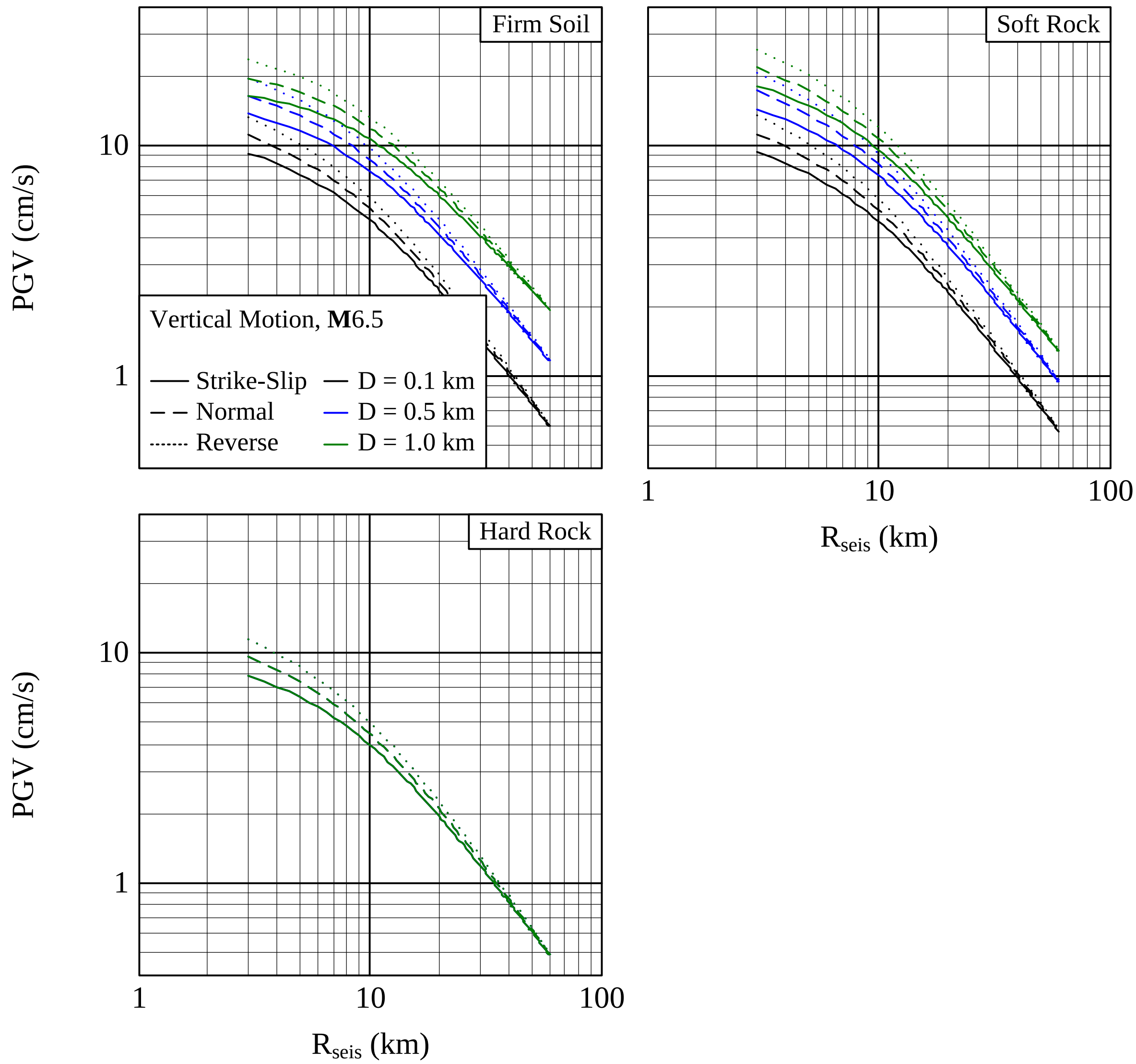


Figure 2-26. PGV as a function of distance for conditions shown.

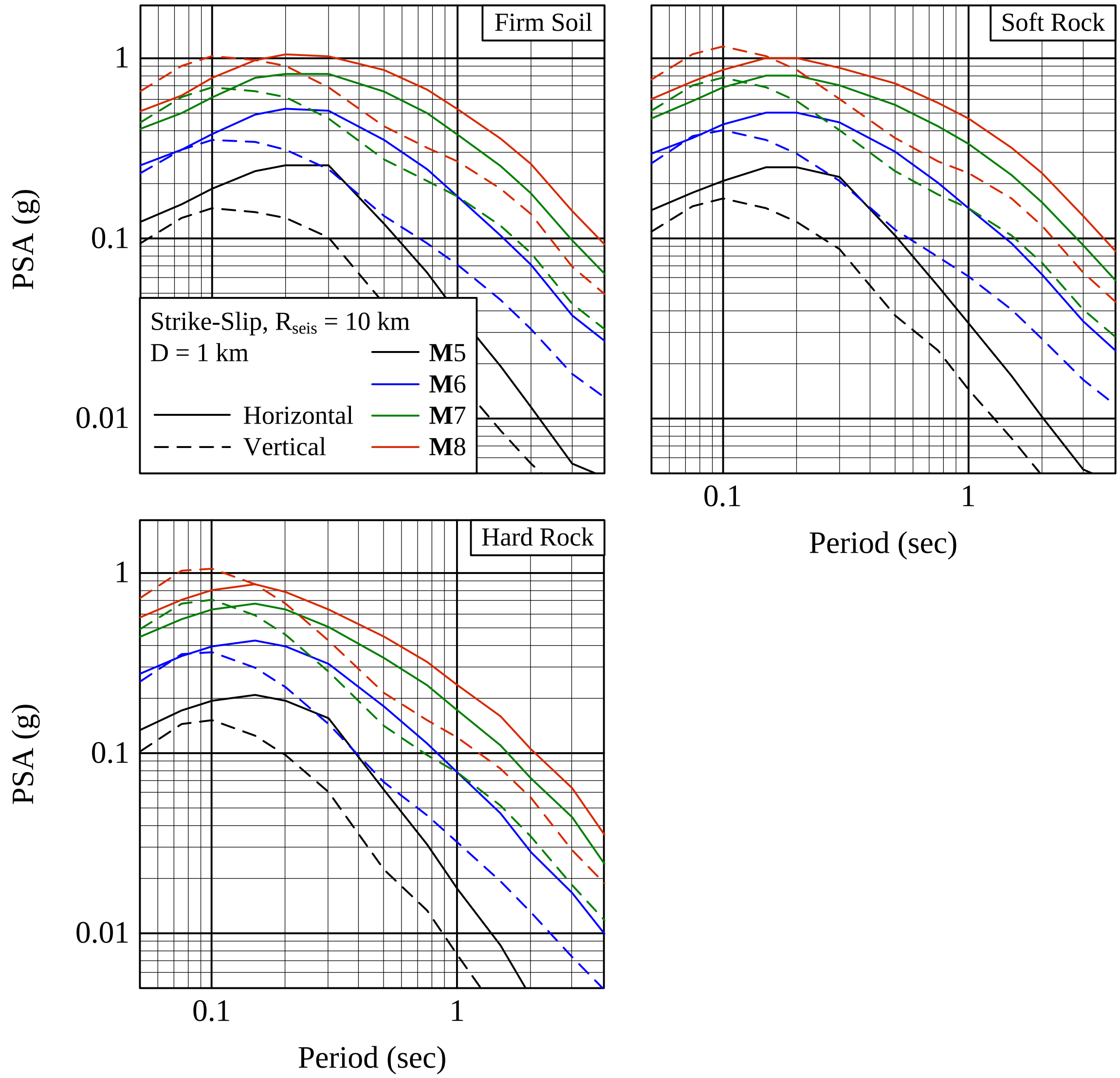


Figure 2-27. PSA as a function of period for conditions shown.

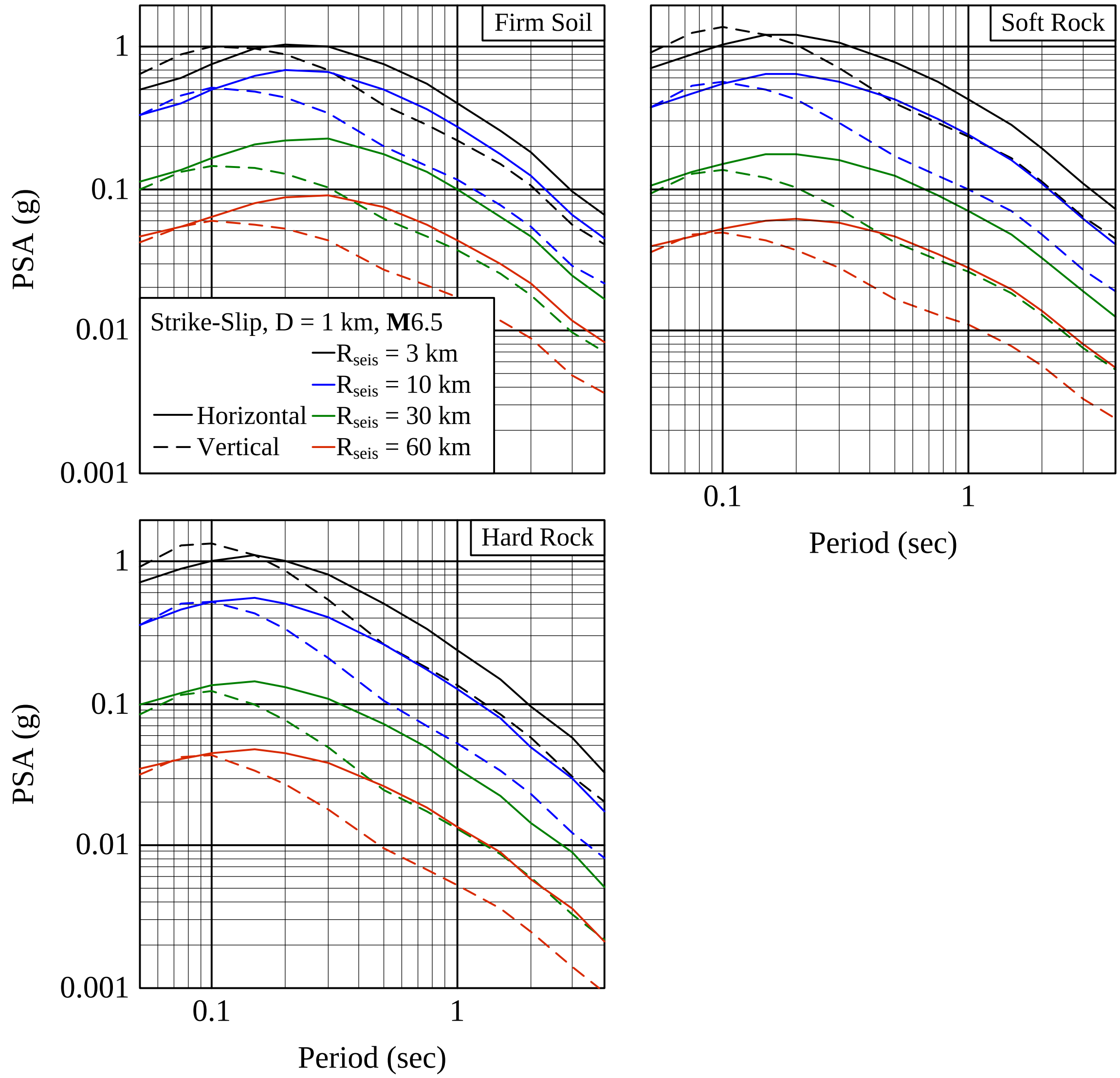


Figure 2-28. PSA as a function of period for conditions shown.

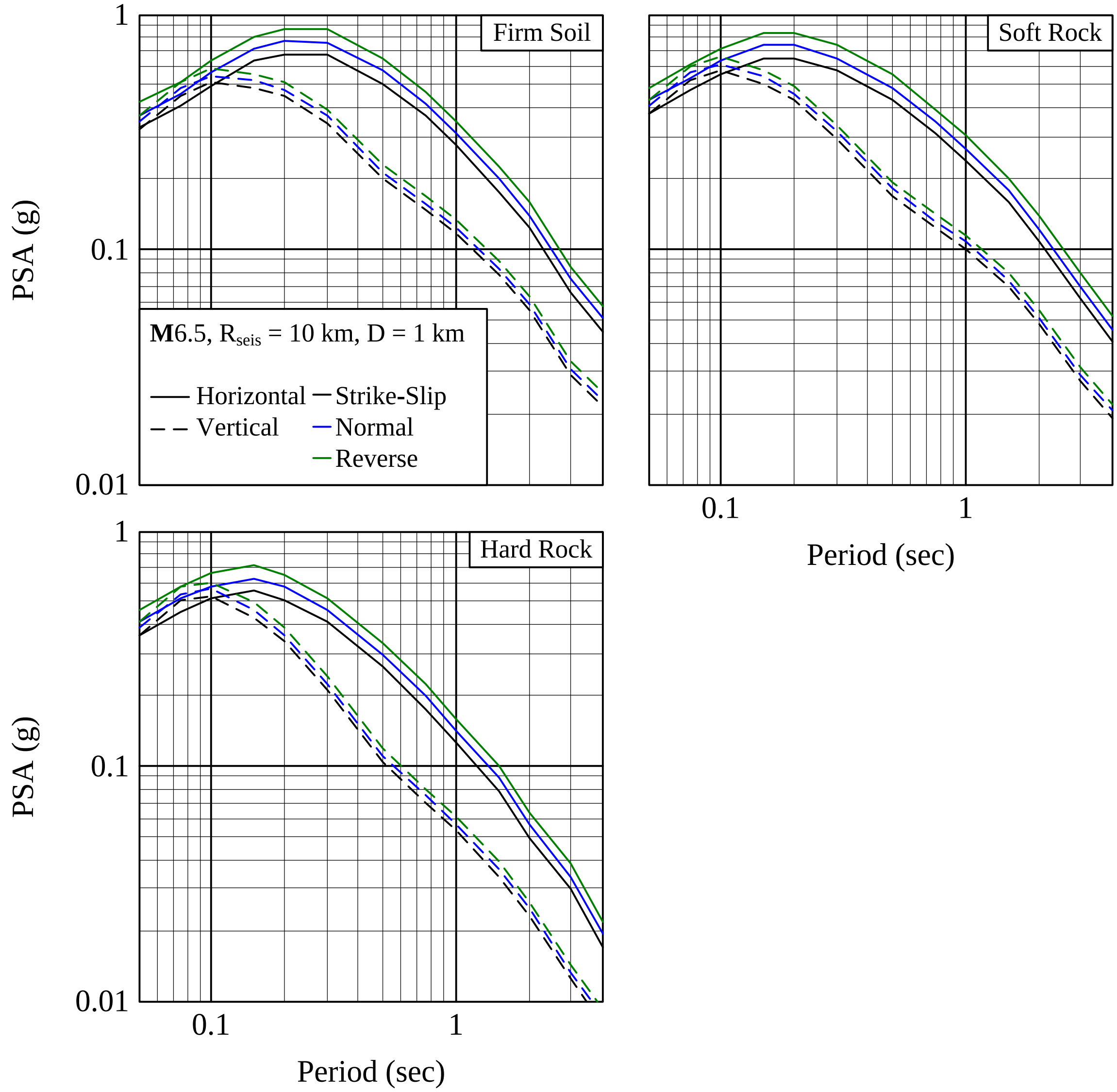


Figure 2-29. PSA as a function of period for conditions shown.

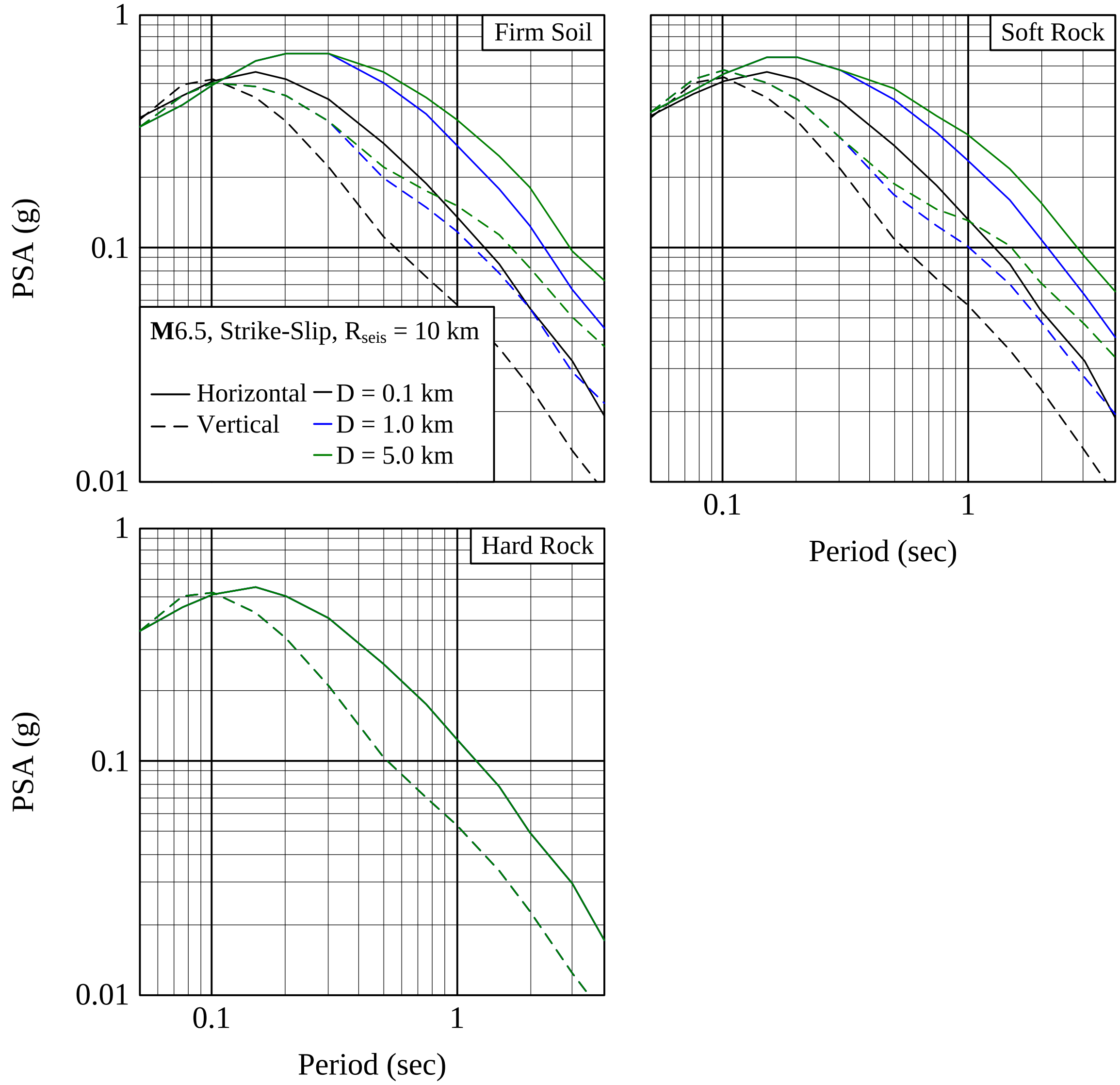


Figure 2-30. PSA as a function of distance for conditions shown.

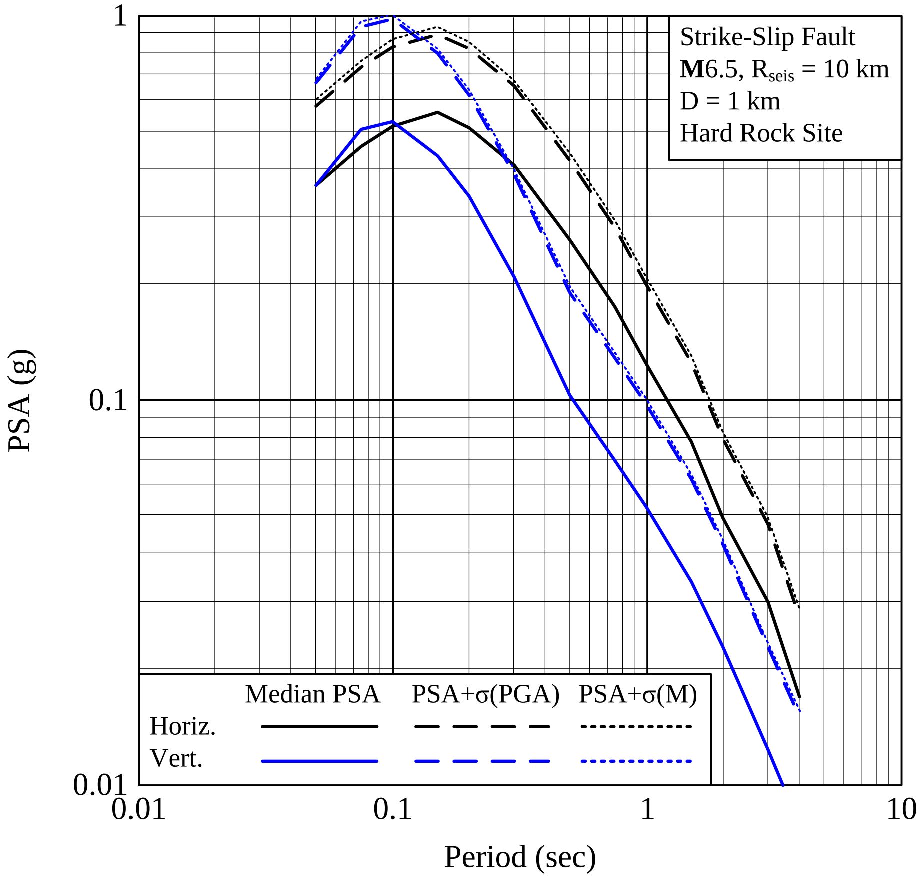


Figure 2-31. Example of application of median PSA plus one standard deviation.

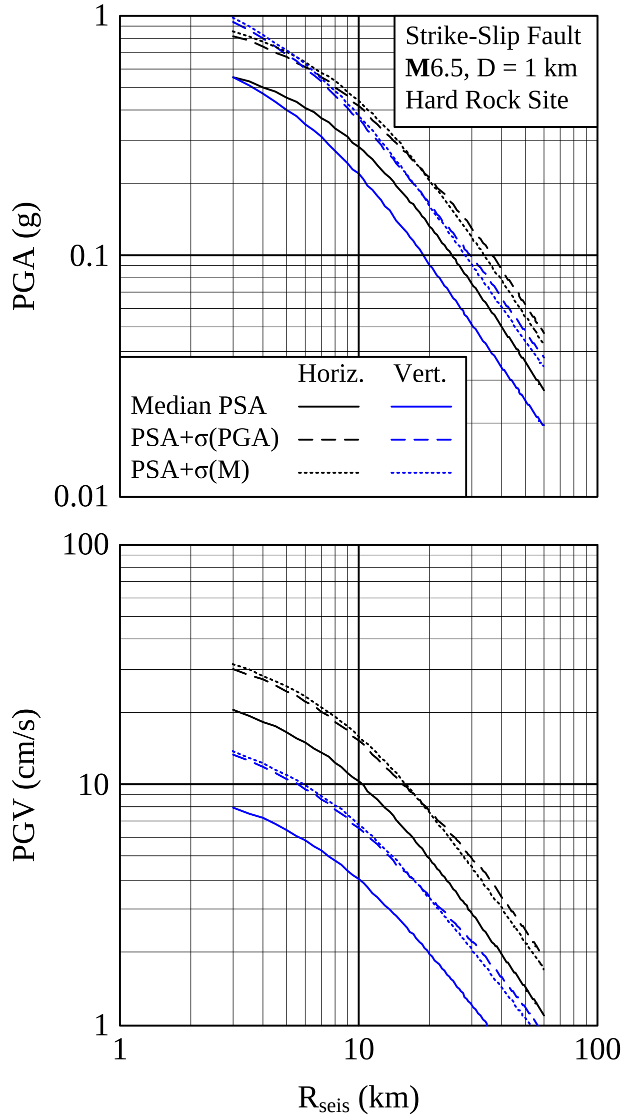


Figure 2-32. Example of application of median PGA and PGV plus one standard deviation.

2.3.5 Database

The table below describes the database used for this model.

Table 2-10. Ground motion database characteristics.

Description	PGA	PGV and PSA
Dates	1957-1993	1933-1987
No. of Recordings	645 (Horizontal); 225 (Vertical)	226 (Horizontal); 173 (Vertical)
No. of Earthquakes	47 (Horizontal); 26 (Vertical)	30 (Horizontal); 22 (Vertical)
Component	Mean of horizontal components; Vertical component	Mean of horizontal components; Vertical component
Magnitude Measure	M_W	M_S for $M_S < 6$; M_L for $M_S \geq 6$
Magnitude Range	4.7-8.0 (Horizontal) 4.7-8.1 (Vertical)	4.7-8.1
Distance Measure	Closest distance to seismogenic rupture (R_{SEIS})	Closest distance to seismogenic rupture (R_{SEIS})
Distance Range (km)	3.0-60.0	3.0-30.0 for $M < 6.25$ 3.0-50.0 for $M \geq 6.25$
Local Site Conditions	Firm Soil > 10m deep; Soft and Hard Rock	Firm Soil > 10m deep; Soft and Hard Rock
Style of Faulting	Strike Slip; Reverse and Thrust	Strike Slip; Reverse and Thrust
Depth of Rupture (km)	Upper crust (< 25 km)	Upper crust (< 25 km)
Recordings Excluded	Basement of buildings; > 2 stories (Soil & Soft Rock); > 5 stories (Hard Rock); Toe and base of dams; Base of bridge columns	Toe and base of dams
Regions	Active tectonic regions; Worldwide	Active tectonic regions; Worldwide

2.3.6 MATLAB Code

```
% by Kathryn A. Gunberg 3/4/2008
% Virginia Tech
% kgunberg@vt.edu
%
% Campbell attenuation equation, 1997
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0 for PGA, -1 for PGV
% M         = Moment magnitude
% C         = Componenet: 1 for vertical, 0 for horizontal
% F         = Fault type: 1 for reverse/thrust, 0.5 for normal, 0 for strike-slip
% Rseis     = Closest distance to rupture plane below seismogenic depth (km)
% D         = Depth to basement rock (km)
% S         = Soil type: 0 for alluvium/firm soil, 1 for soft rock, 2 for hard rock
% sig_type  = Error dependancy: 1 for function of M, 0 for function of PGA
% ---------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration or PGV prediction (g or cm/s)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = C_1997(T, M, C, F, Rseis, D, S, sig_type)
% Coefficients
period =   [-1      0       0.05    0.075   0.1     0.15    0.2     0.3     ...
            0.5     0.75    1       1.5     2       3       4];
c1h    =   [0       0       0.05    0.27    0.48    0.72    0.79    0.77    ...
            -0.28   -1.08   -1.79   -2.65   -3.28   -4.07   -4.26];
c2h    =   [0       0       0       0       0       0       0       0       ...
            0.74    1.23    1.59    1.98    2.23    2.39    2.03];
c3h    =   [0       0       0       0       0       0       0       0       ...
            0.66    0.66    0.66    0.66    0.66    0.66    0.66];
c4h    =   [0       0       -0.0011 -0.0024 -0.0024 -0.0010 0.0011  0.0035  ...
            0.0068  0.0077  0.0085  0.0094  0.0100  0.0108  0.0112];
c5h    =   [0       0       0.000055 0.000095 0.000007 -0.00027 -0.00053 ...
            -0.00072 -0.001 -0.001 -0.001 -0.001 -0.001 -0.001 -0.001];
c6h    =   [0       0       0.20    0.22    0.14    -0.02   -0.18   -0.40   ...
            -0.42   -0.44   -0.38   -0.32   -0.36   -0.22   -0.30];
c7h    =   [0       0       0       0       0       0       0       0       ...
            0.25    0.37    0.57    0.72    0.83    0.86    1.05];
c8h    =   [0       0       0       0       0       0       0       0       ...
            0.62    0.62    0.62    0.62    0.62    0.62    0.62];
c1v    =   [0       0       -1.32   -1.21   -1.29   -1.57   -1.73   -1.98   ...
            -2.03   -1.79   -1.82   -1.81   -1.65   -1.31   -1.35];
c2v    =   [0       0       0       0       0       0       0       0       ...
            0.46    0.67    1.13    1.52    1.65    1.28    1.15];
c3v    =   [0       0       0       0       0       0       0       0       ...
            -0.74   -1.23   -1.59   -1.98   -2.23   -2.39   -2.03];
c4v    =   [0       0       0       0       0       0       0       0       ...
            0       0       0.18    0.57    0.61    1.07    1.26];
c5v    =   [0       0       0       0       0       0       0       0       ...
            0       0       -0.18   -0.49   -0.63   -0.84   -1.17];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = C_1997(T_low, M, C, F, Rseis, D, S);
    [sa_hi,  sigma_hi]  = C_1997(T_hi,  M, C, F, Rseis, D, S);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    SSR = 0;
    SHR = 0;
    if S == 1
```

```
    SSR = 1;
elseif S == 2
    SHR = 1;
end
if D >= 1
    FA = 0;
else
    FA = ((0.405 - 0.222*log(Rseis)) - (0.440 - 0.171*log(Rseis))*SSR)*(1-D)*(1-SHR);
end
AH = exp(-3.512 + 0.904*M - 1.328*log(sqrt(Rseis^2+(0.149*exp(0.647*M))^2)) + ...
    (1.125 - 0.112*log(Rseis) - 0.0957*M)*F + (0.44 - 0.171*log(Rseis))*SSR + ...
    (0.405 - 0.222*log(Rseis))*SHR + FA);
if sig_type == 0
    if AH < 0.068
        sigmaAH = 0.55;
    elseif AH > 0.21
        sigmaAH = 0.39;
    else
        sigmaAH = 0.173 - 0.140*log(AH);
    end
else
    if M < 7.4
        sigmaAH = 0.889 - 0.0691*M;
    else
        sigmaAH = 0.38;
    end
end
if and(C == 0, T == 0)
    Sa = AH;
    sigma = sigmaAH;
    return
end
if D >=1
    FV = 0;
else
    FV = -0.30*(1-D)*(1-0.5*SSR)*(1-SHR);
end
VH = exp(log(AH) + 0.26 + 0.29*M - 1.44*log(Rseis + 0.0203*exp(0.958*M)) + ...
    1.89*log(Rseis + 0.361*exp(0.576*M)) + (0.0001 - 0.000565*M)*Rseis - 0.12*F - ...
    0.15*SSR - 0.30*SHR + 0.75*tanh(0.51*D)*(1-SHR) + FV);
sigmaVH = sqrt(sigmaAH^2 + 0.06^2);
if and(C == 0, T == -1)
    Sa = VH;
    sigma = sigmaVH;
    return
end
if D >=1
    FSA = 0;
else
    FSA = c6h(i)*(1-D)*(1-0.5*SSR)*(1-SHR);
end
SH = exp(log(AH) + c1h(i) + c2h(i)*tanh(c3h(i)*(M - 4.7)) + Rseis*(c4h(i) + ...
    c5h(i)*M) + 0.5*c6h(i)*SSR + c6h(i)*SHR + c7h(i)*tanh(c8h(i)*D)*(1-SHR) + FSA);
sigmaSH = sqrt(sigmaAH^2 + 0.27^2);
if C == 0
    Sa = SH;
    sigma = sigmaSH;
    return
end
if T == 0
    Sa = exp(log(AH) - 1.58 - 0.10*M - 1.5*log(Rseis + 0.079*exp(0.661*M)) + ...
        1.89*log(Rseis + 0.361*exp(0.576*M)) - 0.11*F);
    sigma = sqrt(sigmaAH^2 + 0.36^2);
elseif T == -1
    Sa = exp(log(VH) - 2.15 + 0.07*M - 1.24*log(Rseis + 0.00394*exp(1.17*M)) + ...
        1.44*log(Rseis + 0.0203*exp(0.958*M)) + 0.10*F + (0.46*tanh(2.68*D) - ...
        0.53*tanh(0.47*D))*(1-SHR));
    sigma = sqrt(sigmaVH^2 + 0.30^2);
else
    Sa = exp(log(SH) + c1v(i) - 0.10*M + c2v(i)*tanh(0.71*(M-4.7)) + ...
        c3v(i)*tanh(0.66*(M-4.7)) - 1.50*log(Rseis + 0.079*exp(0.661*M)) + ...
```

```
            1.89*log(Rseis + 0.361*exp(0.576*M)) - 0.11*F + (c4v(i)*tanh(0.51*D) + ...
            c5v(i)*tanh(0.57*D))*(1-SHR));
        sigma = sqrt(sigmaSH^2 + 0.39^2);
    end
end
```

2.4 Sadigh, Chang, Egan, Makdisi and Youngs – 1997

2.4.1 Reference

Sadigh, K., C.-Y. Chang, J. A. Egan, F. Makdisi, and R. R. Youngs (1997). Attenuation Relationship for Shallow Crustal Earthquakes Based on California Strong Motion Data, *Seismological Research Letters* **68**, 180-189.

2.4.2 Abstract

Using strong ground motion data primarily from California earthquakes, an empirical ground-motion model for the average horizontal component was developed. The model predicts peak ground acceleration (PGA, in g) and 5%-damped spectral values (in g) for periods ranging from 0.07 to 4 s for rock and deep soil sites and for strike-slip and reverse faulting earthquakes. The model is applicable for earthquakes of M4.0 to M8.0 for and distances up to 100 km.

2.4.3 Attenuation Relationship

The spectral acceleration is a function of:

T – Period (sec), use 0 s for PGA
M – Moment magnitude
F – Fault Type: 0 for strike-slip, 1 for reverse
R_{rup} – Closest distance to rupture plane (km)
S – Soil type: 0 for rock sites, 1 for firm soil sites

Rock Sites:

$$\ln(Sa) = c_1 + c_2 M + c_3 (8.5 - M)^{2.5} + c_4 \ln\left(R_{rup} + \exp(c_5 + c_6 M)\right) + c_7 \ln\left(R_{rup} + 2\right)$$

Deep Soil Sites:

$$\ln(Sa) = c_1 + c_2 M - c_3 \ln\left(R_{rup} + c_4 \exp(c_5 M)\right) + c_6 + c_7 (8.5 - M)^{2.5}$$

Standard Error

$$\sigma_T = \sigma_{var} - \sigma_{con} \min(M, M_{max})$$

Coefficients

Table 2-11. Coefficients for rock sites and strike-slip earthquakes. For reverse or thrust earthqaues, multiply strike-slip motion by 1.2.

$M \leq 6.5$

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	σ_{var}
PGA	-0.624	1.0	0.000	-2.100	1.29649	0.250	0.000	1.39
0.07	0.110	1.0	0.006	-2.128	1.29649	0.250	-0.082	1.40
0.10	0.275	1.0	0.006	-2.148	1.29649	0.250	-0.041	1.41
0.20	0.153	1.0	-0.004	-2.080	1.29649	0.250	0.000	1.43
0.30	-0.057	1.0	-0.017	-2.028	1.29649	0.250	0.000	1.45
0.40	-0.298	1.0	-0.028	-1.990	1.29649	0.250	0.000	1.48
0.50	-0.588	1.0	-0.040	-1.945	1.29649	0.250	0.000	1.50
0.75	-1.208	1.0	-0.050	-1.865	1.29649	0.250	0.000	1.52
1.0	-1.705	1.0	-0.055	-1.800	1.29649	0.250	0.000	1.53
1.5	-2.407	1.0	-0.065	-1.725	1.29649	0.250	0.000	1.53
2.0	-2.945	1.0	-0.070	-1.670	1.29649	0.250	0.000	1.53
3.0	-3.700	1.0	-0.080	-1.610	1.29649	0.250	0.000	1.53
4.0	-4.230	1.0	-0.100	-1.570	1.29649	0.250	0.000	1.53

$\sigma_{con} = 0.14$, $M_{max} = 7.21$

$M > 6.5$

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	σ_{var}
PGA	-1.274	1.1	0.000	-2.100	-0.48451	0.524	0.000	1.39
0.07	-0.540	1.1	0.006	-2.128	-0.48451	0.524	-0.082	1.40
0.10	-0.375	1.1	0.006	-2.148	-0.48451	0.524	-0.041	1.41
0.20	-0.497	1.1	-0.004	-2.080	-0.48451	0.524	0.000	1.43
0.30	-0.707	1.1	-0.017	-2.028	-0.48451	0.524	0.000	1.45
0.40	-0.948	1.1	-0.028	-1.990	-0.48451	0.524	0.000	1.48
0.50	-1.238	1.1	-0.040	-1.945	-0.48451	0.524	0.000	1.50
0.75	-1.858	1.1	-0.050	-1.865	-0.48451	0.524	0.000	1.52
1.0	-2.355	1.1	-0.055	-1.800	-0.48451	0.524	0.000	1.53
1.5	-3.057	1.1	-0.065	-1.725	-0.48451	0.524	0.000	1.53
2.0	-3.595	1.1	-0.070	-1.670	-0.48451	0.524	0.000	1.53
3.0	-4.350	1.1	-0.080	-1.610	-0.48451	0.524	0.000	1.53
4.0	-4.880	1.1	-0.100	-1.570	-0.48451	0.524	0.000	1.53

$\sigma_{con} = 0.14$, $M_{max} = 7.21$

Table 2-12. Coefficients for Deep Soil Sites.

T (sec)	c_6 Strike-Slip	c_6 Reverse	c_7	σ_{var}
PGA	0.0000	0.0000	0.000	1.520
0.07	0.4572	0.4572	0.005	1.540
0.10	0.6395	0.6395	0.005	1.540
0.20	0.9187	0.9187	-0.004	1.565
0.30	0.9547	0.9547	-0.014	1.580
0.40	0.9251	0.9005	-0.024	1.595
0.50	0.8494	0.8285	-0.033	1.610
0.75	0.7010	0.6802	-0.051	1.635
1.0	0.5665	0.5075	-0.065	1.660
1.5	0.3235	0.2215	-0.090	1.690
2.0	0.1001	-0.0526	-0.108	1.700
3.0	-0.2801	-0.4905	-0.139	1.710
4.0	-0.6274	-0.8907	-0.160	1.710

c_1 = -2.17 for strike-slip, -1.92 for reverse/thrust

c_2 = 1.0

c_3 = 1.7

c_4 = 2.1863 for $M \leq 6.5$, 0.3825 for $M > 6.5$

c_5 = 0.32 for $M \leq 6.5$, 0.5882 for $M > 6.5$

σ_{con} = 0.16, M_{max} = 7

2.4.4 Calibration Plots

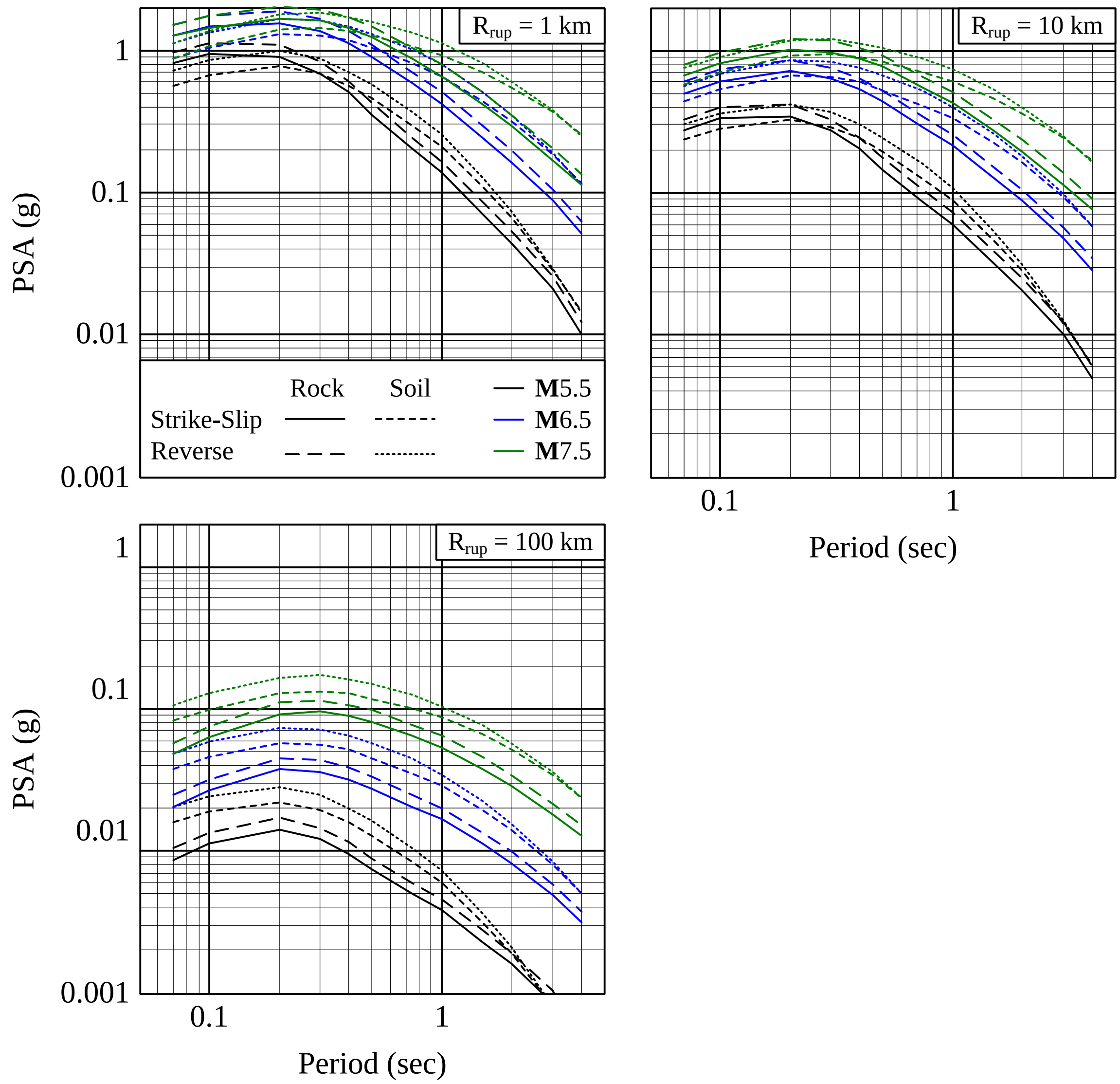


Figure 2-33. PSA as a function of period for conditions given.

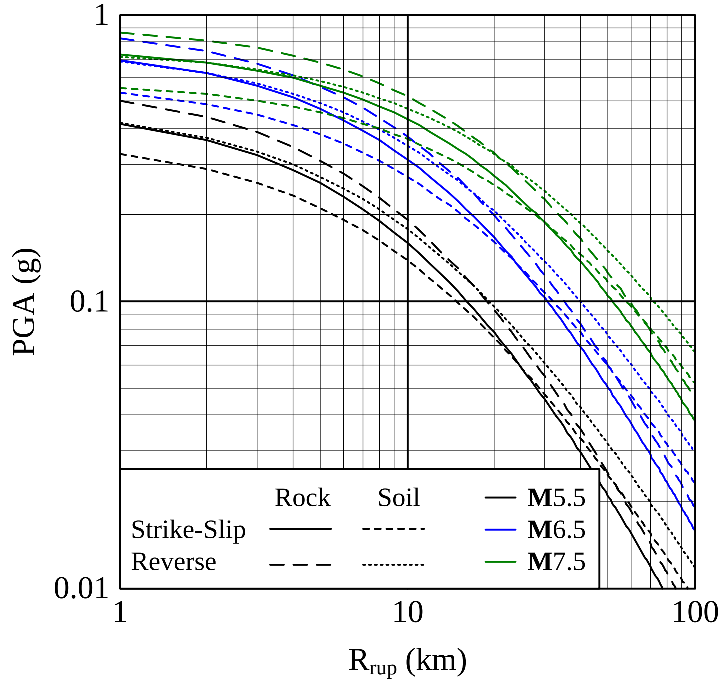


Figure 2-34. PGA as a function of distance for conditions given.

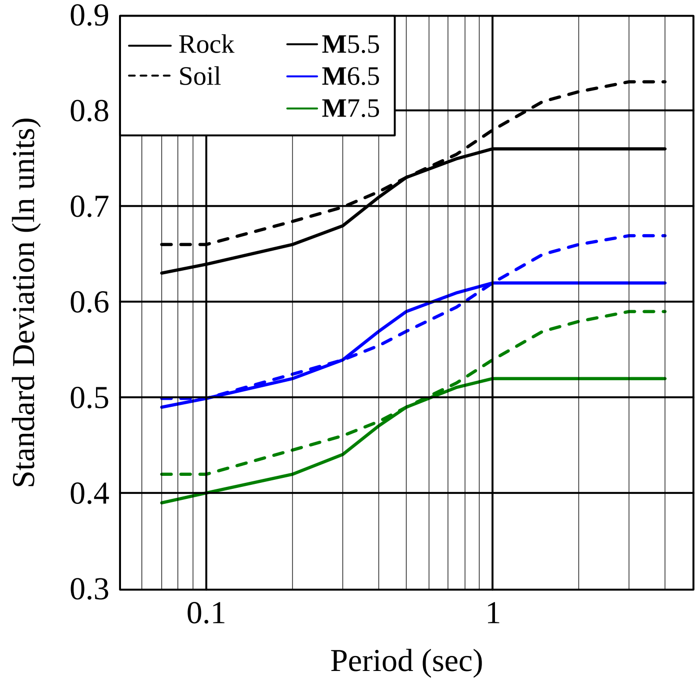


Figure 2-35. Standard Deviation as a function of period for conditions given.

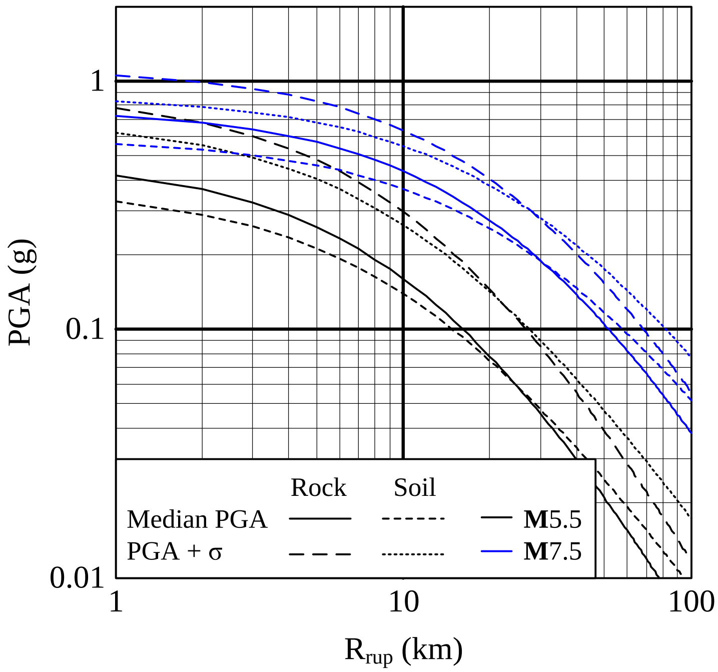
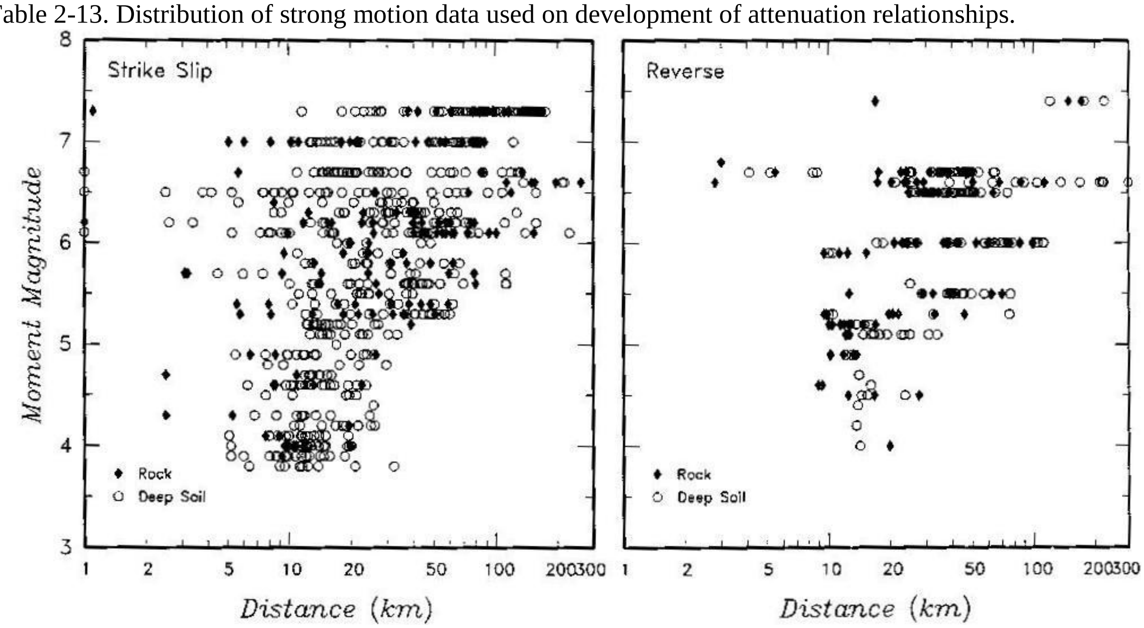


Figure 2-36 Example of application of median PGA plus one standard deviation.

2.4.5 Database

Table 2-13. Distribution of strong motion data used on development of attenuation relationships.



2.4.6 MATLAB Code

```
% by Kathryn A. Gunberg 4/8/2008
% Virginia Tech
% kgunberg@vt.edu
%
% Sadigh, Chang, Egan, Makdisi and Youngs attenuation equation, 1997
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0 for PGA
% M         = Moment magnitude
% F         = Fault type: 0 for strike-slip, 1 for reverse
% Rrup      = Closest distance to rupture plane (km)
% S         = Soil type: 0 for rock sites, 1 firm soil
% --------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = SCEMY_1997(T, M, F, Rrup, S)
% Coefficients
period      =  [0       0.07     0.10    0.20    0.30    0.40    0.50   ...
                0.75    1.00     1.50    2.00    3.00    4.00];
if S == 0
    c3      =  [0.000   0.006   0.006   -0.004  -0.017  -0.028  -0.040  ...
                -0.050  -0.055  -0.065  -0.070  -0.080  -0.100];
    c4      =  [-2.100  -2.128  -2.148  -2.080  -2.028  -1.990  -1.945  ...
                -1.865  -1.800  -1.725  -1.670  -1.610  -1.570];
    c7      =  [0       -0.082  -0.041  0       0       0       0       ...
                0       0       0       0       0       0];
    sigvar  =  [1.39    1.40    1.41    1.43    1.45    1.48    1.50    ...
                1.52    1.53    1.53    1.53    1.53    1.53];
    sigcon  =   0.14;
    Mmax    =   7.21;
    if M <= 6.5
        c1  =  [-0.624  0.110   0.275   0.153   -0.057  -0.298  -0.588  ...
                -1.208  -1.705  -2.407  -2.945  -3.700  -4.230];
        c2  =   1.0;
        c5  =   1.29649;
        c6  =   0.250;
    else
        c1  =  [-1.274  -0.540  -0.375  -0.497  -0.707  -0.948  -1.238  ...
                -1.858  -2.355  -3.057  -3.595  -4.350  -4.880];
        c2  =   1.1;
        c5  =   -0.48451;
        c6  =   0.524;
    end
else
    c2      =   1.0;
    c3      =   1.70;
    c7      =  [0       0.005   0.005   -0.004  -0.014  -0.024  -0.033  ...
                -0.051  -0.065  -0.090  -0.108  -0.139  -0.160];
    sigvar  =  [1.52    1.54    1.54    1.565   1.58    1.595   1.61    ...
                1.635   1.66    1.69    1.70    1.71    1.71];
    sigcon  =   0.16;
    Mmax    =   7;
    if M <= 6.5
        c4  =   2.1863;
        c5  =   0.32;
    else
        c4  =   0.3825;
        c5  =   0.5882;
    end
    if F == 0
        c1  =   -2.17;
        c6  =  [0       0.4572  0.6395  0.9187  0.9547  0.9251  0.8494  ...
                0.7010  0.5665  0.3235  0.1001  -0.2801 -0.6274];
    else
```

```
        c1  =   -1.92;
        c6  =  [0       0.4572  0.6395  0.9187  0.9547  0.9005  0.8285  ...
                0.6802  0.5075  0.2215  -0.0526 -0.4905 -0.8907];
    end
end
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = SCEMY_1997(T_low, M, F, Rrup, S);
    [sa_hi,  sigma_hi]  = SCEMY_1997(T_hi,  M, F, Rrup, S);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    if S == 0
        Sass = exp(c1(i) + c2*M + c3(i)*(8.5-M)^2.5 + c4(i)*log(Rrup + exp(c5 + c6*M)) + ...
            c7(i)*log(Rrup + 2));
        if F == 0
            Sa = Sass;
        else
            Sa = 1.2*Sass;
        end
    else
        Sa = exp(c1 + c2*M - c3*log(Rrup + c4*exp(c5*M)) + c6(i) + c7(i)*(8.5-M)^2.5);
    end
    sigma = sigvar(i) - sigcon*min(M,Mmax);
end
```

2.5 Spudich, Joyner, Lindh, Boore Margaris and Fletcher – 1999

2.5.1 References

Spudich, P., W. B. Joyner, A. G. Lindh, D. M. Boore, B. M. Margaris, and J. B. Fletcher (1999). SEA99: A Revised Ground Motion Prediction Relation for Use in Extensional Tectonic Regimes, *Bulletin of the Seismological Society of America* **89**, 1156–1170.

Pankow, K. L. and J. C. Pechmann (2004). The SEA99 Ground-Motion Predictive Relations for Extensional Tectonic Regimes: Revisions and a New Peak Ground Velocity Relation, *Bulletin of the Seismological Society of America* **94**, 341–348.

Boore, D. M. (2005). Erratum: Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work, *Seismological Research Letters* **76**(3), 368-369.

Spudich, P., and D. M. Boore (2005). Erratum: SEA99: A Revised Ground Motion Prediction Relation for Use in Extensional Tectonic Regimes, *Bulletin of the Seismological Society of America* **95**, 1209.

2.5.2 Abstract

Using 142 records from 38 earthquakes in extensional tectonic regimes (in general, normal faults that tend to produce lower amplitude ground motions), empirical ground-motion models were developed for peak ground acceleration (PGA, in cm/s^2), peak ground velocity (PGV, in cm/s) and 5%-damped pseudo-spectral velocity (PSV, in cm/s) for periods ranging from 0.1 to 2 s. The model is applicable for earthquakes of M5.0 to M7.0, and distances up to 100km. Note that equations are provided to convert to spectral velocitys to acceleration in units of g's. Note: the MATLAB code converts all accelerations to g's.

2.5.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), 0 for PGA, -1 for PGV
- **M** – Moment magnitude
- R_{jb} – Joyner-Boore distance (km)
- S – Soil type: 0 for rock sites, 1 for soil sites
- arb – Error: 0 for error from geometric mean of horizontal components, 1 for arbitrary

$$\log_{10}(Sv, PGA\ or\ PGV) = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \log_{10}\sqrt{{R_{jb}}^2 + h^2} + b_6 S$$

$$Sa = \frac{2\pi}{T} Sv$$

Coefficients

Table 2-14. Coefficients for PGV, PGA and PSV.

T (sec)	b_1	b_2	b_3	b_5	b_6	h	σ_{avg}	σ_{arb}
PGV	2.252	0.490	0.000	-1.196	0.195	7.060	0.246	0.257
PGA	0.237	0.229	0.000	-1.052	0.174	7.270	0.203	0.214
0.10	2.109	0.327	-0.098	-1.250	0.099	9.990	0.273	0.284
0.11	2.120	0.318	-0.100	-1.207	0.099	9.840	0.265	0.276
0.12	2.129	0.313	-0.101	-1.173	0.101	9.690	0.257	0.269
0.13	2.138	0.309	-0.101	-1.145	0.103	9.540	0.252	0.265
0.14	2.145	0.307	-0.100	-1.122	0.107	9.390	0.247	0.260
0.15	2.152	0.305	-0.099	-1.103	0.111	9.250	0.242	0.256
0.16	2.158	0.305	-0.098	-1.088	0.116	9.120	0.239	0.253
0.17	2.163	0.305	-0.096	-1.075	0.121	8.990	0.237	0.251
0.18	2.167	0.306	-0.094	-1.064	0.126	8.860	0.235	0.250
0.19	2.172	0.308	-0.092	-1.055	0.131	8.740	0.234	0.249
0.20	2.175	0.309	-0.090	-1.047	0.137	8.630	0.233	0.248
0.22	2.182	0.313	-0.086	-1.036	0.147	8.410	0.231	0.246
0.24	2.186	0.318	-0.082	-1.029	0.158	8.220	0.231	0.247
0.26	2.190	0.323	-0.078	-1.024	0.168	8.040	0.231	0.247
0.28	2.194	0.329	-0.073	-1.021	0.178	7.870	0.231	0.247
0.30	2.196	0.334	-0.070	-1.020	0.188	7.720	0.232	0.248
0.32	2.198	0.340	-0.066	-1.019	0.196	7.580	0.232	0.249
0.34	2.199	0.345	-0.062	-1.020	0.205	7.450	0.233	0.249
0.36	2.200	0.350	-0.059	-1.021	0.213	7.330	0.234	0.251
0.38	2.200	0.356	-0.055	-1.023	0.221	7.220	0.236	0.253
0.40	2.201	0.361	-0.052	-1.025	0.228	7.110	0.237	0.254
0.42	2.201	0.365	-0.049	-1.027	0.235	7.020	0.238	0.255
0.44	2.201	0.370	-0.047	-1.030	0.241	6.930	0.239	0.256
0.46	2.201	0.375	-0.044	-1.032	0.247	6.850	0.241	0.258
0.48	2.201	0.379	-0.042	-1.035	0.253	6.770	0.242	0.259
0.50	2.199	0.384	-0.039	-1.038	0.259	6.700	0.243	0.260
0.55	2.197	0.394	-0.034	-1.044	0.271	6.550	0.246	0.263
0.60	2.195	0.403	-0.030	-1.051	0.281	6.420	0.249	0.266
0.65	2.191	0.411	-0.026	-1.057	0.291	6.320	0.252	0.269
0.70	2.187	0.418	-0.023	-1.062	0.299	6.230	0.254	0.271
0.75	2.184	0.425	-0.020	-1.067	0.305	6.170	0.257	0.274
0.80	2.179	0.431	-0.018	-1.071	0.311	6.110	0.260	0.277
0.85	2.174	0.437	-0.016	-1.075	0.316	6.070	0.262	0.279
0.90	2.170	0.442	-0.015	-1.078	0.320	6.040	0.264	0.280
0.95	2.164	0.446	-0.014	-1.081	0.324	6.020	0.267	0.284
1.0	2.160	0.450	-0.014	-1.083	0.326	6.010	0.269	0.285
1.1	2.150	0.457	-0.013	-1.085	0.330	6.010	0.273	0.289
1.2	2.140	0.462	-0.014	-1.086	0.332	6.030	0.278	0.294
1.3	2.129	0.466	-0.015	-1.085	0.333	6.070	0.282	0.298
1.4	2.119	0.469	-0.017	-1.083	0.331	6.130	0.286	0.302
1.5	2.109	0.471	-0.019	-1.079	0.329	6.210	0.291	0.307
1.6	2.099	0.472	-0.022	-1.075	0.326	6.290	0.295	0.310
1.7	2.088	0.473	-0.025	-1.070	0.322	6.390	0.299	0.314
1.8	2.079	0.472	-0.029	-1.063	0.317	6.490	0.303	0.318
1.9	2.069	0.472	-0.032	-1.056	0.312	6.600	0.307	0.322
2.0	2.059	0.471	-0.037	-1.049	0.306	6.710	0.312	0.327

Note: standard deviation values correspond to spectral velocity. They need to be adjusted to determine error for spectral acceleration using the equation provided.

2.5.4 Calibration Plots

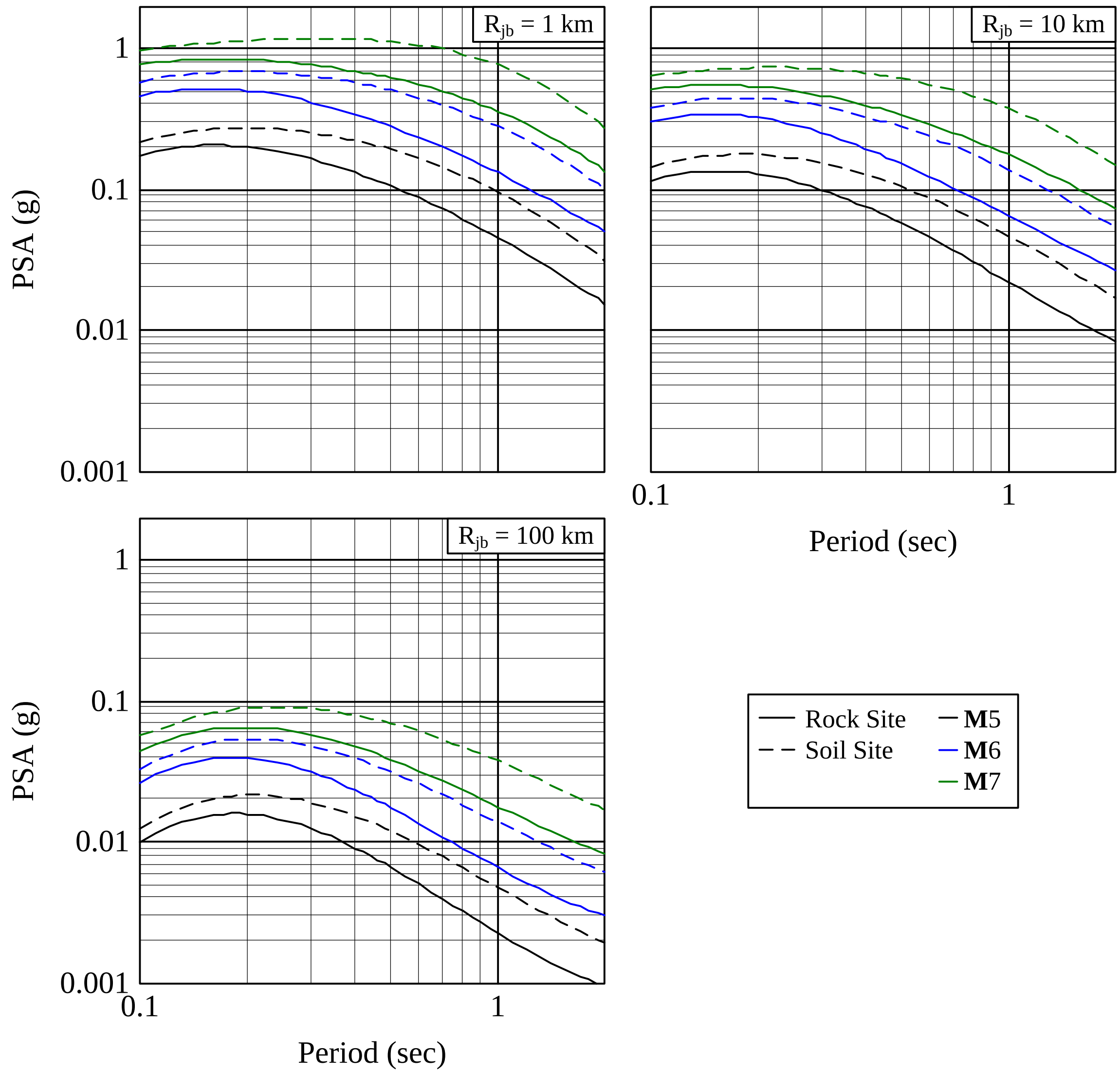


Figure 2-37. PSA as a function of period for different combinations of distance, magnitude and site conditions.

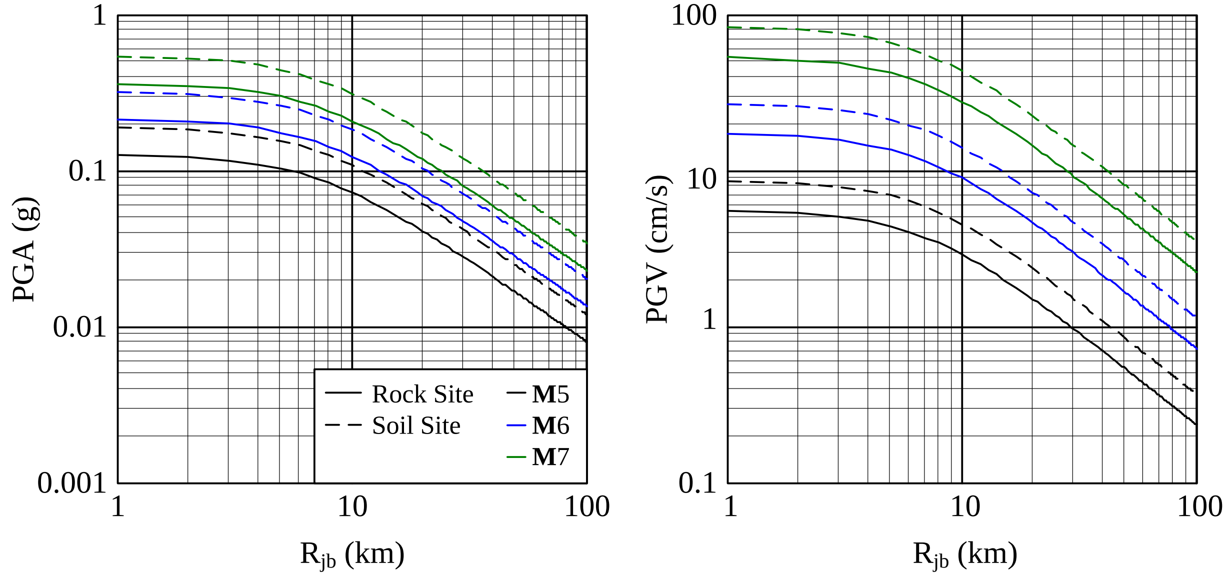


Figure 2-38. PGA and PGV as a function of distance for various magnitude and site condition comibinations.

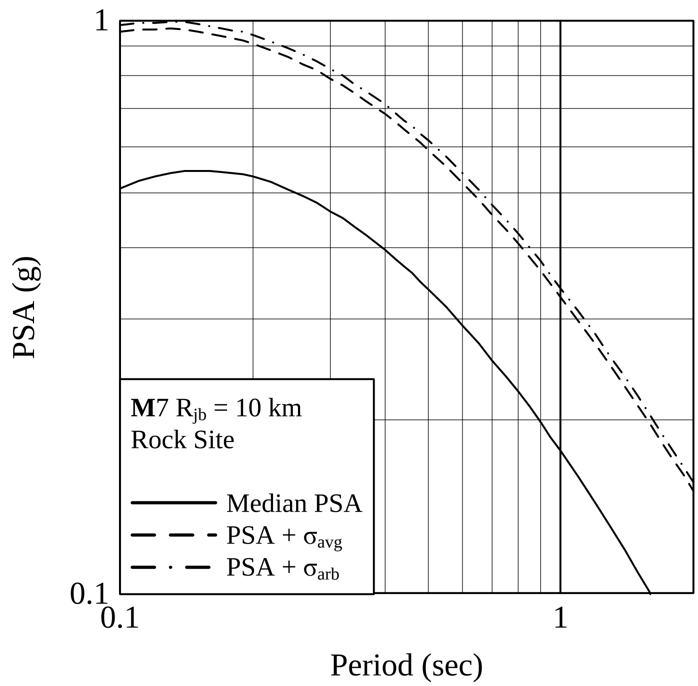


Figure 2-39. Example of application of median PSA plus one standard deviation.

2.5.5 Database

See Spudich et al. (1999) for full list of motions used. No general plots were provided.

2.5.6 MATLAB Code

```
% by Kathryn A. Gunberg 4/23/09
% Virginia Tech
% kgunberg@vt.edu
%
% SEA99 attenuation model with updates and PGV addition by Pankow and
% Pechmann 2004
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T              = Period (0.1 to 2s or 0 for PGA, -1 for PGV)
% M              = Moment Magnitude
% Rjb            = Joyner-Boore distance (km)
% S              = Soil type: 1 for soil sites, 0 for rock sites
% arb            = Error type: 1 for arbitrary, 0 for average
% ---------------------------------------------------------------------------
% Output
% Sa             = median spectral acceleration or PGV prediction (g or cm/s)
% sigma          = logarithmic standard deviation of spectral acceleration
%                  prediction FOR AN ARBITRARY OR AVERAGE COMPONENT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa, sigma] = SEA_1999(T, M, Rjb, S, arb)
% Coefficients
period   = [-1.000  0.000   0.100   0.110   0.120   0.130   0.140   0.150   0.160...
            0.170   0.180   0.190   0.200   0.220   0.240   0.260   0.280   0.300...
            0.320   0.340   0.360   0.380   0.400   0.420   0.440   0.460   0.480...
            0.500   0.550   0.600   0.650   0.700   0.750   0.800   0.850   0.900...
            0.950   1.000   1.100   1.200   1.300   1.400   1.500   1.600   1.700...
            1.800   1.900   2.000];
b1       = [2.252   0.237   2.109   2.120   2.129   2.138   2.145   2.152   2.158...
            2.163   2.167   2.172   2.175   2.182   2.186   2.190   2.194   2.196...
            2.198   2.199   2.200   2.200   2.201   2.201   2.201   2.201   2.201...
            2.199   2.197   2.195   2.191   2.187   2.184   2.179   2.174   2.170...
            2.164   2.160   2.150   2.140   2.129   2.119   2.109   2.099   2.088...
            2.079   2.069   2.059];
b2       = [0.490   0.229   0.327   0.318   0.313   0.309   0.307   0.305   0.305...
            0.305   0.306   0.308   0.309   0.313   0.318   0.323   0.329   0.334...
            0.340   0.345   0.350   0.356   0.361   0.365   0.370   0.375   0.379...
            0.384   0.394   0.403   0.411   0.418   0.425   0.431   0.437   0.442...
            0.446   0.450   0.457   0.462   0.466   0.469   0.471   0.472   0.473...
            0.472   0.472   0.471];
b3       = [0.000   0.000   -0.098  -0.100  -0.101  -0.101  -0.100  -0.099  -0.098...
            -0.096  -0.094  -0.092  -0.090  -0.086  -0.082  -0.078  -0.073  -0.070...
            -0.066  -0.062  -0.059  -0.055  -0.052  -0.049  -0.047  -0.044  -0.042...
            -0.039  -0.034  -0.030  -0.026  -0.023  -0.020  -0.018  -0.016  -0.015...
            -0.014  -0.014  -0.013  -0.014  -0.015  -0.017  -0.019  -0.022  -0.025...
            -0.029  -0.032  -0.037];
b5       = [-1.196  -1.052  -1.250  -1.207  -1.173  -1.145  -1.122  -1.103  -1.088...
            -1.075  -1.064  -1.055  -1.047  -1.036  -1.029  -1.024  -1.021  -1.020...
            -1.019  -1.020  -1.021  -1.023  -1.025  -1.027  -1.030  -1.032  -1.035...
            -1.038  -1.044  -1.051  -1.057  -1.062  -1.067  -1.071  -1.075  -1.078...
            -1.081  -1.083  -1.085  -1.086  -1.085  -1.083  -1.079  -1.075  -1.070...
            -1.063  -1.056  -1.049];
b6       = [0.195   0.174   0.099   0.099   0.101   0.103   0.107   0.111   0.116...
            0.121   0.126   0.131   0.137   0.147   0.158   0.168   0.178   0.188...
            0.196   0.205   0.213   0.221   0.228   0.235   0.241   0.247   0.253...
            0.259   0.271   0.281   0.291   0.299   0.305   0.311   0.316   0.320...
            0.324   0.326   0.330   0.332   0.333   0.331   0.329   0.326   0.322...
            0.317   0.312   0.306];
h        = [7.060   7.270   9.990   9.840   9.690   9.540   9.390   9.250   9.120...
            8.990   8.860   8.740   8.630   8.410   8.220   8.040   7.870   7.720...
            7.580   7.450   7.330   7.220   7.110   7.020   6.930   6.850   6.770...
            6.700   6.550   6.420   6.320   6.230   6.170   6.110   6.070   6.040...
            6.020   6.010   6.010   6.030   6.070   6.130   6.210   6.290   6.390...
            6.490   6.600   6.710];
s_avg    = [0.246   0.203   0.273   0.265   0.257   0.252   0.247   0.242   0.239...
            0.237   0.235   0.234   0.233   0.231   0.231   0.231   0.231   0.232...
            0.232   0.233   0.234   0.236   0.237   0.238   0.239   0.241   0.242...
```

```
            0.243   0.246   0.249   0.252   0.254   0.257   0.260   0.262   0.264...
            0.267   0.269   0.273   0.278   0.282   0.286   0.291   0.295   0.299...
            0.303   0.307   0.312];
s_arb    = [0.257   0.214   0.284   0.276   0.269   0.265   0.260   0.256   0.253...
            0.251   0.250   0.249   0.248   0.246   0.247   0.247   0.247   0.248...
            0.249   0.249   0.251   0.253   0.254   0.255   0.256   0.258   0.259...
            0.260   0.263   0.266   0.269   0.271   0.274   0.277   0.279   0.280...
            0.284   0.285   0.289   0.294   0.298   0.302   0.307   0.310   0.314...
            0.318   0.322   0.327];
% interpolate between periods if neccesary
if (length(find(period == T)) == 0)
    index_low = sum(period<T);
    T_low = period(index_low);
    T_hi = period(index_low+1);
    [sa_low, sigma_low] = SEA_1999(T_low, M, Rjb, S, arb);
    [sa_hi, sigma_hi]   = SEA_1999(T_hi,  M, Rjb, S, arb);
    x = [log10(T_low) log10(T_hi)];
    Y_sa = [log10(sa_low) log10(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = 10^(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i  = find(period == T);
    Sv = 10^(b1(i)+b2(i)*(M-6)+b3(i)*(M-6)^2+b5(i)*log10(sqrt(Rjb^2+h(i)^2))+b6(i)*S);
    if T <= 0
        Sa = Sv;
    else
        Sa = ((2*pi)/T)*Sv/980.665;
    end
    if (arb)
        sigma = s_arb(i);
    else
        sigma = s_avg(i);
    end
end
```

2.6 Field – 2000

2.6.1 Reference

Field, E. H. (2000). A Modified Ground-Motion Attenuation Relationship for Southern California that accounts for Detailed Site Classification and a Basin-Depth Effect, *Bulletin of the Seismological Society of America* **90**, S209-S221.

2.6.2 Abstract

Using the Boore, Joyner and Fumal (1997) attenuation relationship and modifying it for Southern California, empirical ground-motion models were developed for peak ground acceleration (PGA, in g) and 5%-damped spectral values (in g) for periods of 0.3, 1.0 and 3.0 seconds. The model is applicable for earthquakes from M5.0 to M7.5, and distances up to 100km.

2.6.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA
- **M** – Moment magnitude
- F – Fault type: 1 for strike-slip, 2 for reverse
- R_{jb} – Joyner-Boore distance (km)
- V_{S30} – Shear wave velocity in upper 30 m (m/s)
- sig_{type} – 1 for magnitude dependant standard deviation, 0 otherwise

$$\ln(Sa) = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln\sqrt{{R_{jb}}^2 + h^2} + b_V \ln\left(\frac{V_{S30}}{V_A}\right)$$

Standard Deviation

$$\sigma_{total} = \sqrt{\sigma^2 + \tau^2}$$

$$\sigma_{total}(M) = \sqrt{\sigma_c + \sigma_v \min(M, 7)}$$

Coefficients

Table 2-15. Coefficients.

T (sec)	b_{1SS}	b_{1RV}	b_2	b_3	b_5	b_V	h	σ	τ	σ_c	σ_v
PGA	0.853	0.872	0.442	-0.067	-0.960	-0.154	8.90	0.47	0.23	0.93	-0.10
0.30	0.995	1.096	0.501	-0.112	-0.841	-0.350	7.20	0.53	0.26	1.06	-0.11
1.0	-0.164	-0.267	0.903	0.000	-0.914	-0.704	6.20	0.53	0.22	1.00	-0.10
3.0	-2.267	-2.682	1.083	0.000	-0.720	-0.674	3.00	0.52	0.30	-0.57	0.14

Note: V_A = 760 m/s for all cases

2.6.4 *Calibration Plots*

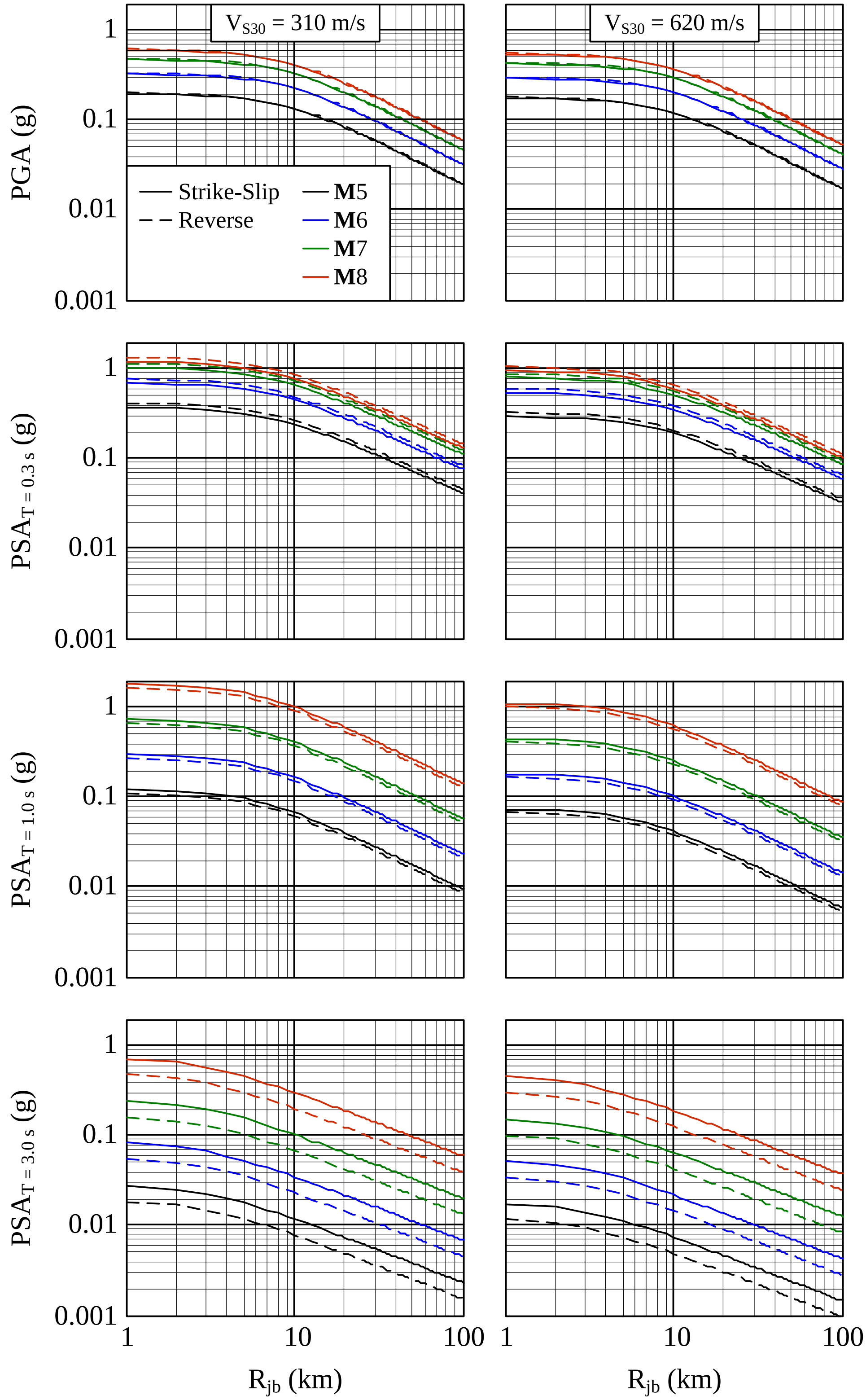


Figure 2-40. Shows variation of attenuation relation for different combinations of inputs.

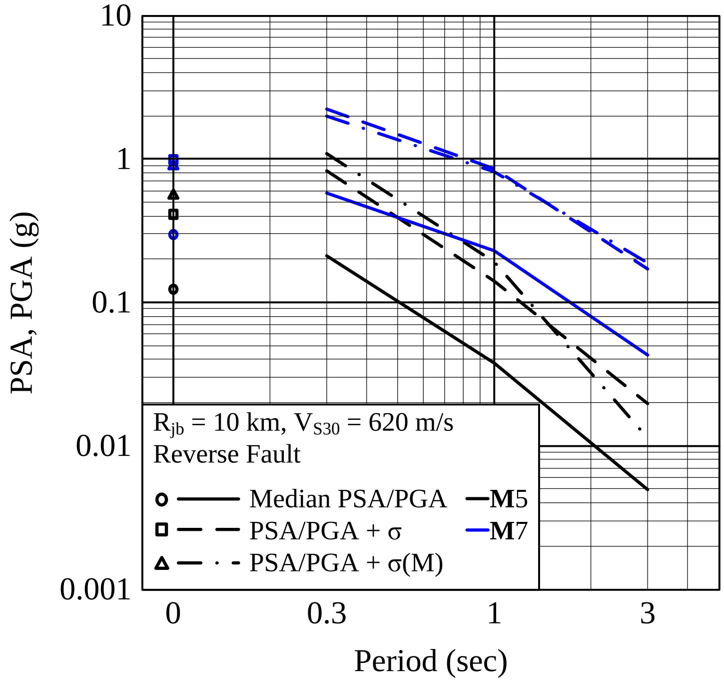


Figure 2-41. Example of application of median PSA and PGA plus one standard deviation.

2.6.5 Database

This study was based on recordings from the Southern California Earthquake Center Phase III database. No plots were provided.

2.6.6 MATLAB Code

```
% by Kathryn A. Gunberg 4/27/09
% Virginia Tech
% kgunberg@vt.edu
%
% Field attenuation model (2000)
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T             = Period, 0 for PGA
% M             = Moment Magnitude
% Rjb           = Joyner-Boore distance (km)
% F             = Fault type: 1 for strike-slip, 2 for reverse-slip
% Vs30          = Shear wave velocity averaged over top 30 m (m/s)
%                 (use 310 for soil, 620 for rock)
% sig_type      = Error dependancy: 1 for magnitude dependant, 0 otherwise
% --------------------------------------------------------------------------
% Output
% Sa            = median spectral acceleration prediction (g)
%   sigma                          =   logarithmic   standard   deviation   of   Sa   prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa, sigma] = F_2000(T, M, F, Rjb, Vs30, sig_type)
% Coefficients
period  =  [0       0.3     1.0     3.0];
if F == 1
    b1  =  [0.853   0.995   -0.164  -2.267];
else
    b1  =  [0.872   1.096   -0.267  -2.681];
end
b2      =  [0.442   0.501   0.903   1.083];
b3      =  [-0.067  -0.112  0       0];
b5      =  [-0.960  -0.841  -0.914  -0.720];
bv      =  [-0.154  -0.350  -0.704  -0.674];
h       =  [8.9     7.2     6.2     3.0];
sig     =  [0.47    0.53    0.53    0.52];
tau     =  [0.23    0.26    0.22    0.30];
sigc    =  [0.93    1.06    1.00    -0.57];
sigv    =  [-0.10   -0.11   -0.10   0.14];
% interpolate between periods if neccesary
if (length(find(period == T)) == 0)
    index_low = sum(period<T);
    T_low = period(index_low);
    T_hi = period(index_low+1);
    [sa_low, sigma_low] = F_2000(T_low, M, F, Rjb, Vs30, sig_type);
    [sa_hi, sigma_hi]   = F_2000(T_hi,  M, F, Rjb, Vs30, sig_type);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(period == T);
    r = sqrt(Rjb^2 + h(i)^2);
    Sa = exp(b1(i) + b2(i)*(M-6) + b3(i)*(M-6)^2 + b5(i)*log(r) + bv(i)*log(Vs30/760));
    if sig_type == 0
        sigma = sqrt(sig(i)^2 + tau(i)^2);
    else
        sigma = sqrt(sigc(i) + sigv(i)*min(M,7));
    end
end
```

2.7 Campbell and Bozorgnia – 2003

2.7.1 Reference

Campbell, K. W. and Y. Bozorgnia (2003). Updated Near-Source Ground-Motion (Attenuation) Relations for the Horizontal and Vertical Components of Peak Ground Acceleration and Acceleration Response Spectra, *Bulletin of the Seismological Society of America* **93**, 314–331.

2.7.2 Abstract

Using 960 accelerograms from 49 earthquakes and 443 processed accelerograms from 36 earthquakes in shallow crustal tectonic regimes, empirical ground-motion models for both horizontal and vertical components were developed for peak ground acceleration (PGA, in g, both for corrected and uncorrected accelerograms) and 5%-damped spectral values (in g) for periods ranging from 0.05 to 4 s. The model is applicable for earthquakes from M5.0 to M7.5, and distances up to 100 km.

2.7.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for corrected PGA, -1 for uncorrected PGA
- **M** – Moment magnitude
- C – Component: 0 for horizontal, 1 for vertical
- δ – Dip angle (degrees)
- F – Fault type: 1 for strike-slip, 2 for reverse, 3 for thrust, 4 for reverse and thrust combined
- R_{jb} – Joyner-Boore distance (km)
- R_{seis} – Closest distance between the site and the rupture plane in the zone of seismogenic rupture (km)
- S – Soil type: 1 for firm soil, 2 for very firm soil, 3 for soft rock, 4 for firm rock
- sig_{type} – 1 for sigma as a function of **M**, 0 for sigma as a function of PGA

$$\ln(Sa) = c_1 + f_1(M) + c_4 \ln\sqrt{f_2(M, R_{seis}, S)} + f_3(F) + f_4(S) + f_5(HW, F, M, R_{seis})$$

where:

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

$$f_2(M, R_{seis}, S) = {R_{seis}}^2 + g(S)^2\{\exp[c_8 M + c_9(8.5 - M)^2]\}^2$$

where:

$$g(S) = c_5 + c_6(S_{VFS} + S_{SR}) + c_7 S_{FR}$$

$$f_3(F) = c_{10} F_{RV} + c_{11} F_{TH}$$

$$f_4(S) = c_{12}S_{VFS} + c_{13}S_{SR} + c_{14}S_{FR}$$

$$f_5(HW, F, M, R_{seis}) = HW f_{HW}(M) f_{HW}(R_{seis})(F_{RV} + F_{TH})$$

where:

$$HW = \begin{cases} 0 & for\ R_{jb} \geq 5\ km\ or\ \delta > 70° \\ (\mathrm{S_{VFS}} + \mathrm{S_{SR}} + \mathrm{S_{FR}})(5 - \mathrm{R_{jb}})/5 & for\ R_{jb} < 5\ km\ and\ \delta \leq 70° \end{cases}$$

$$f_{HW}(M) = \begin{cases} 0 & for\ M < 5.5 \\ M - 5.5 & for\ 5.5 \leq M \leq 6.5 \\ 1 & for\ M > 6.5 \end{cases}$$

$$f_{HW}(R_{seis}) = \begin{cases} \mathrm{c_{15}} \dfrac{\mathrm{R_{seis}}}{8} & for\ R_{seis} < 8\ km \\ \mathrm{c_{15}} & for\ R_{seis} \geq 8\ km \end{cases}$$

Standard Error

$$\sigma_{\ln Y} = \begin{cases} c_{16} - 0.07M & for\ M < 7.4 \\ c_{16} - 0.518 & for\ M \geq 7.4 \end{cases}$$

OR

$$\sigma_{\ln Y} = \begin{cases} c_{17} + 0.351 & for\ PGA \leq 0.07g \\ c_{17} - 0.132 \ln PGA & for\ 0.07g < PGA < 0.25g \\ c_{17} + 0.183 & for\ PGA\ \geq 0.25g \end{cases}$$

Coefficients

Table 2-16. Soil type coefficients.

S	S_{VFS}	S_{SR}	S_{FR}
1: Firm Soil	0	0	0
2: Very Firm Soil	1	0	0
3: Soft Rock	0	1	0
4: Firm Rock	0	0	1

Table 2-17. Fault type coefficients.

F	F_{RV}	F_{TH}
1: Strike-Slip	0	0
2: Reverse	1	0
3: Thrust	0	1
4: Reverse/Thrust	0.5	0.5

Table 2-18. Coefficients for horizontal ground-motions.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}	c_{16}	c_{17}
Unc. PGA	-2.896	0.812	0.000	-1.318	0.187	-0.029	-0.064	0.616	0.000	0.179	0.307	-0.062	-0.195	-0.320	0.370	0.964	0.263
Cor. PGA	-4.033	0.812	0.036	-1.061	0.041	-0.005	-0.018	0.766	0.034	0.343	0.351	-0.123	-0.138	-0.289	0.370	0.920	0.219
0.05	-3.740	0.812	0.036	-1.121	0.058	-0.004	-0.028	0.724	0.032	0.302	0.362	-0.140	-0.158	-0.205	0.370	0.940	0.239
0.075	-3.076	0.812	0.050	-1.252	0.121	-0.005	-0.051	0.648	0.040	0.243	0.333	-0.150	-0.196	-0.208	0.370	0.952	0.251
0.10	-2.661	0.812	0.060	-1.308	0.166	-0.009	-0.068	0.621	0.046	0.224	0.313	-0.146	-0.253	-0.258	0.370	0.958	0.257
0.15	-2.270	0.812	0.041	-1.324	0.212	-0.033	-0.081	0.613	0.031	0.318	0.344	-0.176	-0.267	-0.284	0.370	0.974	0.273
0.20	-2.771	0.812	0.030	-1.153	0.098	-0.014	-0.038	0.704	0.026	0.296	0.342	-0.148	-0.183	-0.359	0.370	0.981	0.280
0.30	-2.999	0.812	0.007	-1.080	0.059	-0.007	-0.022	0.752	0.007	0.359	0.385	-0.162	-0.157	-0.585	0.370	0.984	0.283
0.40	-3.511	0.812	-0.015	-0.964	0.024	-0.002	-0.005	0.842	-0.016	0.379	0.438	-0.078	-0.129	-0.557	0.370	0.987	0.286
0.50	-3.556	0.812	-0.035	-0.964	0.023	-0.002	-0.004	0.842	-0.036	0.406	0.479	-0.122	-0.130	-0.701	0.370	0.990	0.289
0.75	-3.709	0.812	-0.071	-0.964	0.021	-0.002	-0.002	0.842	-0.074	0.347	0.419	-0.108	-0.124	-0.796	0.331	1.021	0.320
1.0	-3.867	0.812	-0.101	-0.964	0.019	0.000	0.000	0.842	-0.105	0.329	0.338	-0.073	-0.072	-0.858	0.281	1.021	0.320
1.5	-4.093	0.812	-0.150	-0.964	0.019	0.000	0.000	0.842	-0.155	0.217	0.188	-0.079	-0.056	-0.954	0.210	1.021	0.320
2.0	-4.311	0.812	-0.180	-0.964	0.019	0.000	0.000	0.842	-0.187	0.060	0.064	-0.124	-0.116	-0.916	0.160	1.021	0.320
3.0	-4.817	0.812	-0.193	-0.964	0.019	0.000	0.000	0.842	-0.200	-0.079	0.021	-0.154	-0.117	-0.873	0.089	1.021	0.320
4.0	-5.211	0.812	-0.202	-0.964	0.019	0.000	0.000	0.842	-0.209	-0.061	0.057	-0.054	-0.261	-0.889	0.039	1.021	0.320

Table 2-19. Coefficients for vertical ground motions.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}	c_{16}	c_{17}
Unc. PGA	-2.807	0.756	0.000	-1.391	0.191	0.044	-0.014	0.544	0.000	0.091	0.223	-0.096	-0.212	-0.199	0.630	1.003	0.302
Cor. PGA	-3.108	0.756	0.000	-1.287	0.142	0.046	-0.040	0.587	0.000	0.253	0.173	-0.135	-0.138	-0.256	0.630	0.975	0.274
0.05	-1.918	0.756	0.000	-1.517	0.309	0.069	-0.023	0.498	0.000	0.058	0.100	-0.195	-0.274	-0.219	0.630	1.031	0.330
0.075	-1.504	0.756	0.000	-1.551	0.343	0.083	0.000	0.487	0.000	0.135	0.182	-0.224	-0.303	-0.263	0.630	1.031	0.330
0.10	-1.672	0.756	0.000	-1.473	0.282	0.062	0.001	0.513	0.000	0.168	0.210	-0.198	-0.275	-0.252	0.630	1.031	0.330
0.15	-2.323	0.756	0.000	-1.280	0.171	0.045	0.008	0.591	0.000	0.223	0.238	-0.170	-0.175	-0.270	0.630	1.031	0.330
0.20	-2.998	0.756	0.000	-1.131	0.089	0.028	0.004	0.668	0.000	0.234	0.256	-0.098	-0.041	-0.311	0.571	1.031	0.330
0.30	-3.721	0.756	0.007	-1.028	0.050	0.010	0.004	0.736	0.007	0.249	0.328	-0.026	0.082	-0.265	0.488	1.031	0.330
0.40	-4.536	0.756	-0.015	-0.812	0.012	0.000	0.000	0.931	-0.018	0.299	0.317	-0.017	0.022	-0.257	0.428	1.031	0.330
0.50	-4.651	0.756	-0.035	-0.812	0.012	0.000	0.000	0.931	-0.043	0.243	0.354	-0.020	0.092	-0.293	0.383	1.031	0.330
0.75	-4.903	0.756	-0.071	-0.812	0.012	0.000	0.000	0.931	-0.087	0.295	0.418	0.078	0.091	-0.349	0.299	1.031	0.330
1.0	-4.950	0.756	-0.101	-0.812	0.012	0.000	0.000	0.931	-0.124	0.266	0.315	0.043	0.101	-0.481	0.240	1.031	0.330
1.5	-5.073	0.756	-0.150	-0.812	0.012	0.000	0.000	0.931	-0.184	0.171	0.211	-0.038	-0.018	-0.518	0.240	1.031	0.330
2.0	-5.292	0.756	-0.180	-0.812	0.012	0.000	0.000	0.931	-0.222	0.114	0.115	0.033	-0.022	-0.503	0.240	1.031	0.330
3.0	-5.748	0.756	-0.193	-0.812	0.012	0.000	0.000	0.931	-0.238	0.179	0.159	-0.010	-0.047	-0.539	0.240	1.031	0.330
4.0	-6.042	0.756	-0.202	-0.812	0.012	0.000	0.000	0.931	-0.248	0.237	0.134	-0.059	-0.267	-0.606	0.240	1.031	0.330

2.7.4 Calibration Plots

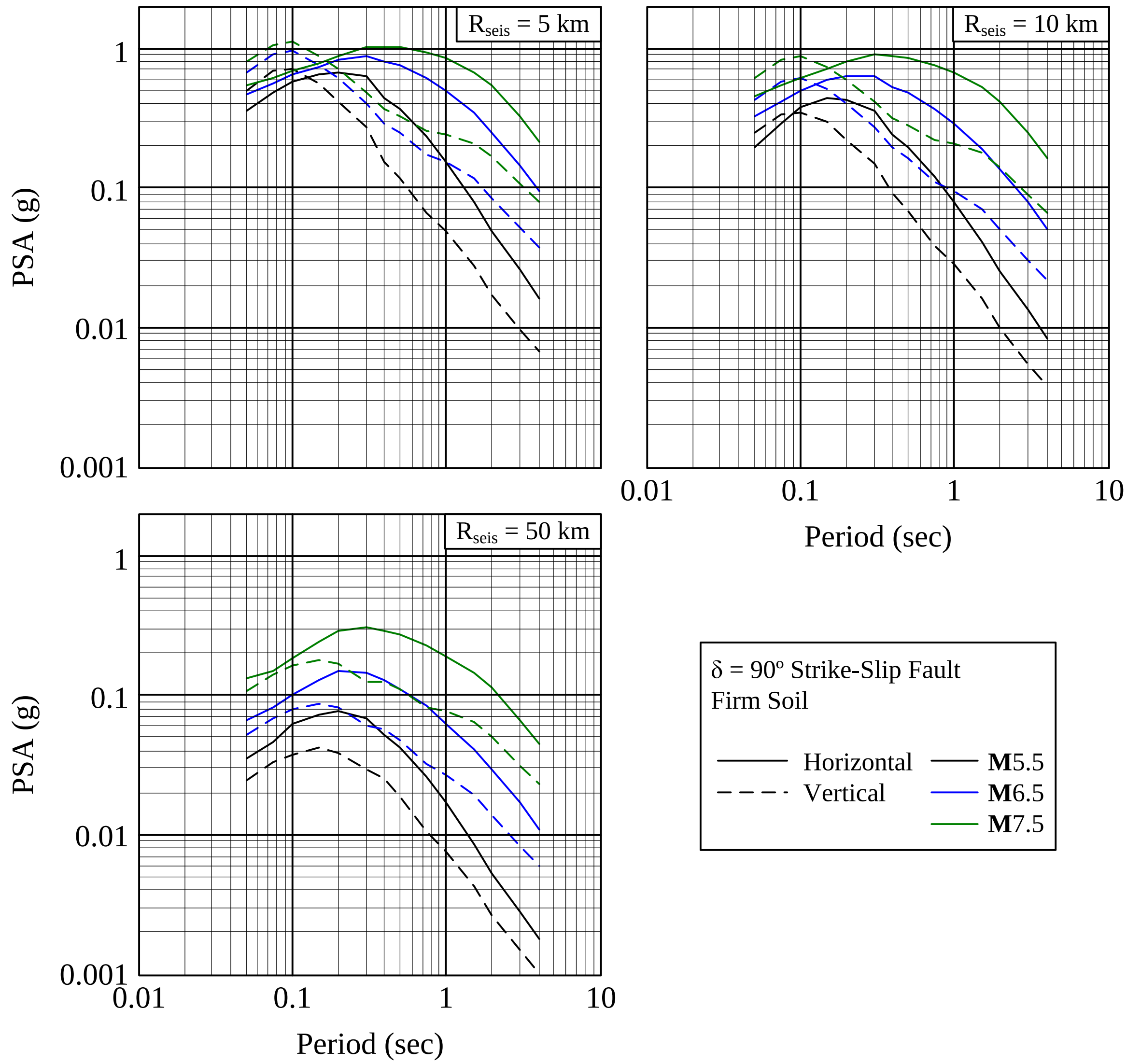


Figure 2-42. Shows variation in f_1 and f_2. Note that R_{jb} and δ values are not significant here and that f_3, f_4 and f_5 are equal to zero.

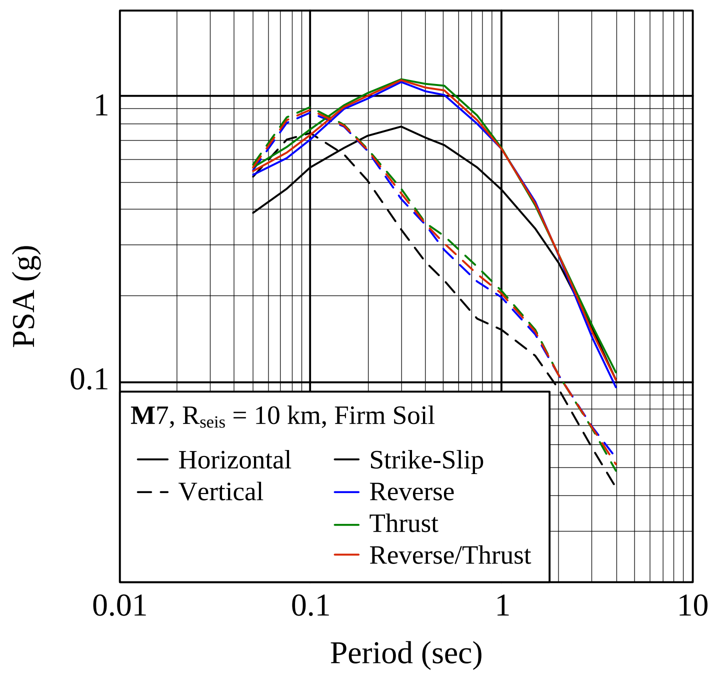


Figure 2-43. Shows variation in f_3. Note that R_{jb} and δ values are not significant here and that f_4 and f_5 are equal to zero.

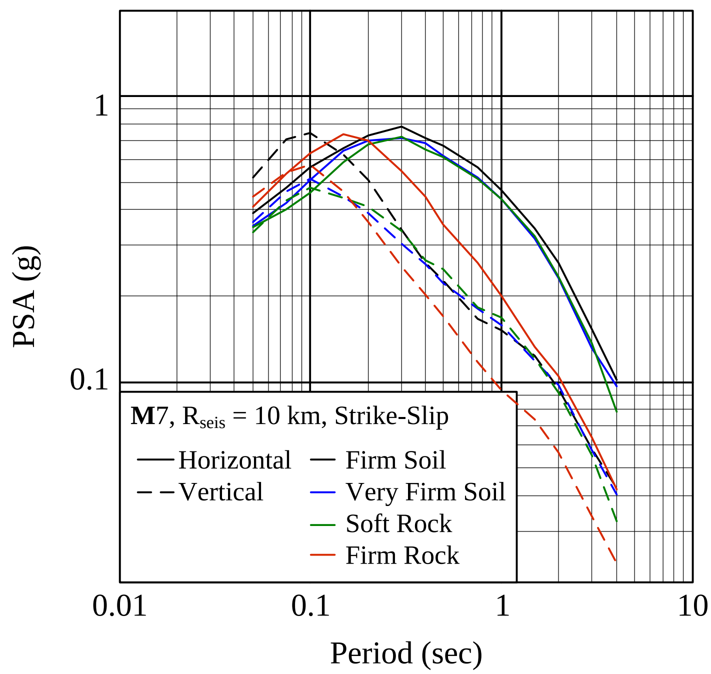


Figure 2-44. Shows variation in f_4. Note that R_{jb} and δ values are not significant here and that f_3 and f_5 are equal to zero.

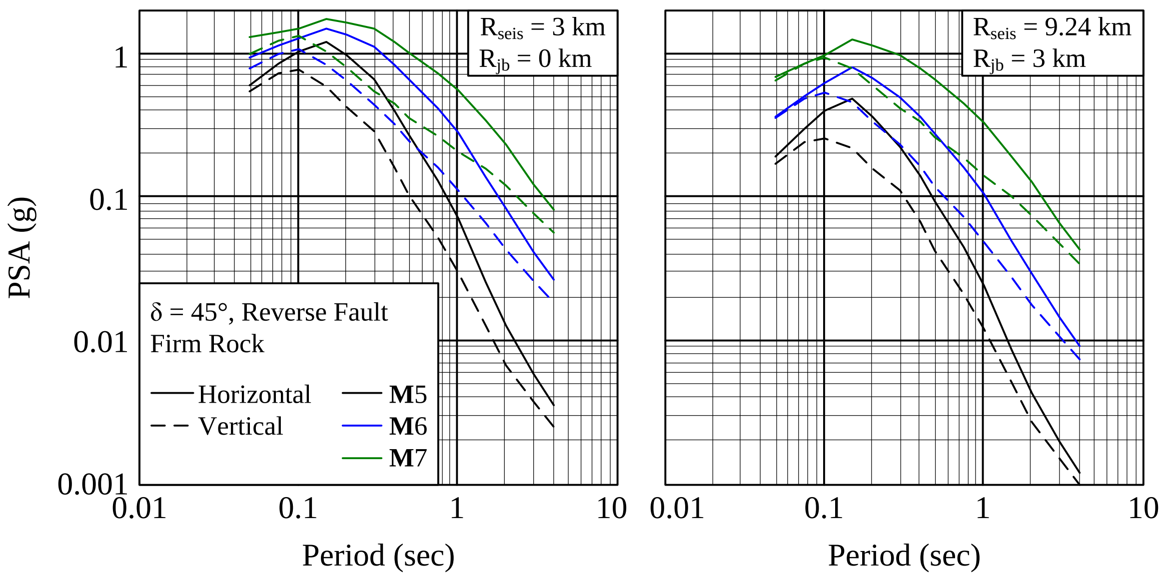


Figure 2-45. Shows variation in f_5.

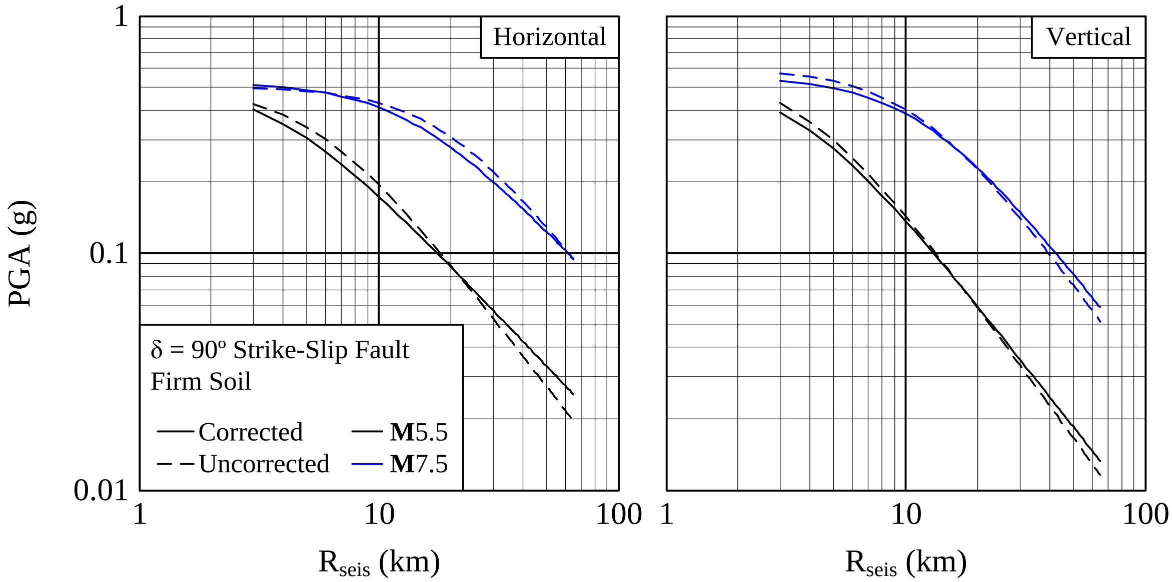


Figure 2-46. Shows variation in f_1 and f_2. Note that R_{jb} and δ values are not significant here and that f_3, f_4 and f_5 are equal to zero.

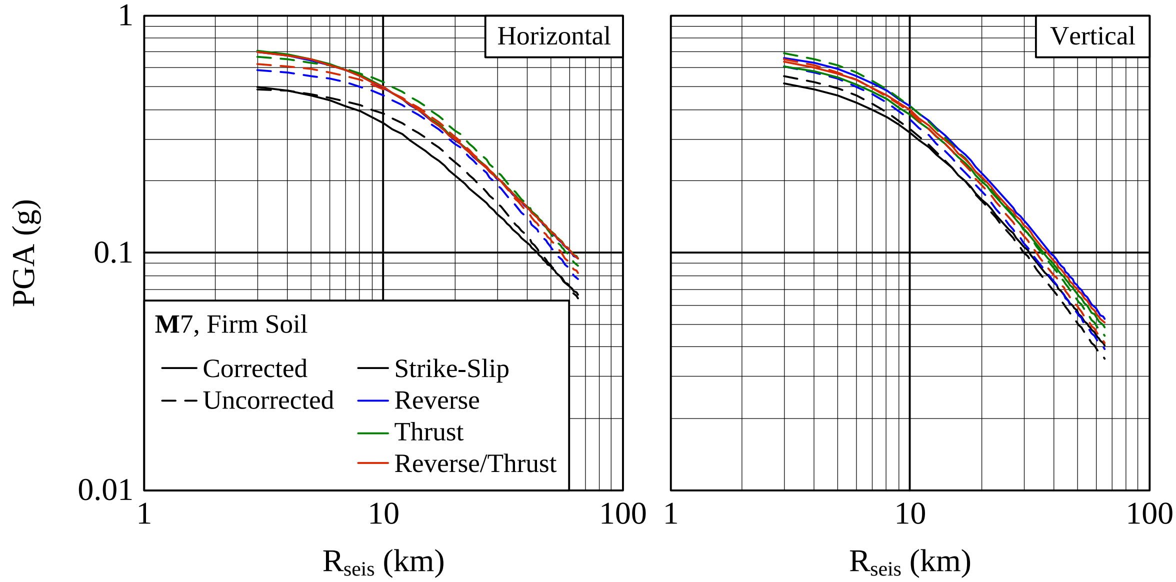


Figure 2-47. Shows variation in f_3. Note that R_{jb} and δ values are not significant here and that f_4 and f_5 are equal to zero.

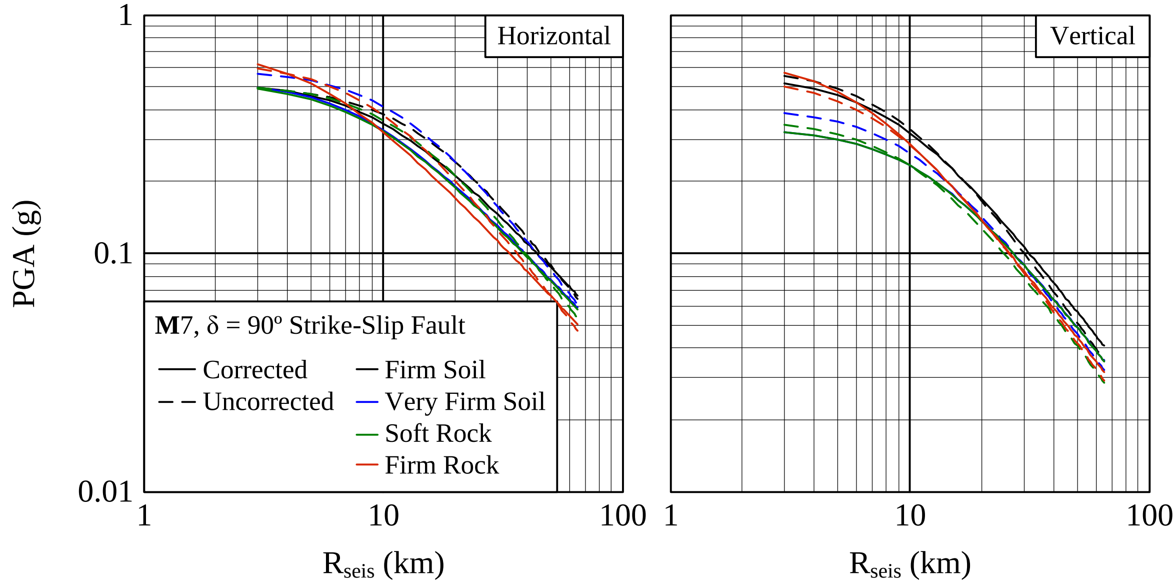


Figure 2-48. Shows variation in f_4. Note that R_{jb} and δ values are not significant here and that f_3 and f_5 are equal to zero.

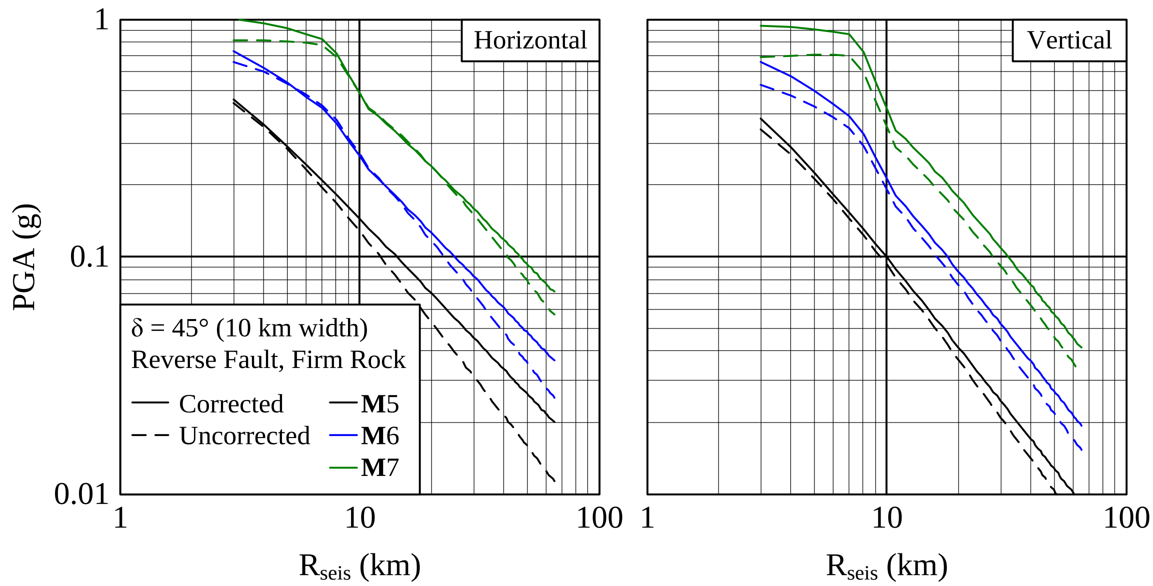


Figure 2-49. Shows variation in f_5.

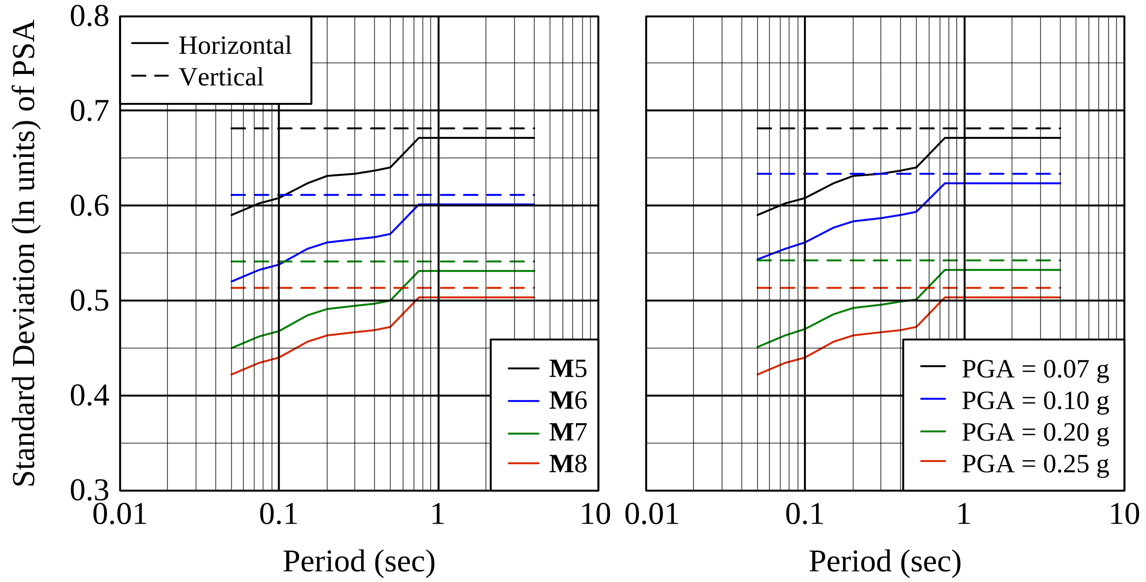


Figure 2-50. The two plots here show the two different cases for standard deviation for PSA.

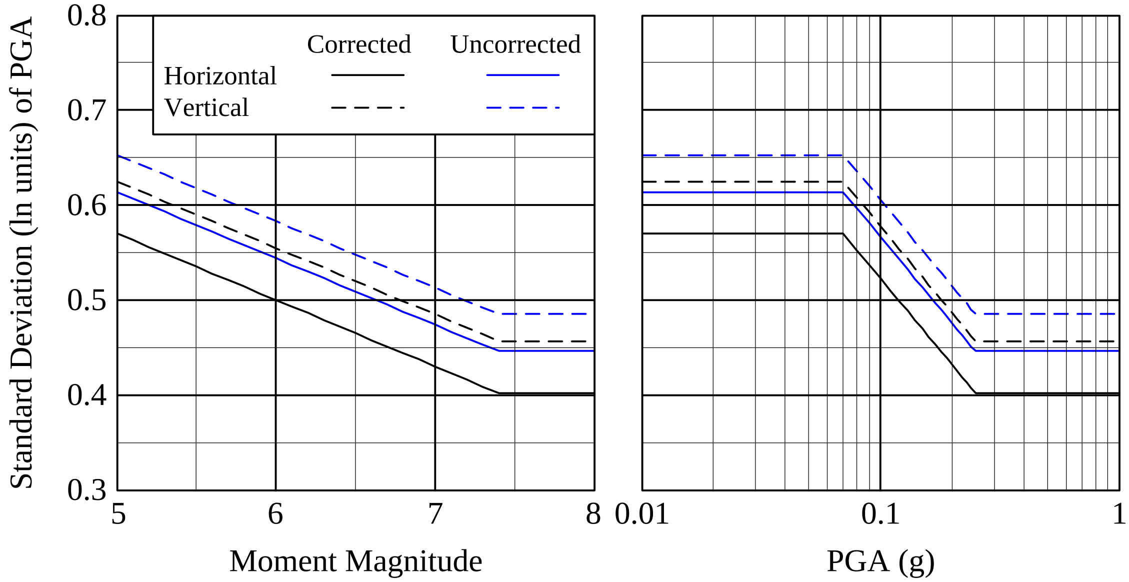


Figure 2-51. The two plots here show the two different cases for standard deviation for PGA.

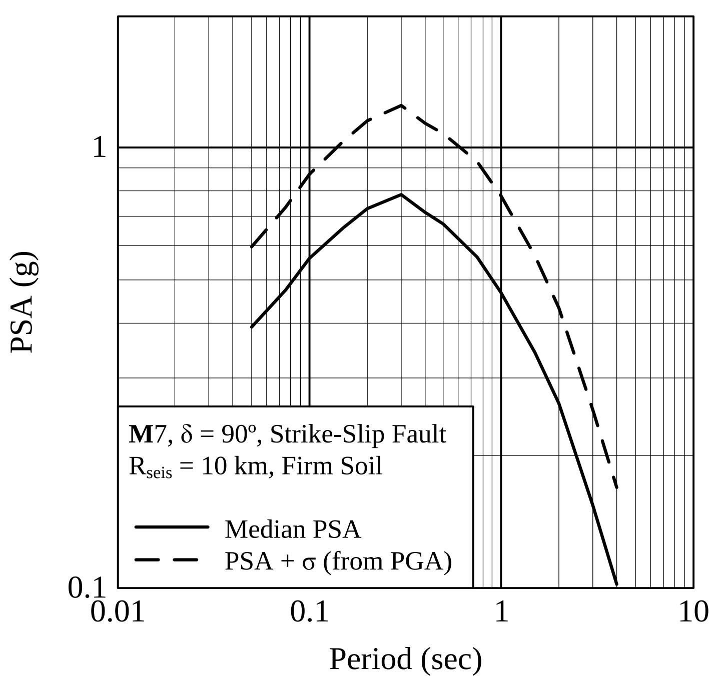


Figure 2-52. Example of application of median PSA plus one standard deviation.

2.7.5 Database

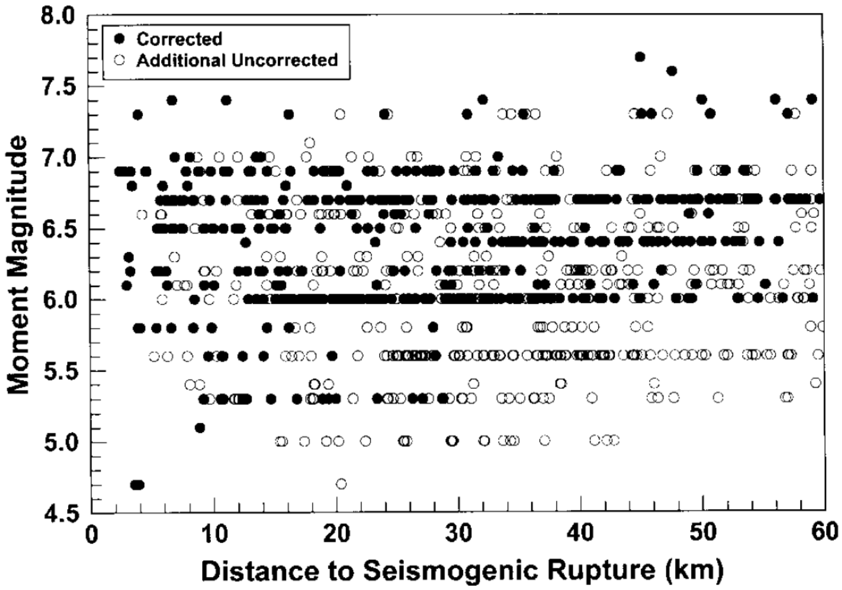


Figure 2-53. Distribution of recordings used in the regression analysis of peak ground acceleration and spectral acceleration (5%-damping). Solid circles represent recordings from the corrected database and open circles represent additional recordings from the uncorrected database.

2.7.6 MATLAB Code

```
% by Katyrn A. Gunberg, 4/15/09
% Virginia Tech
% kgunberg@vt.edu
%
% Campbell and Bozorgnia attenuation equation, 2003
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T              = Period (sec) 0 for corrected PGA, -1 for uncorrected
% M              = Moment magnitude
% C              = Component: 1 for vertical component, 0 for horizontal
% delta          = Dip angle (degree)
% F              = Fault type: 1 for strike-slip and normal, 2 for reverse,
%                  3 for thrust, 4 for reverse and thrust together
% Rjb            = Joyner-Boore distance (km)
% Rseis          = Closest distance to rupture plane below seismogenic depth (km)
% S              = Soil type: 1 for firm soil, 2 for very firm soil, 3 for
%                  soft rock, 4 for firm rock
% sig_type       = Error dependancy: 1 for function of M, 0 for function of PGA
% ispga          = enter 0 (factor to prevent looping for calculation of PGA
%                  for error)
%---------------------------------------------------------------------------
% Output Variables
% Sa             = Median spectral acceleration prediction (g)
% sigma          = logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = CB_2003(T,M,C,delta,F,Rjb,Rseis,S,sig_type,ispga)
% Coefficients
period  =  [-1      0       0.05    0.075   0.1     0.15    0.2     0.3     ...
            0.4     0.5     0.75    1       1.5     2       3       4];
if C == 0
    c1  =  [-2.896  -4.033  -3.740  -3.076  -2.661  -2.270  -2.771  -2.999  ...
            -3.511  -3.556  -3.709  -3.867  -4.093  -4.311  -4.817  -5.211];
    c2  =  [0.812   0.812   0.812   0.812   0.812   0.812   0.812   0.812   ...
            0.812   0.812   0.812   0.812   0.812   0.812   0.812   0.812];
    c3  =  [0.000   0.036   0.036   0.050   0.060   0.041   0.030   0.007   ...
            -0.015  -0.035  -0.071  -0.101  -0.150  -0.180  -0.193  -0.202];
    c4  =  [-1.318  -1.061  -1.121  -1.252  -1.308  -1.324  -1.153  -1.080  ...
            -0.964  -0.964  -0.964  -0.964  -0.964  -0.964  -0.964  -0.964];
    c5  =  [0.187   0.041   0.058   0.121   0.166   0.212   0.098   0.059   ...
            0.024   0.023   0.021   0.019   0.019   0.019   0.019   0.019];
    c6  =  [-0.029  -0.005  -0.004  -0.005  -0.009  -0.033  -0.014  -0.007  ...
            -0.002  -0.002  -0.002  0       0       0       0       0];
    c7  =  [-0.064  -0.018  -0.028  -0.051  -0.068  -0.081  -0.038  -0.022  ...
            -0.005  -0.004  -0.002  0       0       0       0       0];
    c8  =  [0.616   0.766   0.724   0.648   0.621   0.613   0.704   0.752   ...
            0.842   0.842   0.842   0.842   0.842   0.842   0.842   0.842];
    c9  =  [0       0.034   0.032   0.040   0.046   0.031   0.026   0.007   ...
            -0.016  -0.036  -0.074  -0.105  -0.155  -0.187  -0.200  -0.209];
    c10 =  [0.179   0.343   0.302   0.243   0.224   0.318   0.296   0.359   ...
            0.379   0.406   0.347   0.329   0.217   0.060   -0.079  -0.061];
    c11 =  [0.307   0.351   0.362   0.333   0.313   0.344   0.342   0.385   ...
            0.438   0.479   0.419   0.338   0.188   0.064   0.021   0.057];
    c12 =  [-0.062  -0.123  -0.140  -0.150  -0.146  -0.176  -0.148  -0.162  ...
            -0.078  -0.122  -0.108  -0.073  -0.079  -0.124  -0.154  -0.054];
    c13 =  [-0.195  -0.138  -0.158  -0.196  -0.253  -0.267  -0.183  -0.157  ...
            -0.129  -0.130  -0.124  -0.072  -0.056  -0.116  -0.117  -0.261];
    c14 =  [-0.320  -0.289  -0.205  -0.208  -0.258  -0.284  -0.359  -0.585  ...
            -0.557  -0.701  -0.796  -0.858  -0.954  -0.916  -0.873  -0.889];
    c15 =  [0.370   0.370   0.370   0.370   0.370   0.370   0.370   0.370   ...
            0.370   0.370   0.331   0.281   0.210   0.160   0.089   0.039];
    c16 =  [0.964   0.920   0.940   0.952   0.958   0.974   0.981   0.984   ...
            0.987   0.990   1.021   1.021   1.021   1.021   1.021   1.021];
    c17 =  [0.263   0.219   0.239   0.251   0.257   0.273   0.280   0.283   ...
            0.286   0.289   0.320   0.320   0.320   0.320   0.320   0.320];
else
    c1  =  [-2.807  -3.108  -1.918  -1.504  -1.672  -2.323  -2.998  -3.721  ...
```

```
            -4.536  -4.651  -4.903  -4.950  -5.073  -5.292  -5.748  -6.042];
    c2  =  [0.756   0.756   0.756   0.756   0.756   0.756   0.756   0.756   ...
            0.756   0.756   0.756   0.756   0.756   0.756   0.756   0.756];
    c3  =  [0       0       0       0       0       0       0       0.007   ...
            -0.015  -0.035  -0.071  -0.101  -0.150  -0.180  -0.193  -0.202];
    c4  =  [-1.391  -1.287  -1.517  -1.551  -1.473  -1.280  -1.131  -1.028  ...
            -0.812  -0.812  -0.812  -0.812  -0.812  -0.812  -0.812  -0.812];
    c5  =  [0.191   0.142   0.309   0.343   0.282   0.171   0.089   0.050   ...
            0.012   0.012   0.012   0.012   0.012   0.012   0.012   0.012];
    c6  =  [0.044   0.046   0.069   0.083   0.062   0.045   0.028   0.010   ...
            0       0       0       0       0       0       0       0];
    c7  =  [-0.014  -0.040  -0.023  0       0.001   0.008   0.004   0.004   ...
            0       0       0       0       0       0       0       0];
    c8  =  [0.544   0.587   0.498   0.487   0.513   0.591   0.668   0.736   ...
            0.931   0.931   0.931   0.931   0.931   0.931   0.931   0.931];
    c9  =  [0       0       0       0       0       0       0       0.007   ...
            -0.018  -0.043  -0.087  -0.124  -0.184  -0.222  -0.238  -0.248];
    c10 =  [0.091   0.253   0.058   0.135   0.168   0.223   0.234   0.249   ...
            0.299   0.243   0.295   0.266   0.171   0.114   0.179   0.237];
    c11 =  [0.223   0.173   0.100   0.182   0.210   0.238   0.256   0.328   ...
            0.317   0.354   0.418   0.315   0.211   0.115   0.159   0.134];
    c12 =  [-0.096  -0.135  -0.195  -0.224  -0.198  -0.170  -0.098  -0.026  ...
            -0.017  -0.020  0.078   0.043   -0.038  0.033   -0.010  -0.059];
    c13 =  [-0.212  -0.138  -0.274  -0.303  -0.275  -0.175  -0.041  0.082   ...
            0.022   0.092   0.091   0.101   -0.018  -0.022  -0.047  -0.267];
    c14 =  [-0.199  -0.256  -0.219  -0.263  -0.252  -0.270  -0.311  -0.265  ...
            -0.257  -0.293  -0.349  -0.481  -0.518  -0.503  -0.539  -0.606];
    c15 =  [0.630   0.630   0.630   0.630   0.630   0.630   0.571   0.488   ...
            0.428   0.383   0.299   0.240   0.240   0.240   0.240   0.240];
    c16 =  [1.003   0.975   1.031   1.031   1.031   1.031   1.031   1.031   ...
            1.031   1.031   1.031   1.031   1.031   1.031   1.031   1.031];
    c17 =  [0.302   0.274   0.330   0.330   0.330   0.330   0.330   0.330   ...
            0.330   0.330   0.330   0.330   0.330   0.330   0.330   0.330];
end
% interpolate between periods if neccesary
if (length(find(period == T)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low sigma_low] = CB_2003(T_low,M,C,delta,F,Rjb,Rseis,S,sig_type,ispga);
    [sa_hi sigma_hi]   = CB_2003(T_hi ,M,C,delta,F,Rjb,Rseis,S,sig_type,ispga);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(period == T);
    Frv = 0;
    Fth = 0;
    if F == 2
        Frv = 1;
    elseif F == 3
        Fth = 1;
    elseif F == 4
        Frv = 0.5;
        Fth = 0.5;
    end
    Svfs = 0;
    Ssr  = 0;
    Sfr  = 0;
    if S == 2
        Svfs = 1;
    elseif S == 3
        Ssr  = 1;
    elseif S == 4
        Sfr  = 1;
    end
    f1 = c2(i)*M + c3(i)*(8.5 - M)^2;
        g  = c5(i) + c6(i)*(Svfs + Ssr) + c7(i)*Sfr;
    f2 = Rseis^2 + g^2*(exp(c8(i)*M + c9(i)*(8.5 - M)^2))^2;
    f3 = c10(i)*Frv + c11(i)*Fth;
```

```
    f4 = c12(i)*Svfs + c13(i)*Ssr + c14(i)*Sfr;
        if M < 5.5
            fhwM = 0;
        elseif M <= 6.5
            fhwM = M - 5.5;
        else
            fhwM = 1;
        end
        if Rseis < 8
            fhwR = c15(i)*(Rseis/8);
        else
            fhwR = c15(i);
        end
        if or(Rjb >= 5, delta > 70)
            HW = 0;
        else
            HW = (Svfs + Ssr + Sfr)*(5 - Rjb)/5;
        end
    f5 = fhwM*fhwR*HW*(Frv+Fth);
    Sa = exp(c1(i) + f1 + c4(i)*log(sqrt(f2)) + f3 + f4 + f5);
    if sig_type == 1
        sigma = c16(i) - 0.07*min(M,7.4);
    else
        if T >= 0
            Tpga = 0;
        else
            Tpga = -1;
        end
        if ispga == 1
            sigma = 0;
            return
        end
        [PGA, pgasig] = CB_2003(Tpga,M,C,delta,F,Rjb,Rseis,S,sig_type,1);
        if PGA <= 0.07
            sigma = c17(i) + 0.351;
        elseif PGA < 0.25
            sigma = c17(i) - 0.132*log(PGA);
        else
            sigma = c17(i) + 0.183;
        end
    end
end
```

2.8 Abrahamson and Silva – 2008

2.8.1 Reference

Abrahamson, N., and W. Silva (2008). Summary of the Abrahamson & Silva NGA Ground-Motion Relations, *Earthquake Spectra* **24**, 67–97.

2.8.2 Abstract

Using a subset of the PEER NGA database (2754 recordings from 135 earthquakes), an empirical ground-motion model for the average horizontal component was developed. The model predicts peak ground velocity (PGV, in cm/s), peak ground acceleration (PGA, in g) and 5%-damped spectral values (in g) for periods ranging from 0.01 to 10 s. The model is applicable for magnitudes of M5.0 – M8.5 for strike-slip faults, M5.0 – M8.0 for dip-slip faults, and distances up to 200 km.

2.8.3 Attenuation Relationship

The predicted ground motion parameters are a function of:

- T – Period (sec), use 0 for PGA, -1 for PGV
- **M** – Moment magnitude
- δ – Dip angle (degrees)
- λ – Rake angle (degrees)
  - F_{RV} = 1 for λ between -60º and -120º, 0 otherwise
  - F_{NM} = 1 for λ between 30º and 150º, 0 otherwise
- W – Down-dip rupture width (km)
- Z_{TOR} – Depth to top of rupture plane (km)
- F_{AS} – 1 for aftershock, 0 otherwise
- F_{HW} – 1 for sites on hanging wall side, 0 otherwise (boundary defined by vertical projection of the top of the rupture plane)
- R_{rup} – Closest distance to rupture plane (km)
- R_{jb} – Joyner-Boore distance (km)
- R_x – Horizontal distance from the top of the rupture plane, measured perpendicular to the fault strike (km)
- $Z_{1.0}$ – Depth to V_S = 1.0 km/s (m)
- V_{S30} – Shear wave velocity (m/s) averaged over top 30 m
- E – 1 for estimated V_{S30}, 0 for measured

$$\ln(Sa) = f_1(M, R_{rup}) + a_{12}F_{RV} + a_{13}F_{NM} + a_{15}F_{AS} + F_{HW}f_4(R_{jb}, R_{rup}, R_x, W, \delta, Z_{TOR}, M) + f_6(Z_{TOR}) + f_8(R_{rup}, M) + f_{10}(Z_{1.0}, V_{S30}) + f_5(\widehat{PGA}_{1100}, V_{S30})$$

where:

$$f_1(M, R_{rup}) = \begin{cases} a_1 + a_4(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) & for\ M \le c_1 \\ a_1 + a_5(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) & for\ M > c_1 \end{cases}$$

where:

$$R = \sqrt{{R_{rup}}^2 + {c_4}^2}$$

$$f_4(R_{jb}, R_x, \delta, Z_{TOR}, M, W) = a_{14}T_1(R_{jb})T_2(R_x, W, \delta)T_3(R_x, Z_{TOR})T_4(M)T_5(\delta)$$

where:

$$T_1(R_{jb}) = \begin{cases} 1 - \dfrac{R_{jb}}{30} & for\ R_{jb} < 30\ km \\ 0 & for\ R_{jb} \ge 30\ \text{km} \end{cases}$$

$$T_2(R_x, W, \delta) = \begin{cases} 0.5 + \dfrac{R_x}{2W\cos(\delta)} & for\ R_x \le W\cos(\delta) \\ 1 & for\ R_x > W\cos(\delta), or\ \delta = 90 \end{cases}$$

$$T_3(R_x, Z_{TOR}) = \begin{cases} 1 & for\ R_x \ge Z_{TOR} \\ \dfrac{R_x}{Z_{TOR}} & for\ R_x < Z_{TOR} \end{cases}$$

$$T_4(M) = \begin{cases} 0 & for\ M \le 6 \\ M - 6 & for\ 6 < M < 7 \\ 1 & for\ M \ge 7 \end{cases}$$

$$T_5(\delta) = \begin{cases} 1 - \dfrac{\delta - 70}{20} & for\ \delta \ge 70 \\ 1 & for\ \delta < 70 \end{cases}$$

$$f_6(Z_{TOR}) = \begin{cases} \dfrac{a_{16}Z_{TOR}}{10} & for\ Z_{TOR} < 10\ km \\ a_{16} & for\ Z_{TOR} \ge 10\ \text{km} \end{cases}$$

$$f_8(R_{rup}, M) = \begin{cases} 0 & for\ R_{rup} < 100\ km \\ a_{18}(R_{rup} - 100)T_6(M) & for\ R_{rup} \ge 100\ \text{km} \end{cases}$$

where:

$$T_6(M) = \begin{cases} 1 & for\ M < 5.5 \\ 0.5(6.5 - M) + 0.5 & for\ 5.5 \leq M \leq 6.5 \\ 0.5 & for\ M > 6.5 \end{cases}$$

$$f_{10}(Z_{1.0}, V_{S30}) = a_{21} \ln\left(\frac{Z_{1.0} + c_2}{\hat{Z}_{1.0}(V_{S30}) + c_2}\right) + \begin{cases} a_{22} \ln\left(\frac{Z_{1.0}}{200}\right) & for\ Z_{1.0} \geq 200 \\ 0 & for\ Z_{1.0} < 200 \end{cases}$$

where:

$$\ln\left(\hat{Z}_{1.0}(V_{S30})\right) = \begin{cases} 6.745 & for\ V_{S30} < 180\ m/s \\ 6.745 - 1.35\ \ln\left(\frac{V_{S30}}{180}\right) & for\ 180 \leq V_{S30} \leq 500\ \text{m/s} \\ 5.394 - 4.48\ \ln\left(\frac{V_{S30}}{500}\right) & for\ V_{S30} > 500\ \text{m/s} \end{cases}$$

$$a_{21} = \begin{cases} 0 & for\ V_{S30} \geq 1000 \\ \dfrac{-(a_{10} + bN) \ln\left(\frac{V^*{}_{S30}}{\min(V_1, 1000)}\right)}{\ln\left(\frac{Z_{1.0} + c_2}{\hat{Z}_{1.0} + c_2}\right)} & for\ (a_{10} + bN) \ln\left(\frac{V^*{}_{S30}}{\min(V_1, 1000)}\right) \\ & \quad + e_2 \ln\left(\frac{Z_{1.0} + c_2}{\hat{Z}_{1.0} + c_2}\right) < 0 \\ e_2 & otherwise \end{cases}$$

$$e_2 = \begin{cases} 0 & for\ T < 0.35\ sec\ or\ V_{S30} > 1000\ m/s \\ -0.25 \ln\left(\frac{V_{S30}}{1000}\right) \ln\left(\frac{T}{0.35}\right) & for\ 0.35\ \text{sec}\ \leq T \leq 2\ \text{sec} \\ -0.25 \ln\left(\frac{V_{S30}}{1000}\right) \ln\left(\frac{2}{0.35}\right) & for\ T > 2\ \text{sec} \end{cases}$$

$$a_{22} = \begin{cases} 0 & for\ T < 2\ sec \\ 0.0625(T - 2) & for\ T \geq 2\ \text{sec} \end{cases}$$

Note: when calculating a_{21} and a_{22} for PGV, use T = 1 sec, but use coefficients corresponding to PGV.

$$f_5(\widehat{PGA}_{1100}, V^*_{S30}) = \begin{cases} a_{10}\ln\left(\frac{V^*_{S30}}{V_{LIN}}\right) - b\ln(\widehat{PGA}_{1100} + c) \\ \quad + b\ln\left(\widehat{PGA}_{1100} + c\left(\frac{V^*_{S30}}{V_{LIN}}\right)^N\right) & for\ V_{S30} < V_{LIN} \\ (a_{10} + bN)\ln\left(\frac{V^*_{S30}}{V_{LIN}}\right) & for\ V_{S30} \geq V_{LIN} \end{cases}$$

where:

$\widehat{PGA}_{1100}$ is the median predicted PGA at the site with V_{S30} = 1100 m/s and $Z_{1.0}$ = 6 m.

$$\widehat{PGA}_{1100} = \exp[-0.1092955 + f_1(M, R_{rup}) + a_{12}F_{RV} + a_{13}F_{NM} + a_{15}F_{AS} + F_{HW}f_4(R_{jb}, R_x, W, \delta, Z_{TOR}, M) + f_6(Z_{TOR}) + f_8(R_{rup}, M)]$$

$$V^*_{S30} = \begin{cases} V_{S30} & for\ V_{S30} < V_1 \\ V_1 & for\ V_{S30} \geq V_1 \end{cases}$$

where:

$$V_1 = \begin{cases} 1500\ \mathrm{m/s} & for\ T \leq 0.50\ \mathrm{sec} \\ e^{8.0-0.795\ln\left(\frac{T}{0.21}\right)} & for\ 0.50\ \mathrm{sec} < T \leq 1\ \mathrm{sec} \\ e^{6.76-0.297\ln(T)} & for\ 1\ \mathrm{sec} < T < 2\ sec \\ 700\ \mathrm{m/s} & for\ T \geq 2\ \mathrm{sec} \\ 862\ \mathrm{m/s} & for\ PGV \end{cases}$$

The spectral acceleration must be adjusted for high periods.

$$Sa(T) = \begin{cases} Sa(T)\ from\ general\ equation & for\ T \leq T_D \\ Sa(T = T_D, V_{S30} = 1100\ \mathrm{m/s}, Z_{1.0} = 6\ \mathrm{m})\frac{{T_D}^2}{T^2}\exp(\Delta f_5 + \Delta f_{10}) & for\ T > T_D \end{cases}$$

where:

$$\log_{10}(T_D) = -1.25 + 0.3M$$

$$\Delta f = f_5(V_{S30}) - f_5(V_{S30} = 1100\ \mathrm{m/s})$$

$$\Delta f_{10} = f_{10}(Z_{1.0}, V_{S30}) - f_{10}(Z_{1.0} = 6\ \mathrm{m}, V_{S30} = 1100\ \mathrm{m/s},)$$

Standard Deviation

$$\sigma_T = \sqrt{\sigma^2 + \tau^2}$$

where:

$$\sigma\left(T, M, \widehat{PGA}_{1100}, V_{S30}\right) = \begin{bmatrix} \sigma_{\mathrm{B}}(M,T)^2 + \sigma_{Amp}{}^2 \\ + \left(\dfrac{\partial \ln Amp\left(T, \widehat{PGA}_{1100}, V_{S30}\right)}{\partial \ln PGA_{1100}}\right)^2 \sigma_B(M, T = 0)^2 \\ +2\left(\dfrac{\partial \ln Amp\left(T, \widehat{PGA}_{1100}, V_{S30}\right)}{\partial \ln PGA_{1100}}\right) \sigma_B(M,T)\sigma_B(M, T = 0)\rho \end{bmatrix}^{1/2}$$

$$\tau\left(T, M, \widehat{PGA}_{1100}, V_{S30}\right) = \begin{bmatrix} \tau_{\mathrm{B}}(M,T)^2 + \left(\dfrac{\partial \ln Amp\left(T, \widehat{PGA}_{1100}, V_{S30}\right)}{\partial \ln PGA_{1100}}\right)^2 \tau_B(M, T = 0)^2 \\ +2\left(\dfrac{\partial \ln Amp\left(T, \widehat{PGA}_{1100}, V_{S30}\right)}{\partial \ln PGA_{1100}}\right) \tau_B(M,T)\tau_B(M, T = 0)\rho \end{bmatrix}^{1/2}$$

where:

$$\frac{\partial \ln Amp\left(T, \widehat{PGA}_{1100}, V_{S30}\right)}{\partial \ln PGA_{1100}} = \begin{cases} 0 & for\ V_{S30} \geq V_{LIN} \\ \dfrac{b\widehat{PGA}_{1100}}{\widehat{PGA}_{1100} + c\left(\dfrac{V_{S30}}{V_{LIN}}\right)^N} - \dfrac{b\widehat{PGA}_{1100}}{\widehat{PGA}_{1100} + c} & for\ V_{S30} < V_{LIN} \end{cases}$$

$$\sigma_0(M, \mathrm{T}) = \begin{cases} s_1 & for\ M < 5 \\ s_1 + \left(\dfrac{s_2 - s_1}{2}\right)(M - 5) & for\ 5 \leq M \leq 7 \\ s_2 & for\ M > 7 \end{cases}$$

$$\tau_0(M, T) = \begin{cases} s_3 & for\ M < 5 \\ s_3 + \left(\dfrac{s_4 - s_3}{2}\right)(M - 5) & for\ 5 \leq M \leq 7 \\ s_4 & for\ M > 7 \end{cases}$$

$$\sigma_B(M,T) = \sqrt{\sigma_0{}^2(M,T) - \sigma_{Amp}{}^2}$$

$$\sigma_{Amp} = 0.3$$

$$\tau_B(M,T) = \tau_0(M,T)$$

Coefficients

Table 2-20. Period-independent constants for the median ground motion

c_1	c_4	a_3	a_4	a_5	N	c	c_2
6.75	4.5	0.265	-0.231	-0.398	1.18	1.88	50

Table 2-21. Coefficients for the median ground motion

T(sec)	V_{LIN}	b	a_1	a_2	a_8	a_{10}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{18}
PGA	865.1	-1.186	0.804	-0.9679	-0.0372	0.9445	0.0000	-0.0600	1.0800	-0.3500	0.9000	-0.0067
0.010	865.1	-1.186	0.811	-0.9679	-0.0372	0.9445	0.0000	-0.0600	1.0800	-0.3500	0.9000	-0.0067
0.020	865.1	-1.219	0.855	-0.9774	-0.0372	0.9834	0.0000	-0.0600	1.0800	-0.3500	0.9000	-0.0067
0.030	907.8	-1.273	0.962	-1.0024	-0.0372	1.0471	0.0000	-0.0600	1.1331	-0.3500	0.9000	-0.0067
0.040	994.5	-1.308	1.037	-1.0289	-0.0315	1.0884	0.0000	-0.0600	1.1708	-0.3500	0.9000	-0.0067
0.050	1053.5	-1.346	1.133	-1.0508	-0.0271	1.1333	0.0000	-0.0600	1.2000	-0.3500	0.9000	-0.0076
0.075	1085.7	-1.471	1.375	-1.0810	-0.0191	1.2808	0.0000	-0.0600	1.2000	-0.3500	0.9000	-0.0093
0.10	1032.5	-1.624	1.563	-1.0833	-0.0166	1.4613	0.0000	-0.0600	1.2000	-0.3500	0.9000	-0.0093
0.15	877.6	-1.931	1.716	-1.0357	-0.0254	1.8071	0.0181	-0.0600	1.1683	-0.3500	0.9000	-0.0093
0.20	748.2	-2.188	1.687	-0.9700	-0.0396	2.0773	0.0309	-0.0600	1.1274	-0.3500	0.9000	-0.0083
0.25	654.3	-2.381	1.646	-0.9202	-0.0539	2.2794	0.0409	-0.0600	1.0956	-0.3500	0.9000	-0.0069
0.30	587.1	-2.518	1.601	-0.8974	-0.0656	2.4201	0.0491	-0.0600	1.0697	-0.3500	0.9000	-0.0057
0.40	503.0	-2.657	1.511	-0.8677	-0.0807	2.5510	0.0619	-0.0600	1.0288	-0.3500	0.8423	-0.0039
0.50	456.6	-2.669	1.397	-0.8475	-0.0924	2.5395	0.0709	-0.0600	0.9971	-0.3191	0.7458	-0.0025
0.75	410.5	-2.401	1.137	-0.8206	-0.1137	2.1493	0.0800	-0.0600	0.9395	-0.2629	0.5704	0.0000
1.0	400.0	-1.955	0.915	-0.8088	-0.1289	1.5705	0.0800	-0.0600	0.8985	-0.2230	0.4460	0.0000
1.5	400.0	-1.025	0.510	-0.7995	-0.1534	0.3991	0.0800	-0.0600	0.8409	-0.1668	0.2707	0.0000
2.0	400.0	-0.299	0.192	-0.7960	-0.1708	-0.6072	0.0800	-0.0600	0.8000	-0.1270	0.1463	0.0000
3.0	400.0	0.000	-0.280	-0.7960	-0.1954	-0.9600	0.0800	-0.0600	0.4793	-0.0708	-0.0291	0.0000
4.0	400.0	0.000	-0.639	-0.7960	-0.2128	-0.9600	0.0800	-0.0600	0.2518	-0.0309	-0.1535	0.0000
5.0	400.0	0.000	-0.936	-0.7960	-0.2263	-0.9208	0.0800	-0.0600	0.0754	0.0000	-0.2500	0.0000
7.5	400.0	0.000	-1.527	-0.7960	-0.2509	-0.7700	0.0800	-0.0600	0.0000	0.0000	-0.2500	0.0000
10.0	400.0	0.000	-1.993	-0.7960	-0.2683	-0.6630	0.0800	-0.0600	0.0000	0.0000	-0.2500	0.0000
PGV	400.0	-1.955	5.7578	-0.9046	-0.1200	1.5390	0.0800	-0.0600	0.7000	-0.3900	0.6300	0.0000

Table 2-22. Coefficients for the standard deviation

T (sec)	V_{S30} Estimated		V_{S30} Measured		s_3	s_4	ρ
	s_1	s_2	s_1	s_2			
PGA	0.590	0.470	0.576	0.453	0.470	0.300	1.000
0.010	0.590	0.470	0.576	0.453	0.420	0.300	1.000
0.020	0.590	0.470	0.576	0.453	0.420	0.300	1.000
0.030	0.605	0.478	0.591	0.461	0.462	0.305	0.991
0.040	0.615	0.483	0.602	0.466	0.492	0.309	0.982
0.050	0.623	0.488	0.610	0.471	0.515	0.312	0.973
0.075	0.630	0.495	0.617	0.479	0.550	0.317	0.952
0.10	0.630	0.501	0.617	0.485	0.550	0.321	0.929
0.15	0.630	0.509	0.616	0.491	0.550	0.326	0.896
0.20	0.630	0.514	0.614	0.495	0.520	0.329	0.874
0.25	0.630	0.518	0.612	0.497	0.497	0.332	0.856
0.30	0.630	0.522	0.611	0.499	0.479	0.335	0.841
0.40	0.630	0.527	0.608	0.501	0.449	0.338	0.818
0.50	0.630	0.532	0.606	0.504	0.426	0.341	0.783
0.75	0.630	0.539	0.602	0.506	0.385	0.346	0.680
1.0	0.630	0.545	0.594	0.503	0.350	0.350	0.607
1.5	0.615	0.552	0.566	0.497	0.350	0.350	0.504
2.0	0.604	0.558	0.544	0.491	0.350	0.350	0.431
3.0	0.589	0.565	0.527	0.500	0.350	0.350	0.328
4.0	0.578	0.570	0.515	0.505	0.350	0.350	0.255
5.0	0.570	0.587	0.510	0.529	0.350	0.350	0.200
7.5	0.611	0.618	0.572	0.579	0.350	0.350	0.200
10.0	0.640	0.640	0.612	0.612	0.350	0.350	0.200
PGV	0.590	0.470	0.576	0.453	0.420	0.300	0.740

2.8.4 Calibration Plots

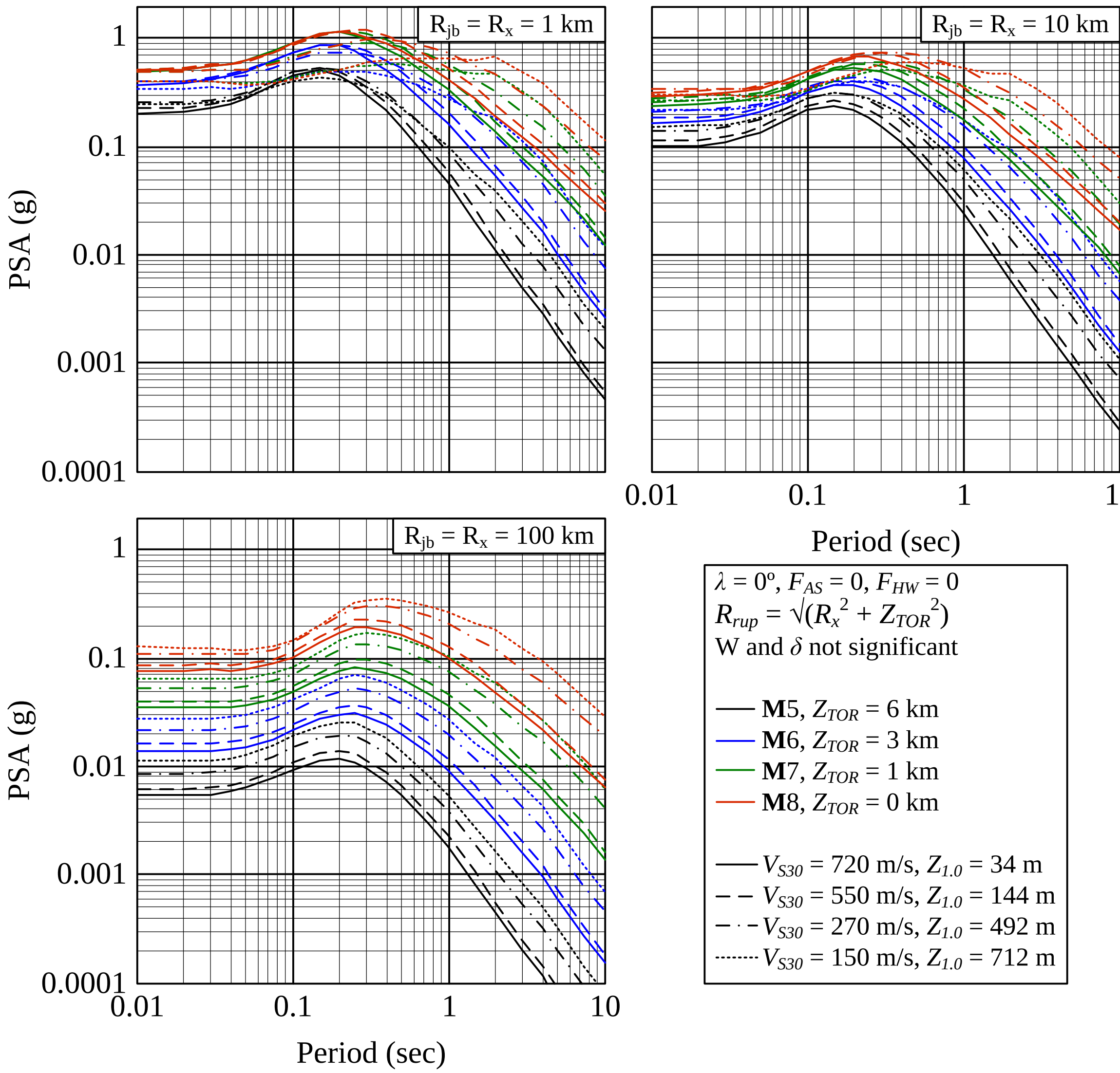


Figure 2-54. PSA as a function of period for given conditions.

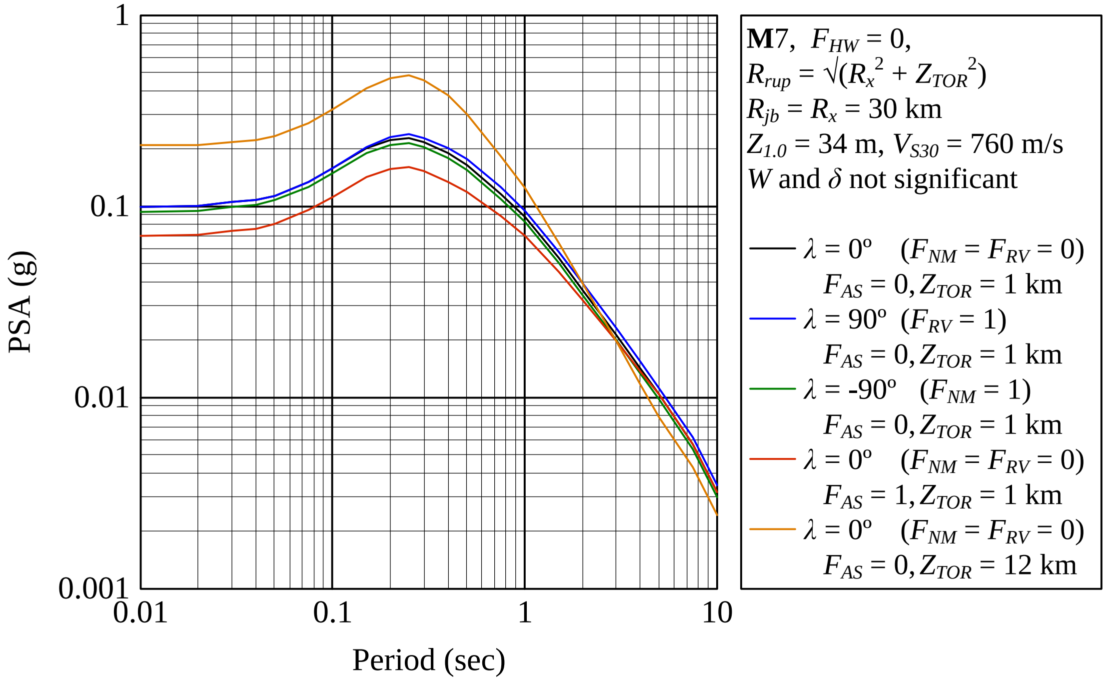
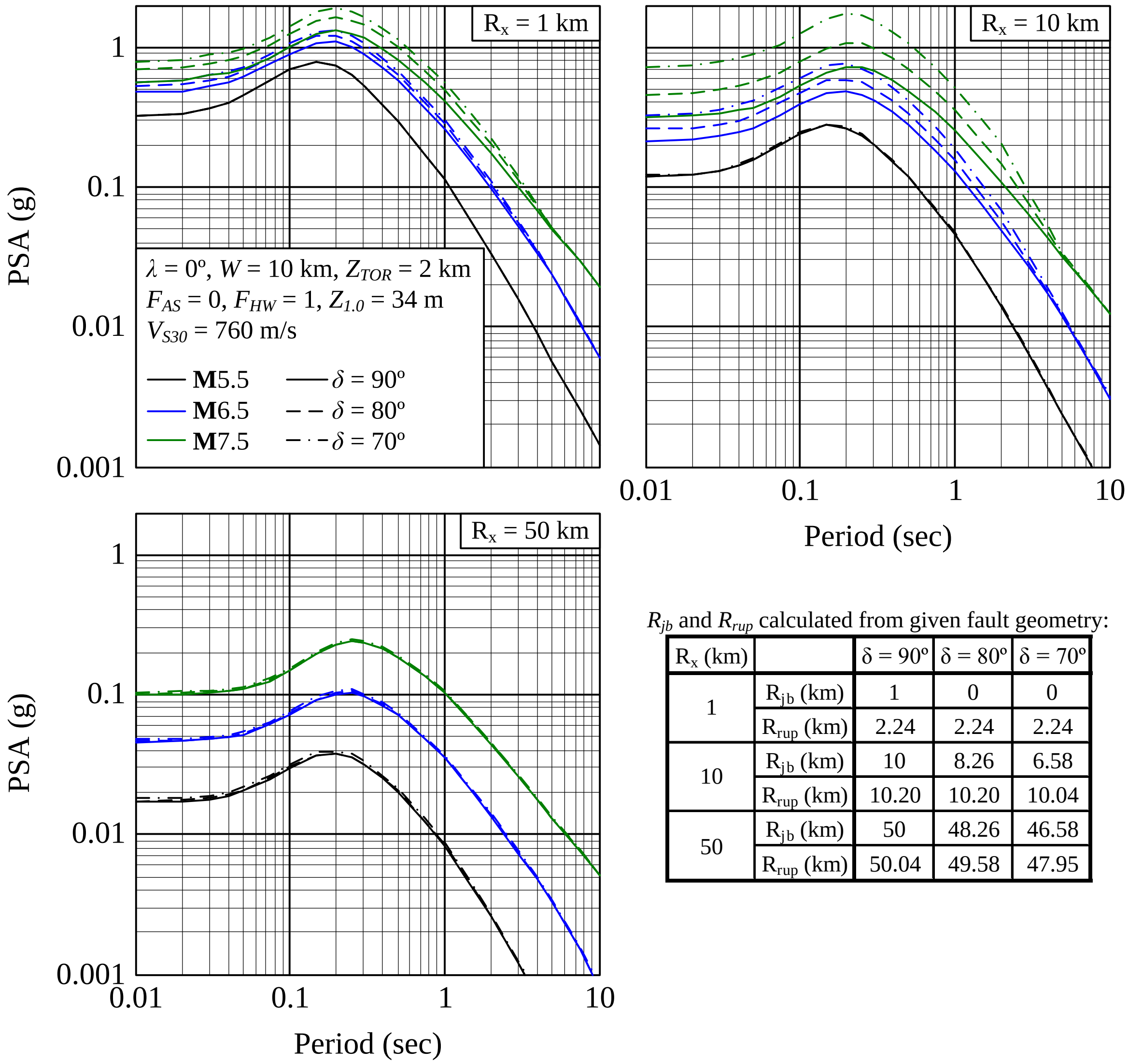


Figure 2-55. PSA as a function of period for given conditions.



R_{jb} and R_{rup} calculated from given fault geometry:

R_x (km)		δ = 90°	δ = 80°	δ = 70°
1	R_{jb} (km)	1	0	0
	R_{rup} (km)	2.24	2.24	2.24
10	R_{jb} (km)	10	8.26	6.58
	R_{rup} (km)	10.20	10.20	10.04
50	R_{jb} (km)	50	48.26	46.58
	R_{rup} (km)	50.04	49.58	47.95

Figure 2-56. PSA as a function of period for given conditions.

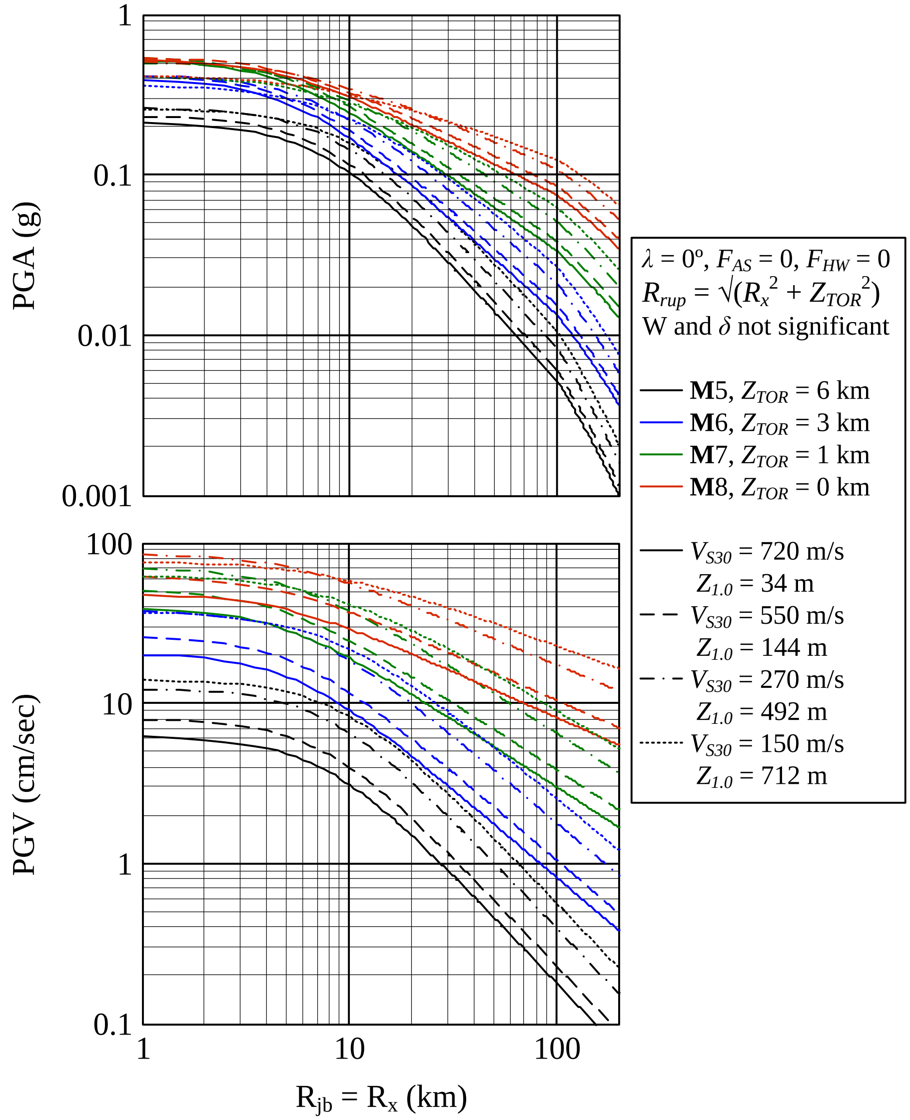


Figure 2-57. PGA and PGV as a function of distance for given conditions.

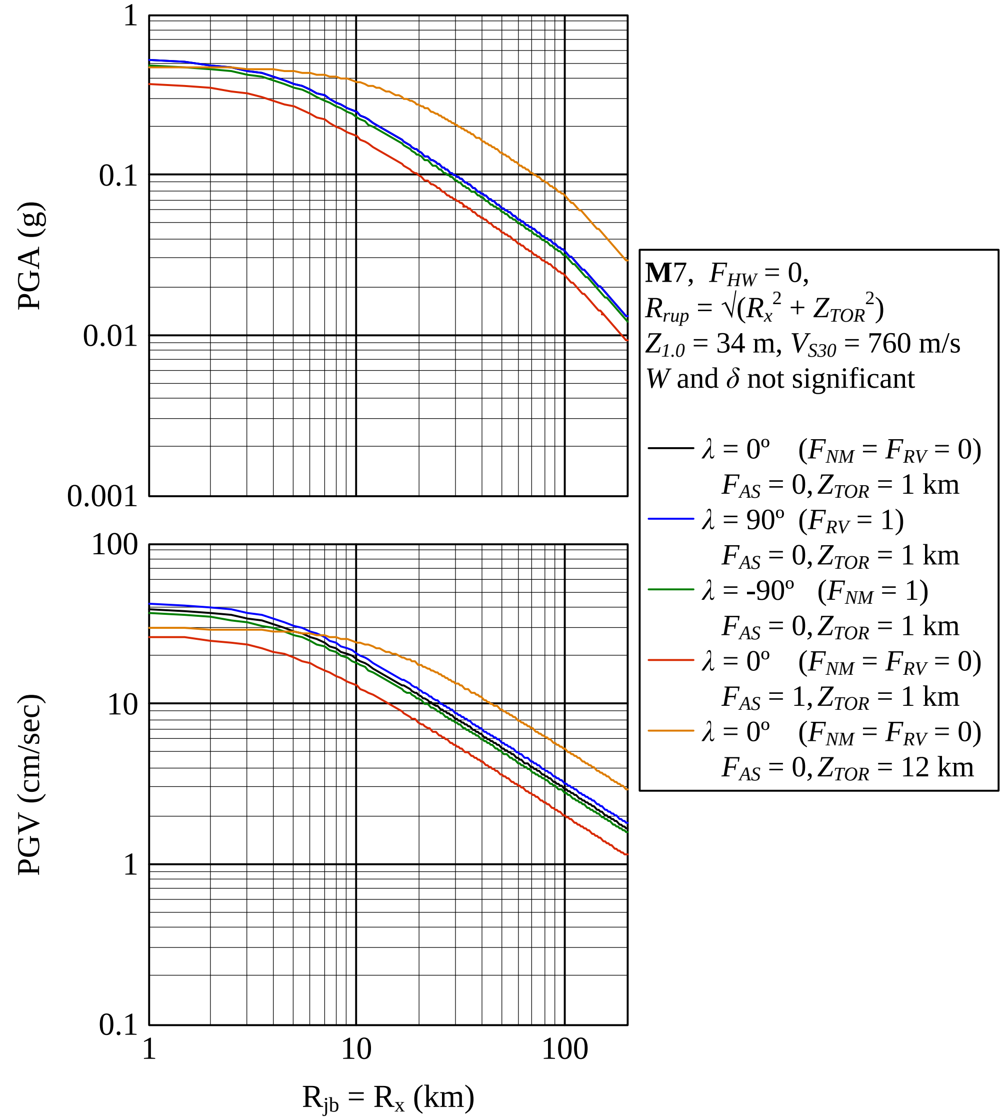
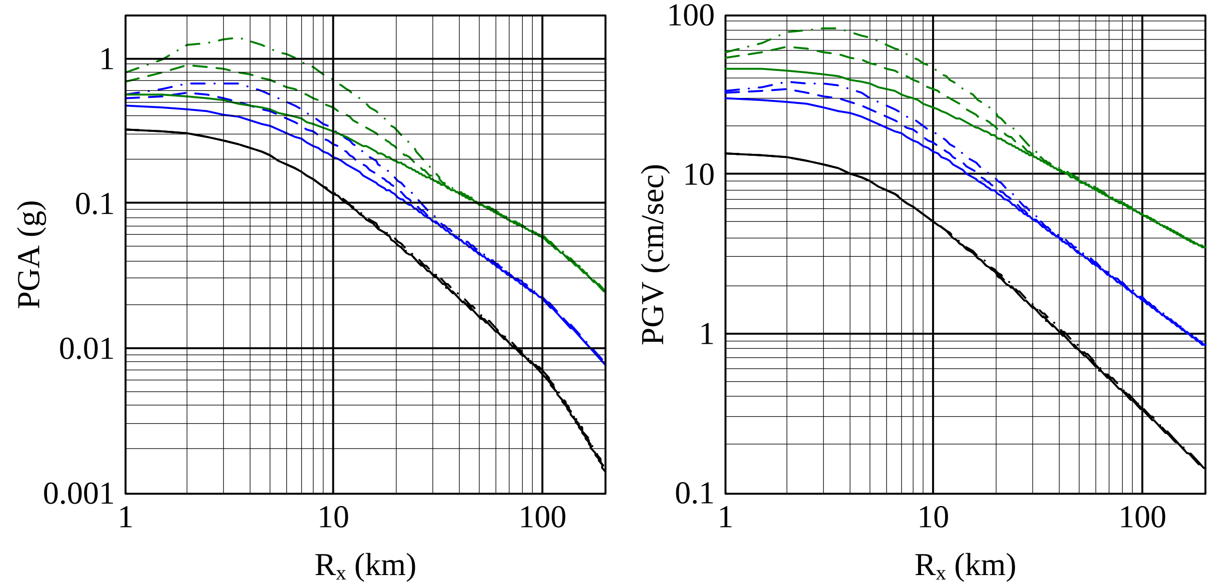


Figure 2-58. PGA and PGV as a function of distance for given conditions.



$$R_{jb} = \begin{cases} 0 & for\ R_x \le W\cos\delta \\ R_x - W\cos\delta & for\ R_x > W\cos\delta \end{cases}$$

$$R_{rup} = \begin{cases} \sqrt{{Z_{TOR}}^2 + {R_x}^2} & for\ R_x \le R_1\ OR\ \delta = 90° \\ \dfrac{Z_{TOR}}{\cos\delta} + (R_x - Z_{TOR}\tan\delta)\sin\delta & for\ R_1 < R_x < R_2 \\ \sqrt{(Z_{TOR} + W\sin\delta)^2 + (R_x - W\cos\delta)^2} & for\ R_x \ge R_2 \end{cases}$$

where:

$$R_1 = Z_{TOR}\tan\delta$$

$$R_2 = Z_{TOR}\tan\delta + \frac{W}{\cos\delta}$$

Figure 2-59. PGA and PGV as a function of distance for given conditions.

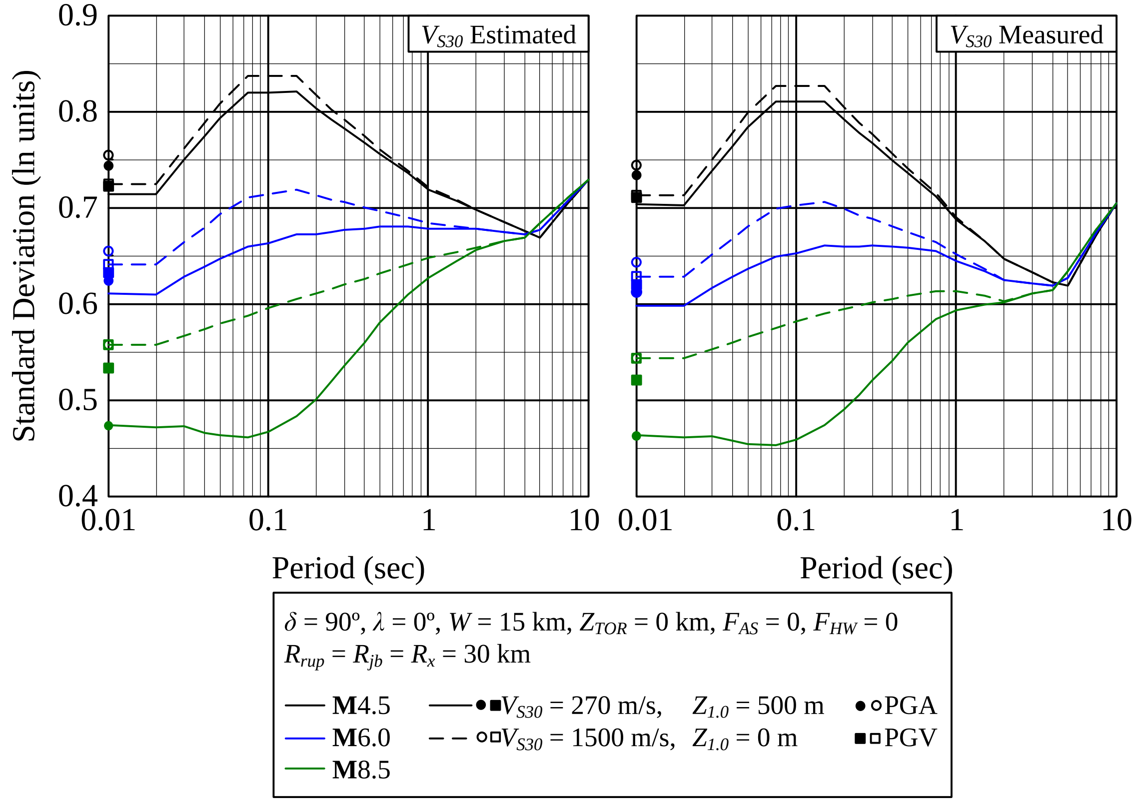


Figure 2-60. Standard deviation as a function of period for given conditions.

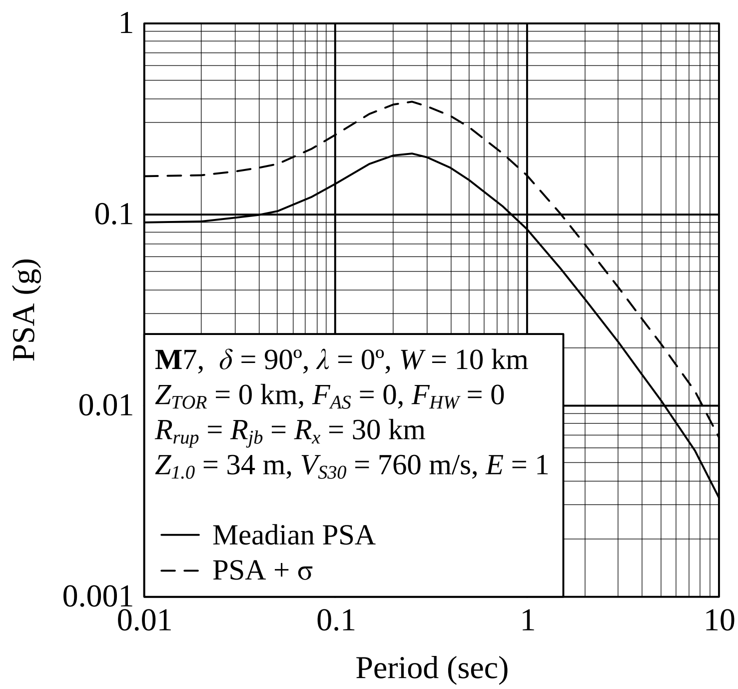


Figure 2-61. Example of application of median PSA plus one standard deviation.

2.8.5 Database

Strong motion database compiled by the "PEER NGA" (Pacific Earthquake Engineering Research Center's Next Generation Attenuation)

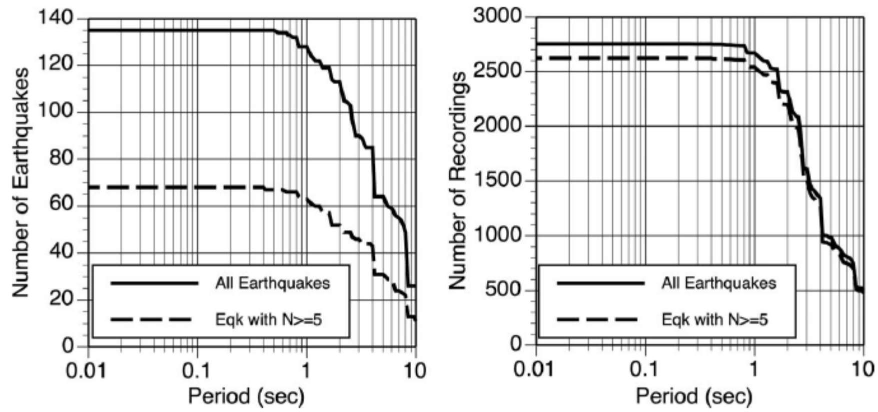


Figure 2-62. Period dependence of the number of earthquakes in subset based on the lowest usable frequency for the average horizontal component listed in the flat-file. N is the number of recordings per earthquake.

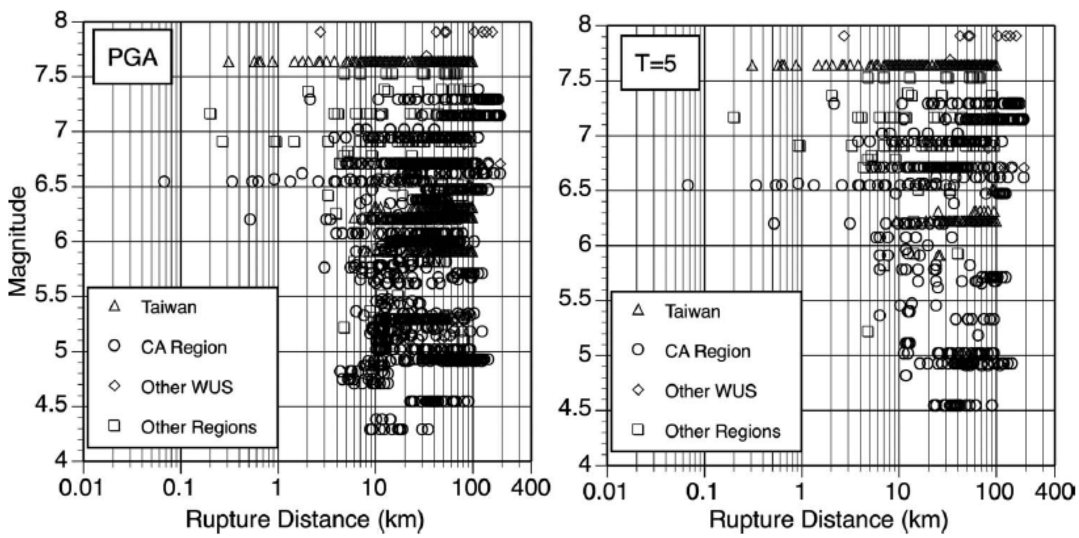


Figure 2-63. Distribution of magnitude-distance pairs for PGA and T = 5 sec.

2.8.6 MATLAB Code:

```
% by Kathryn A. Gunberg 10/20/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Abrahamson & Silva attenuation equation, 2008
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0 for PGA, -1 for PGV
% M         = Magnitude
% delta     = Dip angle (degrees)
% lambda    = Rake angle (degrees)
% W         = Down-dip rupture width (km)
% Ztor      = Depth to top of rupture plane (km)
% Fas       = Aftershock indicator: 1 for aftershock, 0 otherwise
% Fhw       = Hangingwall indicator: 1 for sites on hangingwall, 0 for footwall
% Rrup      = Closest distance to rupture plane (km)
% Rjb       = Joyner-Boore distance (km)
% Rx        = Horizontal distance from the top of the rupture plane,
%             measured perpendicular to the fault strike (km)
% Z1        = Depth to Vs = 1.0 km/s (m)
% Vs30      = Shear wave velocity (m/s) averaged over top 30 m
% E         = 1 for estimated Vs30, 0 for measured
% isTD      = enter 0
% -------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration or PGV prediction (g or cm/s)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = AS_2008_nga(T,M,delta,lambda,W,Ztor,Fas,Fhw,Rrup,Rjb,Rx,Z1,Vs30,E,isTD)
% Coefficients
c1  = 6.75;
c4  = 4.5;
a3  = 0.265;
a4  = -0.231;
a5  = -0.398;
N   = 1.18;
c   = 1.88;
c2  = 50;
period   = [0       0.01    0.02    0.03    0.04    0.05    0.075   ...
    0.1     0.15    0.2     0.25    0.3     0.4     0.5     0.75    ...
    1       1.5     2       3       4       5       7.5     10      -1];
Vlin     = [865.1   865.1   865.1   907.8   994.5   1053.5  1085.7  ...
    1032.5  877.6   748.2   654.3   587.1   503.0   456.6   410.5   ...
    400.0   400.0   400.0   400.0   400.0   400.0   400.0   400.0   400.0];
b        = [-1.186  -1.186  -1.219  -1.273  -1.308  -1.346  -1.471  ...
    -1.624  -1.931  -2.188  -2.381  -2.518  -2.657  -2.669  -2.401  ...
    -1.955  -1.025  -0.299  0       0       0       0       0       -1.955];
a1       = [0.804   0.811   0.855   0.962   1.037   1.133   1.375   ...
    1.563   1.716   1.687   1.646   1.601   1.511   1.397   1.137   ...
    0.915   0.510   0.192   -0.280  -0.639  -0.936  -1.527  -1.993  5.7578];
a2       = [-0.9679 -0.9679 -0.9774 -1.0024 -1.0289 -1.0508 -1.0810 ...
    -1.0833 -1.0357 -0.9700 -0.9202 -0.8974 -0.8677 -0.8475 -0.8206 ...
    -0.8088 -0.7995 -0.7960 -0.7960 -0.7960 -0.7960 -0.7960 -0.7960 -0.9046];
a8       = [-0.0372 -0.0372 -0.0372 -0.0372 -0.0315 -0.0271 -0.0191 ...
    -0.0166 -0.0254 -0.0396 -0.0539 -0.0656 -0.0807 -0.0924 -0.1137 ...
    -0.1289 -0.1534 -0.1708 -0.1954 -0.2128 -0.2263 -0.2509 -0.2683 -0.1200];
a10      = [0.9445  0.9445  0.9834  1.0471  1.0884  1.1333  1.2808  ...
    1.4613  1.8071  2.0773  2.2794  2.4201  2.5510  2.5395  2.1493  ...
    1.5705  0.3991  -0.6072 -0.9600 -0.9600 -0.9208 -0.7700 -0.6630 1.5390];
a12      = [0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  ...
    0.0000  0.0181  0.0309  0.0409  0.0491  0.0619  0.0709  0.0800  ...
    0.0800  0.0800  0.0800  0.0800  0.0800  0.0800  0.0800  0.0800  0.0800];
a13      = [-0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 ...
    -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 ...
    -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600 -0.0600];
a14      = [1.0800  1.0800  1.0800  1.1331  1.1708  1.2000  1.2000  ...
    1.2000  1.1683  1.1274  1.0956  1.0697  1.0288  0.9971  0.9395  ...
```

```
    0.8985  0.8409  0.8000  0.4793  0.2518  0.0754  0.0000  0.0000  0.7000];
a15      = [-0.3500 -0.3500 -0.3500 -0.3500 -0.3500 -0.3500 -0.3500 ...
    -0.3500 -0.3500 -0.3500 -0.3500 -0.3500 -0.3500 -0.3191 -0.2629 ...
    -0.2230 -0.1668 -0.1270 -0.0708 -0.0309 0.0000  0.0000  0.0000  -0.3900];
a16      = [0.9000  0.9000  0.9000  0.9000  0.9000  0.9000  0.9000  ...
    0.9000  0.9000  0.9000  0.9000  0.9000  0.8423  0.7458  0.5704  ...
    0.4460  0.2707  0.1463  -0.0291 -0.1535 -0.2500 -0.2500 -0.2500 0.6300];
a18      = [-0.0067 -0.0067 -0.0067 -0.0067 -0.0067 -0.0076 -0.0093 ...
    -0.0093 -0.0093 -0.0083 -0.0069 -0.0057 -0.0039 -0.0025 0.0000  ...
    0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000];
s1e      = [0.590   0.590   0.590   0.605   0.615   0.623   0.630   ...
    0.630   0.630   0.630   0.630   0.630   0.630   0.630   0.630   ...
    0.630   0.615   0.604   0.589   0.578   0.570   0.611   0.640   0.590];
s2e      = [0.470   0.470   0.470   0.478   0.483   0.488   0.495   ...
    0.501   0.509   0.514   0.518   0.522   0.527   0.532   0.539   ...
    0.545   0.552   0.558   0.565   0.570   0.587   0.618   0.640   0.470];
s1m      = [0.576   0.576   0.576   0.591   0.602   0.610   0.617   ...
    0.617   0.616   0.614   0.612   0.611   0.608   0.606   0.602   ...
    0.594   0.566   0.544   0.527   0.515   0.510   0.572   0.612   0.576];
s2m      = [0.453   0.453   0.453   0.461   0.466   0.471   0.479   ...
    0.485   0.491   0.495   0.497   0.499   0.501   0.504   0.506   ...
    0.503   0.497   0.491   0.500   0.505   0.529   0.579   0.612   0.453];
s3       = [0.470   0.420   0.420   0.462   0.492   0.515   0.550   ...
    0.550   0.550   0.520   0.497   0.479   0.449   0.426   0.385   ...
    0.350   0.350   0.350   0.350   0.350   0.350   0.350   0.350   0.420];
s4       = [0.300   0.300   0.300   0.305   0.309   0.312   0.317   ...
    0.321   0.326   0.329   0.332   0.335   0.338   0.341   0.346   ...
    0.350   0.350   0.350   0.350   0.350   0.350   0.350   0.350   0.300];
rho      = [1.000   1.000   1.000   0.991   0.982   0.973   0.952   ...
    0.929   0.896   0.874   0.856   0.841   0.818   0.783   0.680   ...
    0.607   0.504   0.431   0.328   0.255   0.200   0.200   0.200   0.740];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low,sig_low]=AS_2008_nga(T_low,M,delta,lambda,W,Ztor,Fas,Fhw,Rrup,Rjb,Rx,Z1,Vs30,E,isTD);
    [sa_hi, sig_hi] =AS_2008_nga(T_hi, M,delta,lambda,W,Ztor,Fas,Fhw,Rrup,Rjb,Rx,Z1,Vs30,E,isTD);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sig_T = [sig_low sig_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sig_T,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    Frv = lambda >= 30 & lambda <= 150; % Frv: 1 for lambda between 30 and 150, 0 otherwise
    Fnm = lambda >= -120 & lambda <= -60; % Fnm: 1 for lambda between -120 and -60, 0 otherwise
    if Vs30 < Vlin(i)
        [PGA1100 sig_TPGA] = AS_2008_nga(0,M,delta,lambda,W,Ztor,Fas,Fhw,Rrup,Rjb,Rx,6,1100,E,1);
    end
    % Base Model
    R = sqrt(Rrup^2+c4^2);
    if M <= c1
        f1 = a1(i) + a4*(M - c1) + a8(i)*(8.5 - M)^2 + (a2(i) + a3*(M - c1))*log(R);
    else
        f1 = a1(i) + a5*(M - c1) + a8(i)*(8.5 - M)^2 + (a2(i) + a3*(M - c1))*log(R);
    end
    % Site Response Model
    if T < 0
        V1 = 862;
    elseif T <= 0.50
        V1 = 1500;
    elseif T <= 1
        V1 = exp(8.0 - 0.795 * log(T/0.21));
    elseif T < 2
        V1 = exp(6.76 - 0.297 * log(T));
    else
        V1 = 700;
    end
    if Vs30 < V1
        Vstar = Vs30;
    else
```

```
    Vstar = V1;
end
if Vs30 < Vlin(i)
    f5 = a10(i)*log(Vstar/Vlin(i))-b(i)*log(PGA1100+c)+b(i)*log(PGA1100+c*(Vstar/Vlin(i))^N);
else
    f5 = (a10(i) + b(i) * N) * log(Vstar / Vlin(i));
end
% Hanging Wall Model
if Rjb < 30
    T1 = 1 - Rjb/30;
else
    T1 = 0;
end
if Rx <= W * cosd(delta)
    T2 = 0.5 + Rx / (2 * W * cosd(delta));
else
    T2 = 1;
end
if Rx >= Ztor
    T3 = 1;
else
    T3 = Rx/Ztor;
end
if M <= 6
    T4 = 0;
elseif M < 7
    T4 = M - 6;
else
    T4 = 1;
end
if delta >= 70
    T5 = 1 - (delta - 70) / 20;
else
    T5 = 1;
end
f4 = a14(i) * T1 * T2 * T3 * T4 * T5;
% Depth-to-Top of Rupture Model
if Ztor < 10
    f6 = a16(i) * Ztor / 10;
else
    f6 = a16(i);
end
% Large Distance Model
if M < 5.5
    T6 = 1;
elseif M <= 6.5
    T6 = 0.5 * (6.5 - M) + 0.5;
else
    T6 = 0.5;
end
if Rrup < 100
    f8 = 0;
else
    f8 = a18(i) * (Rrup - 100) * T6;
end
% Soil Depth Model
if Vs30 < 180
    lnZ1hat = 6.745;
elseif Vs30 <= 500
    lnZ1hat = 6.745 - 1.35 * log(Vs30 / 180);
else
    lnZ1hat = 5.394 - 4.48 * log(Vs30 / 500);
end
Z1hat = exp(lnZ1hat);
if Vs30 > 1000
    e2 = 0;
elseif T == -1
    e2 = -0.25 * log(Vs30 / 1000) * log(1 / 0.35);
elseif T < 0.35
    e2 = 0;
elseif T <= 2
```

```
        e2 = -0.25 * log(Vs30 / 1000) * log(min(T,2) / 0.35);
    end
    if Vs30 >= 1000
        a21 = 0;
    elseif ((a10(i) + b(i)*N)*log(Vstar/min(V1,1000)) + e2*log((Z1 + c2)/(Z1hat + c2))) < 0
        a21 = -((a10(i) + b(i)*N)*log(Vstar/min(V1,1000))/log((Z1 + c2)/(Z1hat + c2)));
    else
        a21 = e2;
    end
    if T < 2
        a22 = 0;
    else
        a22 = 0.0625 * (T - 2);
    end
    if Z1 >= 200
        f10 = a21 * log((Z1 + c2)/(Z1hat + c2)) + a22 * log(Z1 / 200);
    else
        f10 = a21 * log((Z1 + c2)/(Z1hat + c2));
    end
    % Median Ground Motion
    lnSa = f1 + a12(i)*Frv + a13(i)*Fnm + a15(i)*Fas + f5 + Fhw*f4 + f6 + f8 + f10;
    Sa_preTD = exp(lnSa);
    % Constant Displacement Model
    TD = 10^(-1.25 + 0.3 * M);
    if or(T <= TD, isTD == 1)
        Sa = Sa_preTD;
    else
        [Sa1  sig_T1]  = AS_2008_nga(T, M,delta,lambda,W,Ztor,Fas,Fhw,Rrup,Rjb,Rx,Z1,Vs30,E,1);
        [Sa2  sig_T2]  = AS_2008_nga(T, M,delta,lambda,W,Ztor,Fas,Fhw,Rrup,Rjb,Rx,6, 1100,E,1);
        [SaTD sig_TTD] = AS_2008_nga(TD,M,delta,lambda,W,Ztor,Fas,Fhw,Rrup,Rjb,Rx,6, 1100,E,1);
        Sa = exp(log(Sa1)-log(Sa2)) * TD^2 / T^2 * SaTD;
    end
    sigmaAmp = 0.3;
    if E == 1
        s1 = s1e;
        s2 = s2e;
    else
        s1 = s1m;
        s2 = s2m;
    end
    if M < 5
        sigma0T   = s1(i);
        sigma0pga = s1(1);
        tau0T     = s3(i);
        tau0pga   = s3(1);
    elseif M <= 7
        sigma0T   = s1(i) + (s2(i) - s1(i)) / 2 * (M - 5);
        sigma0pga = s1(1) + (s2(1) - s1(1)) / 2 * (M - 5);
        tau0T     = s3(i) + (s4(i) - s3(i)) / 2 * (M - 5);
        tau0pga   = s3(1) + (s4(1) - s3(1)) / 2 * (M - 5);
    else
        sigma0T   = s2(i);
        sigma0pga = s2(1);
        tau0T     = s4(i);
        tau0pga   = s4(1);
    end
    sigmaBT   = sqrt(sigma0T^2 - sigmaAmp^2);
    sigmaBpga = sqrt(sigma0pga^2 - sigmaAmp^2);
    tauBT     = tau0T;
    tauBpga   = tau0pga;
    if Vs30 >= Vlin(i)
        dAmp_dPGA = 0;
    else
        dAmp_dPGA = b(i)*PGA1100*(-1/(PGA1100 + c) + 1/(PGA1100 + c*(Vs30/Vlin(i))^N));
    end
    sig   = sqrt(sigmaBT^2 + sigmaAmp^2 + dAmp_dPGA^2 * sigmaBpga^2 + ...
        2 * dAmp_dPGA * sigmaBT * sigmaBpga * rho(i));
    tau   = sqrt(tau0T^2 + dAmp_dPGA^2 * tauBpga^2 + ...
        2 * dAmp_dPGA * tauBT * tauBpga * rho(i));
    sigma = sqrt(sig^2 + tau^2);
end
```

2.9 Boore and Atkinson – 2008

2.9.1 References

Boore, D. M., and G. M. Atkinson (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s, *Earthquake Spectra* **24**, 99–138.

Boore, D. M., and G. M. Atkinson (2008). Notes on the equation to use for *pga*4*nl*, *unpublished notes*, available from http://quake.wr.usgs.gov/~boore/pubs_online.php.

Boore, D. M. (2008). ERRATUM: 27 August 2008. Noted at: http://quake.usgs.gov/~boore/pubs_online.php.

Atkinson, G. M., and D. M. Boore. (2011). Modifications to Existing Ground-Motion Prediction Equations in Light of New Data, *Bulletin of the Seismological Society of America.* (*in process*)

2.9.2 Abstract

Using a subset of the PEER NGA database (1574 recordings from 58 earthquakes), an empirical ground-motion model for the average horizontal component was developed. The model predicts peak ground velocity (PGV, in cm/s), peak ground acceleration (PGA, in g) and 5%-damped spectral values (in g) for periods ranging from 0.01 to 10 s. The model is applicable for earthquakes from M5.0 to M8.0, Joyner-Boore distances from 0 to 200 km, and average shear wave velocity in the upper 30 meters from 180 to 1300 m/s.

The 2011 publication, noted above, provides an adjustment to the original GMPE's applicable to both northern and southern California earthquakes from M3.5 to M5.75 (i.e. small-to-moderate magnitude or SMM). For this magnitude range, this adjustment is intended to replace the original equations. No change to the standard deviations were deemed necessary.

2.9.3 Attenuation Relationship

The predicted ground motion parameters are a function of:

- T – Period (sec), use 0 for PGA, -1 for PGV
- **M** – Moment magnitude
- F – 1 for unspecified, 2 for strike-slip, 3 for normal or 4 for reverse
- R_{jb} – Joyner-Boore distance (km)
- V_{S30} – Shear wave velocity (m/s) averaged over top 30 m
- SMM – 1 for SMM adjustment, 0 othewise

$$\ln(Sa) = F_M(M) + F_D\left(R_{jb}, M\right) + F_S\left(V_{S30}, R_{jb}, M\right)$$

where:

$$F_M(M) = \begin{cases} e_1U + e_2SS + e_3NS + e_4RS + e_5(M - M_h) + e_6(M - M_h)^2 & for\ M \leq M_h \\ e_1U + e_2SS + e_3NS + e_4RS + e_7(M - M_h) & for\ M > M_h \end{cases}$$

$$F_D(R_{jb}, M) = [c_1 + c_2(M - M_{ref})] \ln(R/R_{ref}) + c_3(R - R_{ref})$$

where:

$$R = \sqrt{{R_{jb}}^2 + h^2}$$

$$F_S(V_{S30}, R_{jb}, M) = F_{LIN} + F_{NL}$$

where:

$$F_{LIN} = b_{lin} \ln\left(\frac{V_{S30}}{V_{ref}}\right)$$

$$\mathrm{F_{NL}} = \begin{cases} b_{nl} \ln\left(\frac{pga\_low}{0.1}\right) & for\ pga4nl \leq a_1 \\ b_{nl} \ln\left(\frac{pga\_low}{0.1}\right) + c\left[\ln\left(\frac{pga4nl}{a_1}\right)\right]^2 & \\ \qquad + d\left[\ln\left(\frac{pga4nl}{a_1}\right)\right]^3 & for\ a_1 < pga4nl \leq a_2 \\ b_{nl} \ln\left(\frac{pga4nl}{0.1}\right) & for\ pga4nl > a_2 \end{cases}$$

where:

pga4nl is the median predicted PGA (*Sa* for *T* = 0 sec) in g as given by the general equation for $F_S = 0$

$$b_{nl} = \begin{cases} b_1 & for\ V_{S30} \leq V_1 \\ (b_1 - b_2) \ln\left(\frac{V_{S30}}{V_2}\right) \Big/ \ln\left(\frac{V_1}{V_2}\right) + b_2 & for\ V_1 < V_{S30} \leq V_2 \\ b_2 \ln\left(\frac{V_{S30}}{V_{ref}}\right) \Big/ \ln\left(\frac{V_2}{V_{ref}}\right) & for\ V_2 < V_{S30} < V_{ref} \\ 0 & for\ V_{S30} \geq V_{ref} \end{cases}$$

$$c = (3\Delta y - b_{nl}\Delta x)/\Delta x^2$$

$$d = -(2\Delta y - b_{nl}\Delta x)/\Delta x^3$$

where:

$$\Delta x = \ln\left(\frac{a_2}{a_1}\right)$$

$$\Delta y = b_{nl} \ln\left(\frac{a_2}{pga\_low}\right)$$

SMM adjustment

$$Sa' = Sa \cdot F_{BA08}$$

where:

Sa' is the adjusted ground motion prediction,

Sa is the unadjusted ground motion prediction, and

$$\log_{10}(F_{BA08}) = \max(0, 3.888 - 0.674M) - \max(0, 2.933 - 0.510M) \log_{10}\left(R_{jb} + 10\right)$$

Standard Deviation

$$\sigma_T = \sqrt{\sigma^2 + \tau^2}$$

Coefficients

Table 2-23. Values of dummy variables for different fault types

Fault Type	U	SS	NS	RS
Unspecified	1	0	0	0
Strike-slip	0	1	0	0
Normal	0	0	1	0
Thrust/reverse	0	0	0	1

Table 2-24. Period-dependent site-amplification coefficients

T (sec)	b_{lin}	b_1	b_2
PGV	-0.600	-0.500	-0.06
PGA	-0.360	-0.640	-0.14
0.010	-0.360	-0.640	-0.14
0.020	-0.340	-0.630	-0.12
0.030	-0.330	-0.620	-0.11
0.050	-0.290	-0.640	-0.11
0.075	-0.230	-0.640	-0.11
0.10	-0.250	-0.600	-0.13
0.15	-0.280	-0.530	-0.18
0.20	-0.310	-0.520	-0.19
0.25	-0.390	-0.520	-0.16
0.30	-0.440	-0.520	-0.14
0.40	-0.500	-0.510	-0.10
0.50	-0.600	-0.500	-0.06
0.75	-0.690	-0.470	0.00
1.0	-0.700	-0.440	0.00
1.5	-0.720	-0.400	0.00
2.0	-0.730	-0.380	0.00
3.0	-0.740	-0.340	0.00
4.0	-0.750	-0.310	0.00
5.0	-0.750	-0.291	0.00
7.5	-0.692	-0.247	0.00
10.0	-0.650	-0.215	0.00

Table 2-25. Period-independent site-amplification coefficients

Coefficient	Value
a_1	0.03 g
pga_low	0.06 g
a_2	0.09 g
V_1	180 m/s
V_2	300 m/s
V_{ref}	760 m/s

Table 2-26. Distance-scaling coefficients (M_{ref} = 4.5 and R_{ref} = 1.0 km for all periods)

T (sec)	c_1	c_2	c_3	h
PGV	-0.87370	0.10060	-0.00334	2.54
PGA	-0.66050	0.11970	-0.01151	1.35
0.010	-0.66220	0.12000	-0.01151	1.35
0.020	-0.66600	0.12280	-0.01151	1.35
0.030	-0.69010	0.12830	-0.01151	1.35
0.050	-0.71700	0.13170	-0.01151	1.35
0.075	-0.72050	0.12370	-0.01151	1.55
0.10	-0.70810	0.11170	-0.01151	1.68
0.15	-0.69610	0.09884	-0.01113	1.86
0.20	-0.58300	0.04273	-0.00952	1.98
0.25	-0.57260	0.02977	-0.00837	2.07
0.30	-0.55430	0.01955	-0.00750	2.14
0.40	-0.64430	0.04394	-0.00626	2.24
0.50	-0.69140	0.06080	-0.00540	2.32
0.75	-0.74080	0.07518	-0.00409	2.46
1.0	-0.81830	0.10270	-0.00334	2.54
1.5	-0.83030	0.09793	-0.00255	2.66
2.0	-0.82850	0.09432	-0.00217	2.73
3.0	-0.78440	0.07282	-0.00191	2.83
4.0	-0.68540	0.03758	-0.00191	2.89
5.0	-0.50960	-0.02391	-0.00191	2.93
7.5	-0.37240	-0.06568	-0.00191	3.00
10.0	-0.09824	-0.13800	-0.00191	3.04

Table 2-27. Magnitude-scaling coefficients

T (sec)	e_1	e_2	e_3	e_4	e_5	e_6	e_7	M_h
PGV	5.00121	5.04727	4.63188	5.08210	0.18322	-0.12736	0.00000	8.50
PGA	-0.53804	-0.50350	-0.75472	-0.50970	0.28805	-0.10164	0.00000	6.75
0.010	-0.52883	-0.49429	-0.74551	-0.49966	0.28897	-0.10019	0.00000	6.75
0.020	-0.52192	-0.48508	-0.73906	-0.48895	0.25144	-0.11006	0.00000	6.75
0.030	-0.45285	-0.41831	-0.66722	-0.42229	0.17976	-0.12858	0.00000	6.75
0.050	-0.28476	-0.25022	-0.48462	-0.26092	0.06369	-0.15752	0.00000	6.75
0.075	0.00767	0.04912	-0.20578	0.02706	0.01170	-0.17051	0.00000	6.75
0.10	0.20109	0.23102	0.03058	0.22193	0.04697	-0.15948	0.00000	6.75
0.15	0.46128	0.48661	0.30185	0.49328	0.17990	-0.14539	0.00000	6.75
0.20	0.57180	0.59253	0.40860	0.61472	0.52729	-0.12964	0.00102	6.75
0.25	0.51884	0.53496	0.33880	0.57747	0.60880	-0.13843	0.08607	6.75
0.30	0.43825	0.44516	0.25356	0.51990	0.64472	-0.15694	0.10601	6.75
0.40	0.39220	0.40602	0.21398	0.46080	0.78610	-0.07843	0.02262	6.75
0.50	0.18957	0.19878	0.00967	0.26337	0.76837	-0.09054	0.00000	6.75
0.75	-0.21338	-0.19496	-0.49176	-0.10813	0.75179	-0.14053	0.10302	6.75
1.0	-0.46896	-0.43443	-0.78465	-0.39330	0.67880	-0.18257	0.05393	6.75
1.5	-0.86271	-0.79593	-1.20902	-0.88085	0.70689	-0.25950	0.19082	6.75
2.0	-1.22652	-1.15514	-1.57697	-1.27669	0.77989	-0.29657	0.29888	6.75
3.0	-1.82979	-1.74690	-2.22584	-1.91814	0.77966	-0.45384	0.67466	6.75
4.0	-2.24656	-2.15906	-2.58228	-2.38168	1.24961	-0.35874	0.79508	6.75
5.0	-1.28408	-1.21270	-1.50904	-1.41093	0.14271	-0.39006	0.00000	8.50
7.5	-1.43145	-1.31632	-1.81022	-1.59217	0.52407	-0.37578	0.00000	8.50
10.0	-2.15446	-2.16137	-2.53323	-2.14635	0.40387	-0.48492	0.00000	8.50

Table 2-28. Aleatory uncertainties (σ: intra-event uncertainty; τ: inter-event uncertainty; σ_T: combined uncertainty($\sqrt{\sigma^2+\tau^2}$); subscripts U, M for fault type unspecified and specified respectively)

T (sec)	σ	τ_U	σ_{TU}	τ_M	σ_{TM}
PGV	0.500	0.286	0.576	0.256	0.560
PGA	0.502	0.265	0.566	0.260	0.564
0.010	0.502	0.267	0.569	0.262	0.566
0.020	0.502	0.267	0.569	0.262	0.566
0.030	0.507	0.276	0.578	0.274	0.576
0.050	0.516	0.286	0.589	0.286	0.589
0.075	0.513	0.322	0.606	0.320	0.606
0.10	0.520	0.313	0.608	0.318	0.608
0.15	0.518	0.288	0.592	0.290	0.594
0.20	0.523	0.283	0.596	0.288	0.596
0.25	0.527	0.267	0.592	0.267	0.592
0.30	0.546	0.272	0.608	0.269	0.608
0.40	0.541	0.267	0.603	0.267	0.603
0.50	0.555	0.265	0.615	0.265	0.615
0.75	0.571	0.311	0.649	0.299	0.645
1.0	0.573	0.318	0.654	0.302	0.647
1.5	0.566	0.382	0.684	0.373	0.679
2.0	0.580	0.398	0.702	0.389	0.700
3.0	0.566	0.410	0.700	0.401	0.695
4.0	0.583	0.394	0.702	0.385	0.698
5.0	0.601	0.414	0.730	0.437	0.744
7.5	0.626	0.465	0.781	0.477	0.787
10.0	0.645	0.355	0.735	0.477	0.801

2.9.4 *Calibration Plots (unadjusted for SMM earthquakes unless specified)*

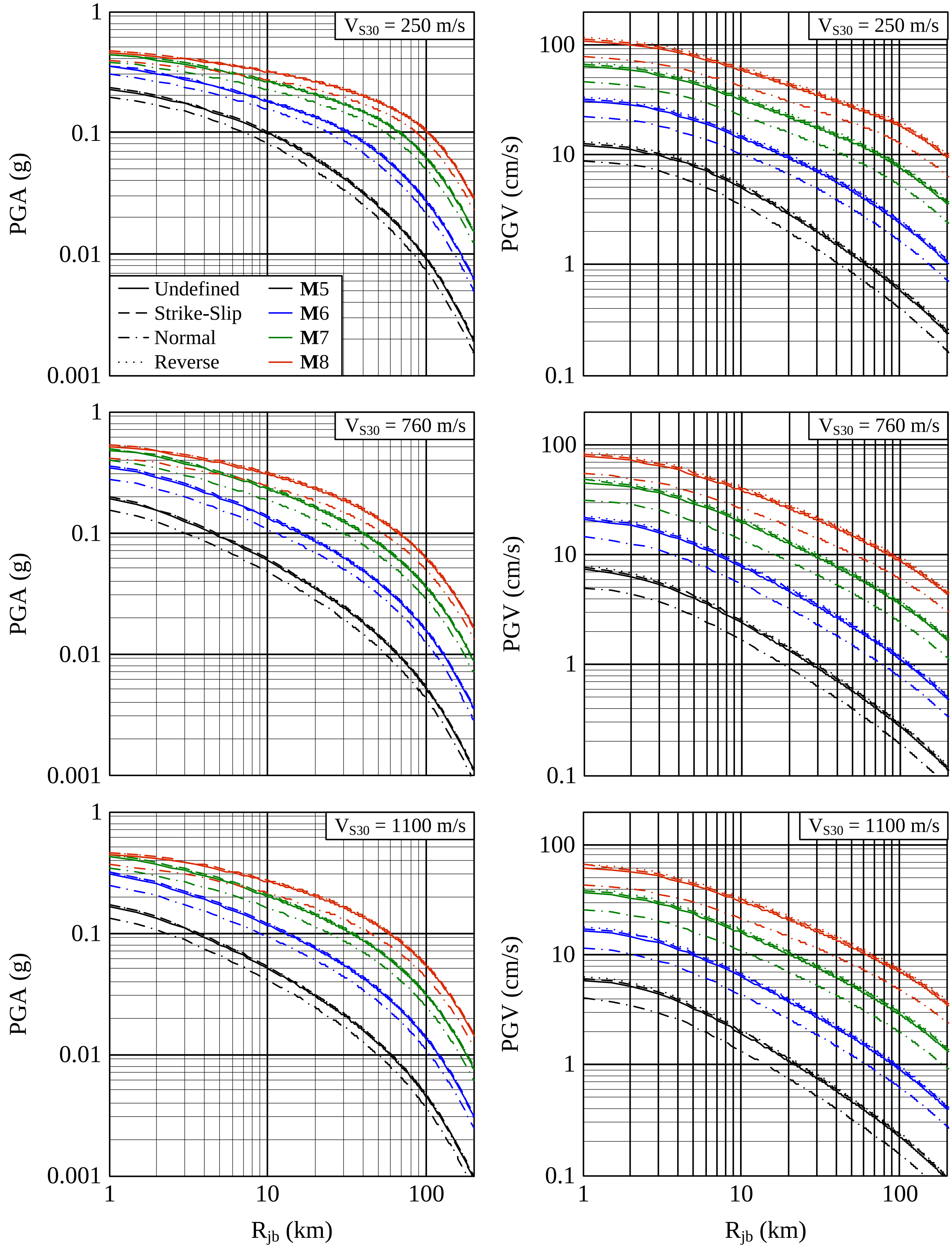


Figure 2-64 PGA and PGV as a function of distances for various faults, magnitudes and shear wave velocities.

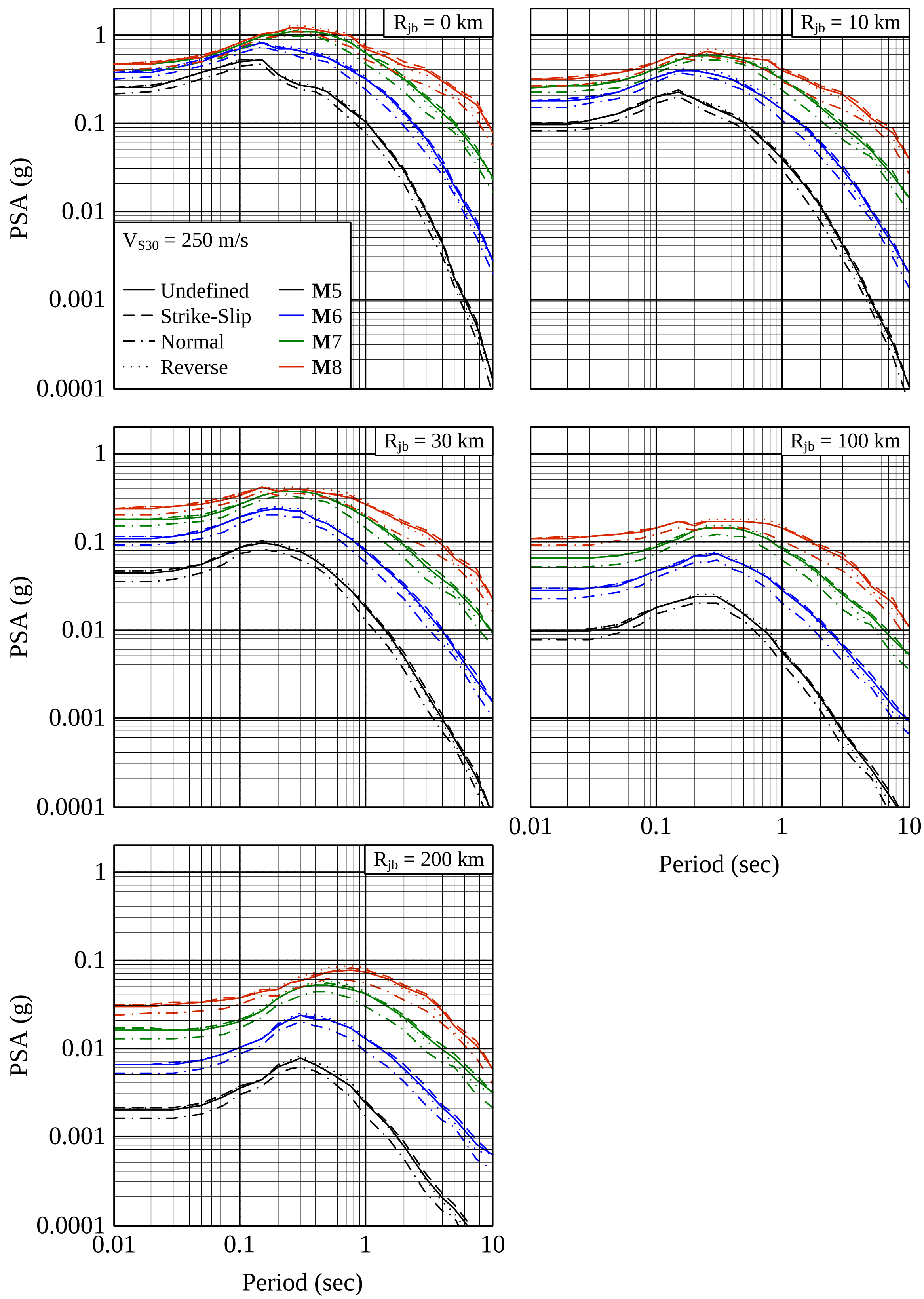


Figure 2-65. PSA as a function of period for various fault types, magnitudes and distances with V_{S30} = 250 m/s.

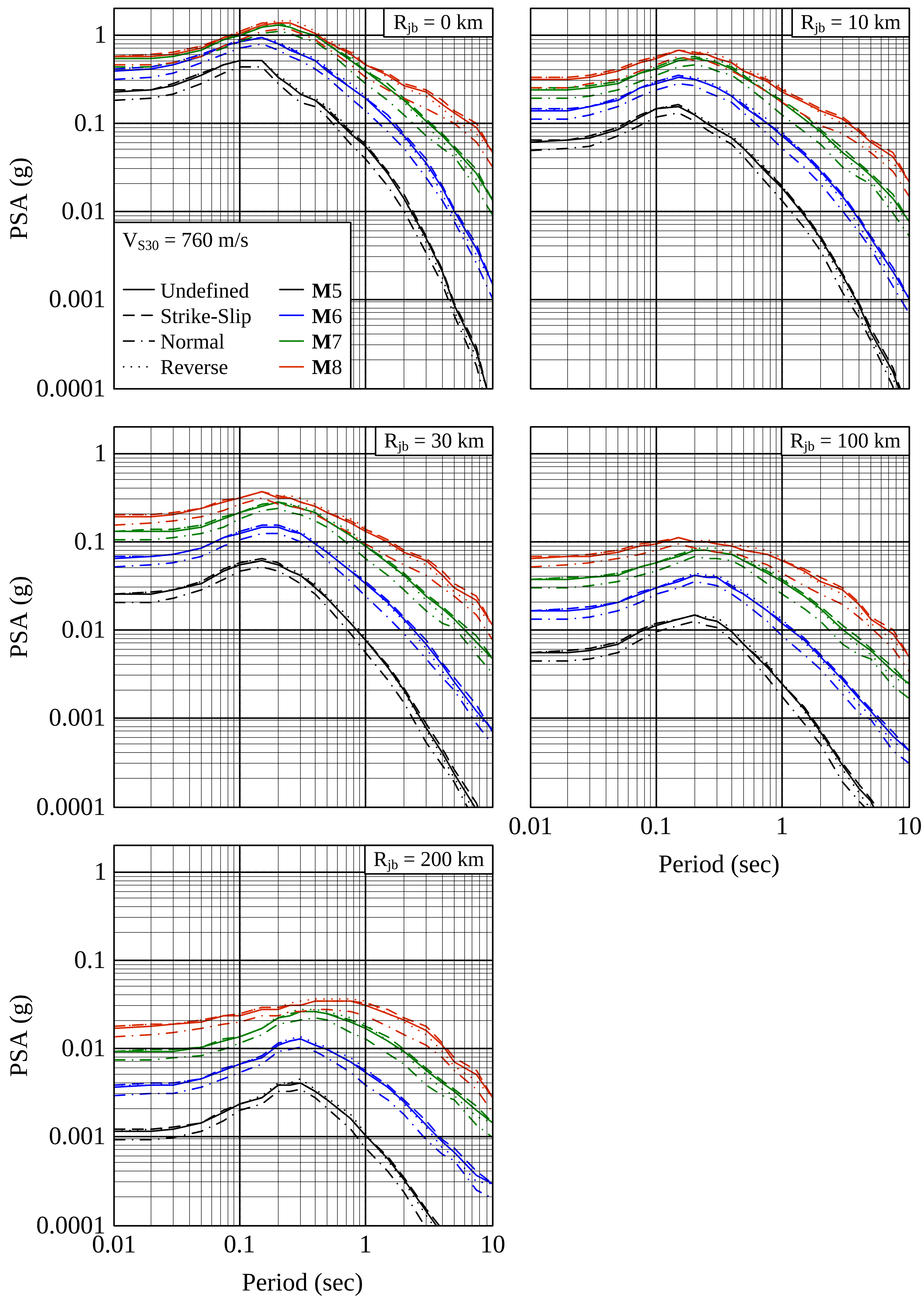


Figure 2-66. PSA as a function of period for various fault types, magnitudes and distances with V_{S30} = 760 m/s.

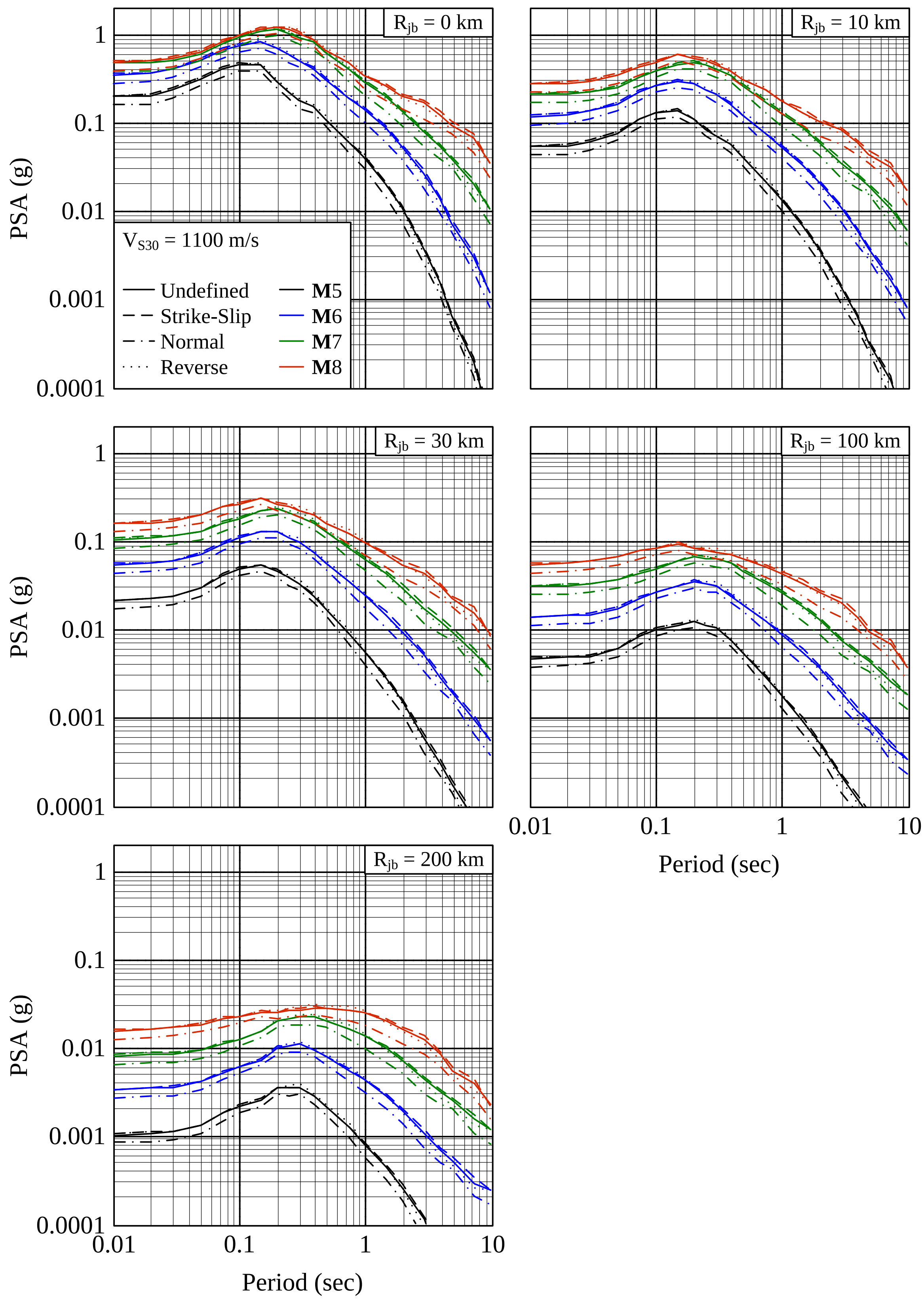


Figure 2-67. PSA as a function of period for various fault types, magnitudes and distances with V_{S30} = 1100 m/s.

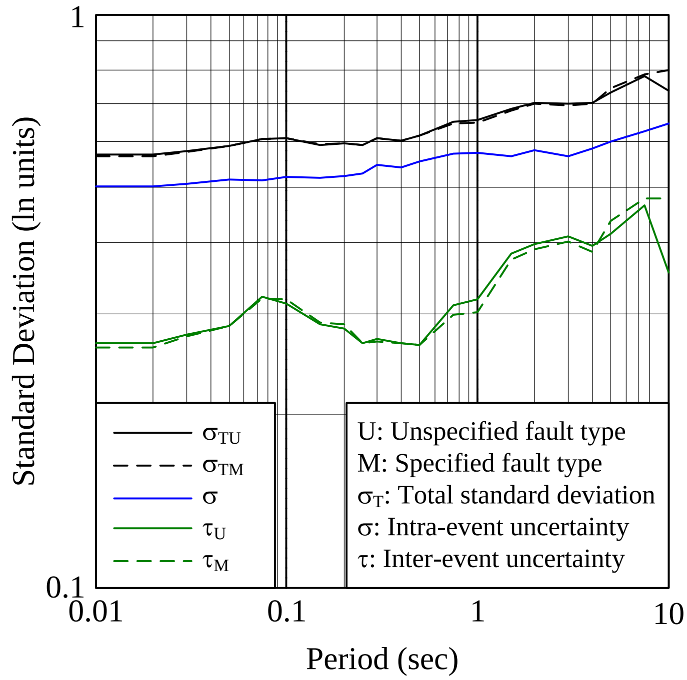


Figure 2-68. Standard deviations as a function of period.

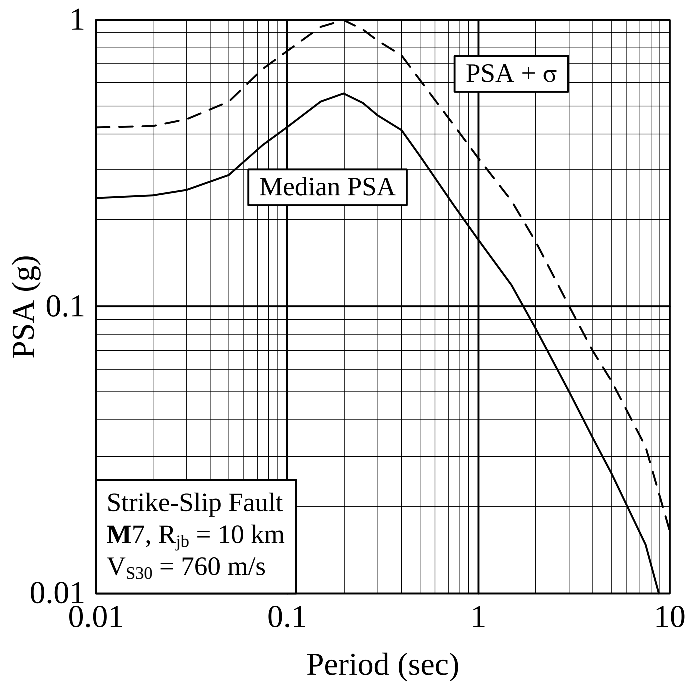


Figure 2-69. Example of application of median PSA plus one standard deviation.

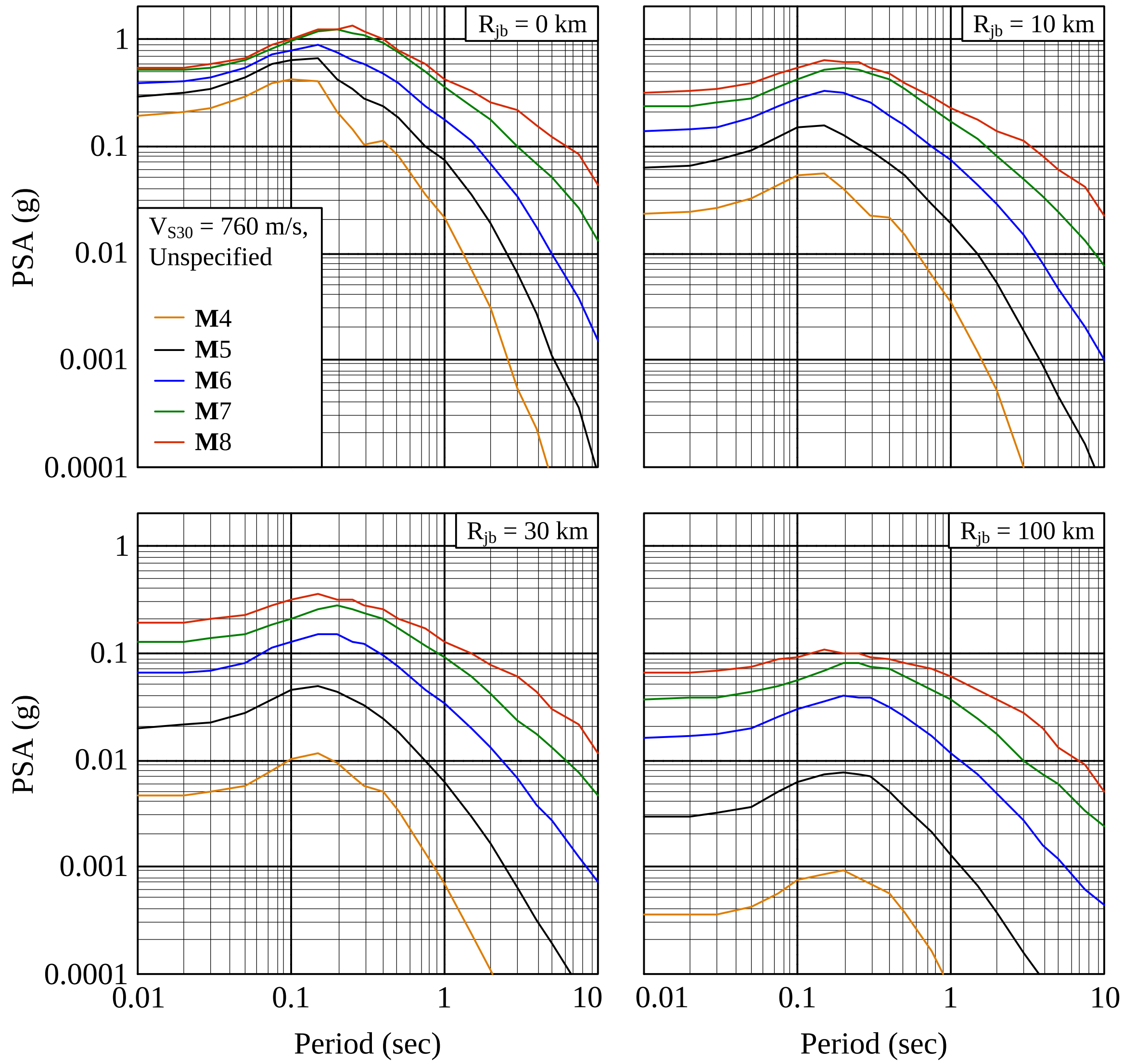


Figure 2-70. Calibration plots for SMM adjustment. PSA as a function of period for various magnitudes and distances with unspecified fault type, V_{S30} = 760 m/s. (Note that for M ≥ 5.75 there is no change.)

2.9.5 Database

Two databases were used. First the strong motion database compiled by the "PEER NGA" (Pacific Earthquake Engineering Research Center's Next Generation Attenuation) for the original GMPEs. Second, the small-to-moderate magnitude (SMM) ShakeMap database for the moderate California earthquake adjustment.

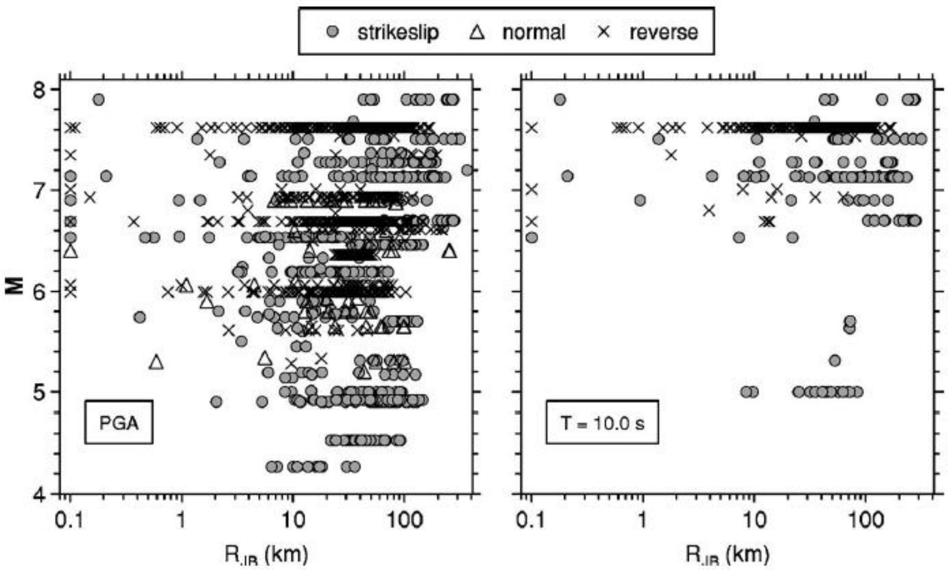


Figure 2-71. Distribution of data in NGA database used to derive regression equations for PGA and for PSA at a period of 10.0 s, differentiated by fault type (points with R_{jb} less than 0.1 km plotted at 0.1 km). The overall distributions for periods less than about 4 s are similar to those for PGA, although there are fewer recordings (the number of available recordings decreases noticeably for periods longer than 2 s).

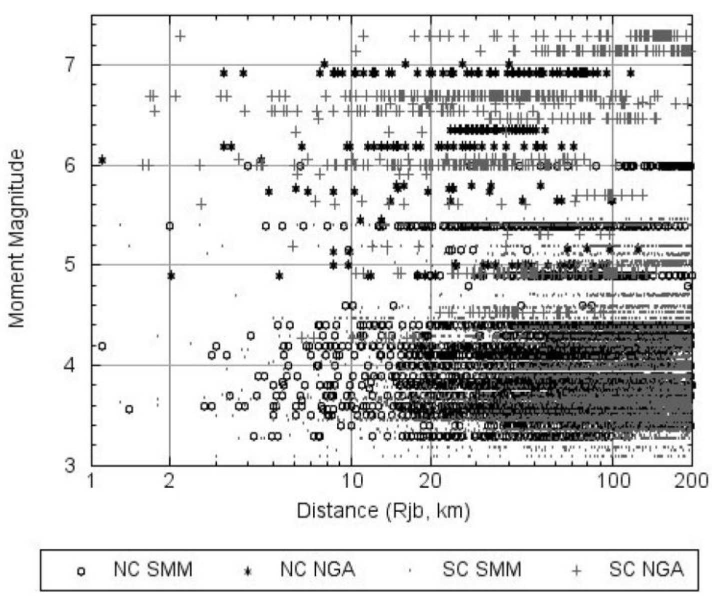


Figure 2-72. Magnitude-distance distribution of data from Northern California (NC) and Southern California (SC) in the NGA and SMM (Chiou et al., 2010) ShakeMap databases.

2.9.6 MATLAB Code

```
% by Nirmal Jayaram, 4/27/07
% Stanford University
% nirmalj@stanford.edu
%
% edits:
% by Kathryn A. Gunberg 1/27/08
% Virginia Tech
% kgunberg@vt.edu
%
% Boore and Atkinson attenuation equation, 2008
% edited from: Boore and Atkinson, 2007
%
% The edits by Gunberg take into account the new evaluation procedure for
% the pga4nl term as updated in Boore and Atkinson, 2008. Also added is the
% small-to-moderate magnitude adjustment from Atkinson and Boore, 2011.
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T             = Period (sec), 0 for PGA, -1 for PGV
% M             = Moment magnitude
% F             = Faut type: 1 for unspecified, 2 for strike-slip, 3 for
%                 normal, 4 for reverse
% Rjb           = Joyner-Boore distance (km)
% Vs30          = shear wave velocity averaged over top 30 m (m/s)
% SMM           = 1 to include SMM, 0 otherwise
% ---------------------------------------------------------------------------
% Output Variables
% Sa:           Median spectral acceleration or PGV prediction (g or cm/s)
% sigma:        logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = BA_2008_nga(T, M, F, Rjb, Vs30, SMM)
% Coefficients
a1      = 0.03;
pga_low = 0.06;
a2      = 0.09;
v1      = 180;
v2      = 300;
vref    = 760;
mref    = 4.5;
rref    = 1;
period  =  [-1          0           0.01        0.02        0.03        0.05        ...
            0.075       0.1         0.15        0.2         0.25        0.3         ...
            0.4         0.5         0.75        1           1.5         2           ...
            3           4           5           7.5         10];
e01     =  [5.00121     -0.53804    -0.52883    -0.52192    -0.45285    -0.28476    ...
            0.00767     0.20109     0.46128     0.5718      0.51884     0.43825     ...
            0.3922      0.18957     -0.21338    -0.46896    -0.86271    -1.22652    ...
            -1.82979    -2.24656    -1.28408    -1.43145    -2.15446];
e02     =  [5.04727     -0.5035     -0.49429    -0.48508    -0.41831    -0.25022    ...
            0.04912     0.23102     0.48661     0.59253     0.53496     0.44516     ...
            0.40602     0.19878     -0.19496    -0.43443    -0.79593    -1.15514    ...
            -1.7469     -2.15906    -1.2127     -1.31632    -2.16137];
e03     =  [4.63188     -0.75472    -0.74551    -0.73906    -0.66722     -0.48462   ...
            -0.20578    0.03058     0.30185     0.4086      0.3388      0.25356     ...
            0.21398     0.00967     -0.49176    -0.78465    -1.20902    -1.57697    ...
            -2.22584    -2.58228    -1.50904    -1.81022    -2.53323];
e04     =  [5.0821      -0.5097     -0.49966    -0.48895    -0.42229    -0.26092    ...
            0.02706     0.22193     0.49328     0.61472     0.57747     0.5199      ...
            0.4608      0.26337     -0.10813    -0.3933     -0.88085    -1.27669    ...
            -1.91814    -2.38168    -1.41093    -1.59217    -2.14635];
e05     =  [0.18322     0.28805     0.28897     0.25144     0.17976     0.06369     ...
            0.0117      0.04697     0.1799      0.52729     0.6088      0.64472     ...
            0.7861      0.76837     0.75179     0.6788      0.70689     0.77989     ...
            0.77966     1.24961     0.14271     0.52407     0.40387];
e06     =  [-0.12736    -0.10164    -0.10019    -0.11006    -0.12858    -0.15752    ...
            -0.17051    -0.15948    -0.14539    -0.12964    -0.13843    -0.15694    ...
            -0.07843    -0.09054    -0.14053    -0.18257    -0.2595     -0.29657    ...
            -0.45384    -0.35874    -0.39006    -0.37578    -0.48492];
e07     =  [0           0           0           0           0           0           ...
            0           0           0           0.00102     0.08607     0.10601     ...
```

```
            0.02262     0           0.10302     0.05393     0.19082     0.29888     ...
            0.67466     0.79508     0           0           0];
mh      =  [8.5         6.75        6.75        6.75        6.75        6.75        ...
            6.75        6.75        6.75        6.75        6.75        6.75        ...
            6.75        6.75        6.75        6.75        6.75        6.75        ...
            6.75        6.75        8.5         8.5         8.5];
c01     =  [-0.8737     -0.6605     -0.6622     -0.666      -0.6901     -0.717      ...
            -0.7205     -0.7081     -0.6961     -0.583      -0.5726     -0.5543     ...
            -0.6443     -0.6914     -0.7408     -0.8183     -0.8303     -0.8285     ...
            -0.7844     -0.6854     -0.5096     -0.3724     -0.09824];
c02     =  [0.1006      0.1197      0.12        0.1228      0.1283      0.1317      ...
            0.1237      0.1117      0.09884     0.04273     0.02977     0.01955     ...
            0.04394     0.0608      0.07518     0.1027      0.09793     0.09432     ...
            0.07282     0.03758     -0.02391    -0.06568    -0.138];
c03     =  [-0.00334    -0.01151    -0.01151    -0.01151    -0.01151    -0.01151    ...
            -0.01151    -0.01151    -0.01113    -0.00952    -0.00837    -0.0075     ...
            -0.00626    -0.0054     -0.00409    -0.00334    -0.00255    -0.00217    ...
            -0.00191    -0.00191    -0.00191    -0.00191    -0.00191];
h       =  [2.54        1.35        1.35        1.35        1.35        1.35        ...
            1.55        1.68        1.86        1.98        2.07        2.14        ...
            2.24        2.32        2.46        2.54        2.66        2.73        ...
            2.83        2.89        2.93        3           3.04];
blin    =  [-0.6        -0.36       -0.36       -0.34       -0.33       -0.29       ...
            -0.23       -0.25       -0.28       -0.31       -0.39       -0.44       ...
            -0.5        -0.6        -0.69       -0.7        -0.72       -0.73       ...
            -0.74       -0.75       -0.75       -0.692      -0.65];
b1      =  [-0.5        -0.64       -0.64       -0.63       -0.62       -0.64       ...
            -0.64       -0.6        -0.53       -0.52       -0.52       -0.52       ...
            -0.51       -0.5        -0.47       -0.44       -0.4        -0.38       ...
            -0.34       -0.31       -0.291      -0.247      -0.215];
b2      =  [-0.06       -0.14       -0.14       -0.12       -0.11       -0.11       ...
            -0.11       -0.13       -0.18       -0.19       -0.16       -0.14       ...
            -0.1        -0.06       0           0           0           0           ...
            0           0           0           0           0];
sig     =  [0.5         0.502       0.502       0.502       0.507       0.516       ...
            0.513       0.52        0.518       0.523       0.527       0.546       ...
            0.541       0.555       0.571       0.573       0.566       0.58        ...
            0.566       0.583       0.601       0.626       0.645];
tauu    =  [0.286       0.265       0.267       0.267       0.276       0.286       ...
            0.322       0.313       0.288       0.283       0.267       0.272       ...
            0.267       0.265       0.311       0.318       0.382       0.398       ...
            0.41        0.394       0.414       0.465       0.355];
sigTu   =  [0.576       0.566       0.569       0.569       0.578       0.589       ...
            0.606       0.608       0.592       0.596       0.592       0.608       ...
            0.603       0.615       0.649       0.654       0.684       0.702       ...
            0.7         0.702       0.73        0.781       0.735];
taum    =  [0.256       0.26        0.262       0.262       0.274       0.286       ...
            0.32        0.318       0.29        0.288       0.267       0.269       ...
            0.267       0.265       0.299       0.302       0.373       0.389       ...
            0.401       0.385       0.437       0.477       0.477];
sigTm   =  [0.56        0.564       0.566       0.566       0.576       0.589       ...
            0.606       0.608       0.594       0.596       0.592       0.608       ...
            0.603       0.615       0.645       0.647       0.679       0.7         ...
            0.695       0.698       0.744       0.787       0.801];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = BA_2008_nga(T_low, M, F, Rjb, Vs30, SMM);
    [sa_hi, sigma_hi]   = BA_2008_nga(T_hi,  M, F, Rjb, Vs30, SMM);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i       = find(abs((period - T)) < 0.0001); % Identify the period index
    inl     = find(abs((period - 0)) < 0.0001); % Identify location of pga
    % Magnitude Scaling
    U = (F == 1);
    S = (F == 2);
    N = (F == 3);
    R = (F == 4);
    if M <= mh (i)
```

```
        Fm = e01(i)*U + e02(i)*S + e03(i)*N + e04(i)*R + e05(i)*(M-mh(i)) + e06(i)*(M-mh(i))^2;
    else
        Fm = e01(i)*U + e02(i)*S + e03(i)*N + e04(i)*R + e07(i)*(M - mh(i));
    end
    % Distance Scaling
    r = sqrt (Rjb^2 + h(i)^2);
    Fd = (c01(i) + c02(i) * (M - mref)) * log (r / rref) + c03(i) * (r - rref);
    % Site Amplification
    Flin = blin(i) * log (Vs30 / vref);
    if M <= mh(inl)
        Fmnl = e01(inl)*U + e02(inl)*S + e03(inl)*N + e04(inl)*R + e05(inl)*(M - mh(inl)) + ...
            e06(inl)*(M - mh(inl))^2;
    else
        Fmnl = e01(inl)*U + e02(inl)*S + e03(inl)*N + e04(inl)*R + e07(inl)*(M - mh(inl));
    end
    rnl = sqrt (Rjb^2 + h(inl)^2);
    Fdnl = (c01(inl) + c02(inl)*(M - mref))*log(rnl/rref) + c03(inl)*(rnl - rref);
    pga4nl = exp(Fmnl + Fdnl);
    if Vs30 <= v1
        bnl = b1(i);
    elseif (Vs30 <= v2)
        bnl = b2(i) + (b1(i) - b2(i))*log(Vs30/v2)/log(v1/v2);
    elseif (Vs30 < vref)
        bnl = b2(i) * log (Vs30 / vref) / log (v2 / vref);
    else
        bnl = 0;
    end
    deltax = log (a2 / a1);
    deltay = bnl * log (a2 / pga_low);
    c = (3 *deltay - bnl * deltax) / (deltax^2);
    d = - (2 * deltay - bnl * deltax) / (deltax^3);
    if pga4nl <= a1
        Fnl = bnl*log(pga_low/0.1);
    elseif (pga4nl <= a2)
        Fnl = bnl*log(pga_low/0.1) + c*(log(pga4nl/a1))^2 + d*(log(pga4nl/a1))^3;
    else
        Fnl = bnl * log (pga4nl / 0.1);
    end
    Fs = Flin + Fnl;
    lnSa = Fm + Fd + Fs;
    % SMM adjustment
    if SMM == 0
        Sa = exp(lnSa);
    else
        log10Fba = max(0,3.888-0.674*M)-max(0,2.933-0.510*M)*log10(Rjb+10);
        Sa = exp(lnSa)*10^log10Fba;
    end
    if F == 1
        sigma = sigTu(i);
    else
        sigma = sigTm(i);
    end
end
```

2.10 Campbell and Bozorgnia – 2008

2.10.1 References

Campbell, K. W., and Y. Bozorgnia (2008). NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s, *Earthquake Spectra* **24**, 139–171.

Campbell, K. W. (2008). EQECAT Inc., Beaverton, OR. Written communication.

2.10.2 Abstract

Using a subset of the PEER NGA database (1561 recordings from 64 earthquakes), an empirical ground-motion model for the average horizontal component was developed. The model predicts peak ground displacement (PGD, in cm), peak ground velocity (PGV, in cm/s), peak ground acceleration (PGA, in g) and 5%-damped spectral values (in g) for periods ranging from 0.01 to 10 s. The model is applicable for earthquakes of M4.0 – M7.5 for normal faulting, M4.0 – M8.0 for reverse faulting, M4.0 – M8.5 for strike-slip faulting, distances from 0 – 200 km, average shear wave velocity in the upper 30 meters from 150 – 1500 m/s, depth to 2.5 km/s shear wave velocity horizon from 0 to 10 km, depth to top of rupture plane from 0 to 15 km and dip angle from 15° to 90°.

2.10.3 Attenuation Relationship

The predicted ground motion parameters are a function of:

- T – Period (sec), use 0 for PGA, -1 for PGV, -10 for PGD
- **M** – Moment magnitude
- δ – Average dip (degree)
- λ – Rake angle (degree)
- Z_{TOR} – Depth to the top of the rupture plane (km)
- R_{rup} – Closest distance to rupture plane (km)
- R_{jb} – Joyner-Boore distance (km)
- $Z_{2.5}$ – Depth to the 2.5 km/s shear-wave velocity horizon (km)
- V_{S30} – Shear wave velocity (m/s) averaged over top 30 m
- arb – Error: 0 for error from geometric mean of horizontal components, 1 for arbitrary

$$\ln(Sa) = f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed}$$

where:

$$f_{mag} = \begin{cases} c_0 + c_1 M & for\ M \leq 5.5 \\ c_0 + c_1 M + c_2(M - 5.5) & for\ 5.5 < M \leq 6.5 \\ c_0 + c_1 M + c_2(M - 5.5) + c_3(M - 6.5) & for\ M > 6.5 \end{cases}$$

$$f_{dis} = (c_4 + c_5 M) \ln \sqrt{{R_{rup}}^2 + {c_6}^2}$$

$$f_{flt} = c_7 F_{RV} f_{flt,Z} + c_8 F_{NM}$$

where:

$$f_{flt,Z} = \begin{cases} Z_{TOR} & for\ Z_{TOR} < 1 \\ 1 & for\ Z_{TOR} \geq 1 \end{cases}$$

$$F_{RV} = \begin{cases} 1 & for\ 30° < \lambda < 150° \\ 0 & otherwise \end{cases}$$

$$F_{NM} = \begin{cases} 1 & for\ -150° < \lambda < -30° \\ 0 & otherwise \end{cases}$$

$$f_{hng} = c_9 f_{hng,R} f_{hng,M} f_{hng,Z} f_{hng,\delta}$$

where:

$$f_{hng,R} = \begin{cases} 1 & for\ R_{jb} = 0 \\ \dfrac{\max\left(R_{rup}, \sqrt{{R_{jb}}^2 + 1}\right) - R_{JB}}{\max\left(R_{rup}, \sqrt{{R_{jb}}^2 + 1}\right)} & for\ R_{jb} > 0, Z_{TOR} < 1 \\ \dfrac{R_{rup} - R_{jb}}{R_{rup}} & for\ R_{jb} > 0, Z_{TOR} \geq 1 \end{cases}$$

$$f_{hng,M} = \begin{cases} 0 & M \leq 6.0 \\ 2(M - 6.0) & 6.0 < M < 6.5 \\ 1 & M \geq 6.5 \end{cases}$$

$$f_{hng,Z} = \begin{cases} 0 & Z_{TOR} \geq 20 \\ (20 - Z_{TOR})/20 & 0 \leq Z_{TOR} < 20 \end{cases}$$

$$f_{hng,\delta} = \begin{cases} 1 & \delta \leq 70 \\ (90 - \delta)/20 & \delta > 70 \end{cases}$$

$$f_{site} = \begin{cases} c_{10}\ln\left(\frac{V_{S30}}{k_1}\right) + k_2\left\{\ln\left[A_{1100} + c\left(\frac{V_{S30}}{k_1}\right)^n\right] - \ln[A_{1100} + c]\right\} & for\ V_{S30} < k_1 \\ (c_{10} + k_2 n)\ln\left(\frac{V_{S30}}{k_1}\right) & for\ k_1 \leq V_{S30} < 1100 \\ (c_{10} + k_2 n)\ln\left(\frac{1100}{k_1}\right) & for\ V_{S30} \geq 1100 \end{cases}$$

where: A_{1100} is the median predicted PGA on a reference rock outcrop (V_{S30} = 1100 m/s)

$$f_{sed} = \begin{cases} c_{11}(Z_{2.5} - 1) & for\ Z_{2.5} < 1 \\ 0 & for\ 1 \leq Z_{2.5} \leq 3 \\ c_{12}k_3 e^{-0.75}\left[1 - e^{-0.25(Z_{2.5}-3)}\right] & for\ Z_{2.5} > 3 \end{cases}$$

Standard Deviation:

$$\sigma_T = \sqrt{\sigma^2 + \tau^2}$$

if uncertainty of arbitrary horizontal component desired:

$$\sigma_{Arb} = \sqrt{{\sigma_T}^2 + {\sigma_C}^2}$$

where:

$$\tau = \tau_{\ln Y}$$

$$\sigma = \sqrt{{\sigma_{\ln Y_B}}^2 + {\sigma_{\ln AF}}^2 + \alpha^2 {\sigma_{\ln A_B}}^2 + 2\alpha\rho\sigma_{\ln Y_B}\sigma_{\ln A_B}}$$

where:

$${\sigma_{\ln Y_B}}^2 = {\sigma_{\ln Y}}^2 - {\sigma_{\ln AF}}^2$$

$${\sigma_{\ln A_B}}^2 = {\sigma_{\ln PGA}}^2 - {\sigma_{\ln AF}}^2$$

$$\alpha = \begin{cases} k_2 A_{1100}\left\{\left[A_{1100} + c\left(\frac{V_{S30}}{k_1}\right)^n\right]^{-1} - (A_{1100} + c)^{-1}\right\} & for\ V_{S30} < k_1 \\ 0 & for\ V_{S30} \geq k_1 \end{cases}$$

$$\sigma_{\ln AF} = 0.30$$

Coefficients

Table 2-29. Coefficients for the geometric mean and arbitrary horizontal components of the median ground motion model

T (sec)	c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7
0.010	-1.715	0.500	-0.530	-0.262	-2.118	0.170	5.60	0.280
0.020	-1.680	0.500	-0.530	-0.262	-2.123	0.170	5.60	0.280
0.030	-1.552	0.500	-0.530	-0.262	-2.145	0.170	5.60	0.280
0.050	-1.209	0.500	-0.530	-0.267	-2.199	0.170	5.74	0.280
0.075	-0.657	0.500	-0.530	-0.302	-2.277	0.170	7.09	0.280
0.10	-0.314	0.500	-0.530	-0.324	-2.318	0.170	8.05	0.280
0.15	-0.133	0.500	-0.530	-0.339	-2.309	0.170	8.79	0.280
0.20	-0.486	0.500	-0.446	-0.398	-2.220	0.170	7.60	0.280
0.25	-0.890	0.500	-0.362	-0.458	-2.146	0.170	6.58	0.280
0.30	-1.171	0.500	-0.294	-0.511	-2.095	0.170	6.04	0.280
0.40	-1.466	0.500	-0.186	-0.592	-2.066	0.170	5.30	0.280
0.50	-2.569	0.656	-0.304	-0.536	-2.041	0.170	4.73	0.280
0.75	-4.844	0.972	-0.578	-0.406	-2.000	0.170	4.00	0.280
1.0	-6.406	1.196	-0.772	-0.314	-2.000	0.170	4.00	0.255
1.5	-8.692	1.513	-1.046	-0.185	-2.000	0.170	4.00	0.161
2.0	-9.701	1.600	-0.978	-0.236	-2.000	0.170	4.00	0.094
3.0	-10.556	1.600	-0.638	-0.491	-2.000	0.170	4.00	0.000
4.0	-11.212	1.600	-0.316	-0.770	-2.000	0.170	4.00	0.000
5.0	-11.684	1.600	-0.070	-0.986	-2.000	0.170	4.00	0.000
7.5	-12.505	1.600	-0.070	-0.656	-2.000	0.170	4.00	0.000
10.0	-13.087	1.600	-0.070	-0.422	-2.000	0.170	4.00	0.000
PGA	-1.715	0.500	-0.530	-0.262	-2.118	0.170	5.60	0.280
PGV	0.954	0.696	-0.309	-0.019	-2.016	0.170	4.00	0.245
PGD	-5.270	1.600	-0.070	0.000	-2.000	0.170	4.00	0.000

Note: c = 1.88 and n = 1.18 for all periods (t); PGA and PSA have units of g; PGV and PGD have units of cm/s and cm respectively.

Table 2-30. continued from Table 2-29.

T (sec)	c_8	c_9	c_{10}	c_{11}	c_{12}	k_1	k_2	k_3
0.010	-0.120	0.490	1.058	0.040	0.610	865	-1.186	1.839
0.020	-0.120	0.490	1.102	0.040	0.610	865	-1.219	1.840
0.030	-0.120	0.490	1.174	0.040	0.610	908	-1.273	1.841
0.050	-0.120	0.490	1.272	0.040	0.610	1054	-1.346	1.843
0.075	-0.120	0.490	1.438	0.040	0.610	1086	-1.471	1.845
0.10	-0.099	0.490	1.604	0.040	0.610	1032	-1.624	1.847
0.15	-0.048	0.490	1.928	0.040	0.610	878	-1.931	1.852
0.20	-0.012	0.490	2.194	0.040	0.610	748	-2.188	1.856
0.25	0.000	0.490	2.351	0.040	0.700	654	-2.381	1.861
0.30	0.000	0.490	2.460	0.040	0.750	587	-2.518	1.865
0.40	0.000	0.490	2.587	0.040	0.850	503	-2.657	1.874
0.50	0.000	0.490	2.544	0.040	0.883	457	-2.669	1.883
0.75	0.000	0.490	2.133	0.077	1.000	410	-2.401	1.906
1.0	0.000	0.490	1.571	0.150	1.000	400	-1.955	1.929
1.5	0.000	0.490	0.406	0.253	1.000	400	-1.025	1.974
2.0	0.000	0.371	-0.456	0.300	1.000	400	-0.299	2.019
3.0	0.000	0.154	-0.820	0.300	1.000	400	0.000	2.110
4.0	0.000	0.000	-0.820	0.300	1.000	400	0.000	2.200
5.0	0.000	0.000	-0.820	0.300	1.000	400	0.000	2.291
7.5	0.000	0.000	-0.820	0.300	1.000	400	0.000	2.517
10.0	0.000	0.000	-0.820	0.300	1.000	400	0.000	2.744
PGA	-0.120	0.490	1.058	0.040	0.610	865	-1.186	1.839
PGV	0.000	0.358	1.694	0.092	1.000	400	-1.955	1.929
PGD	0.000	0.000	-0.820	0.300	1.000	400	0.000	2.744

Table 2-31. Standard deviations and correlation coefficients for the aleatory uncertainty model (σ_C, σ_T and σ_{Arb} directly applicable for $V_{S30} \geq k_1$)

T (sec)	$\sigma_{\ln Y}$	$\tau_{\ln Y}$	σ_C	σ_T	σ_{Arb}	ρ
0.010	0.478	0.219	0.166	0.526	0.551	1.000
0.020	0.480	0.219	0.166	0.528	0.553	0.999
0.030	0.489	0.235	0.165	0.543	0.567	0.989
0.050	0.510	0.258	0.162	0.572	0.594	0.963
0.075	0.520	0.292	0.158	0.596	0.617	0.922
0.10	0.531	0.286	0.170	0.603	0.627	0.898
0.15	0.532	0.280	0.180	0.601	0.628	0.890
0.20	0.534	0.249	0.186	0.589	0.618	0.871
0.25	0.534	0.240	0.191	0.585	0.616	0.852
0.30	0.544	0.215	0.198	0.585	0.618	0.831
0.40	0.541	0.217	0.206	0.583	0.618	0.785
0.50	0.550	0.214	0.208	0.590	0.626	0.735
0.75	0.568	0.227	0.221	0.612	0.650	0.628
1.0	0.568	0.255	0.225	0.623	0.662	0.534
1.5	0.564	0.296	0.222	0.637	0.675	0.411
2.0	0.571	0.296	0.226	0.643	0.682	0.331
3.0	0.558	0.326	0.229	0.646	0.686	0.289
4.0	0.576	0.297	0.237	0.648	0.690	0.261
5.0	0.601	0.359	0.237	0.700	0.739	0.200
7.5	0.628	0.428	0.271	0.760	0.807	0.174
10.0	0.667	0.485	0.290	0.825	0.874	0.174
PGA	0.478	0.219	0.166	0.526	0.551	1.000
PGV	0.484	0.203	0.190	0.525	0.558	0.691
PGD	0.667	0.485	0.290	0.825	0.874	0.174

2.10.4 Calibration Plots

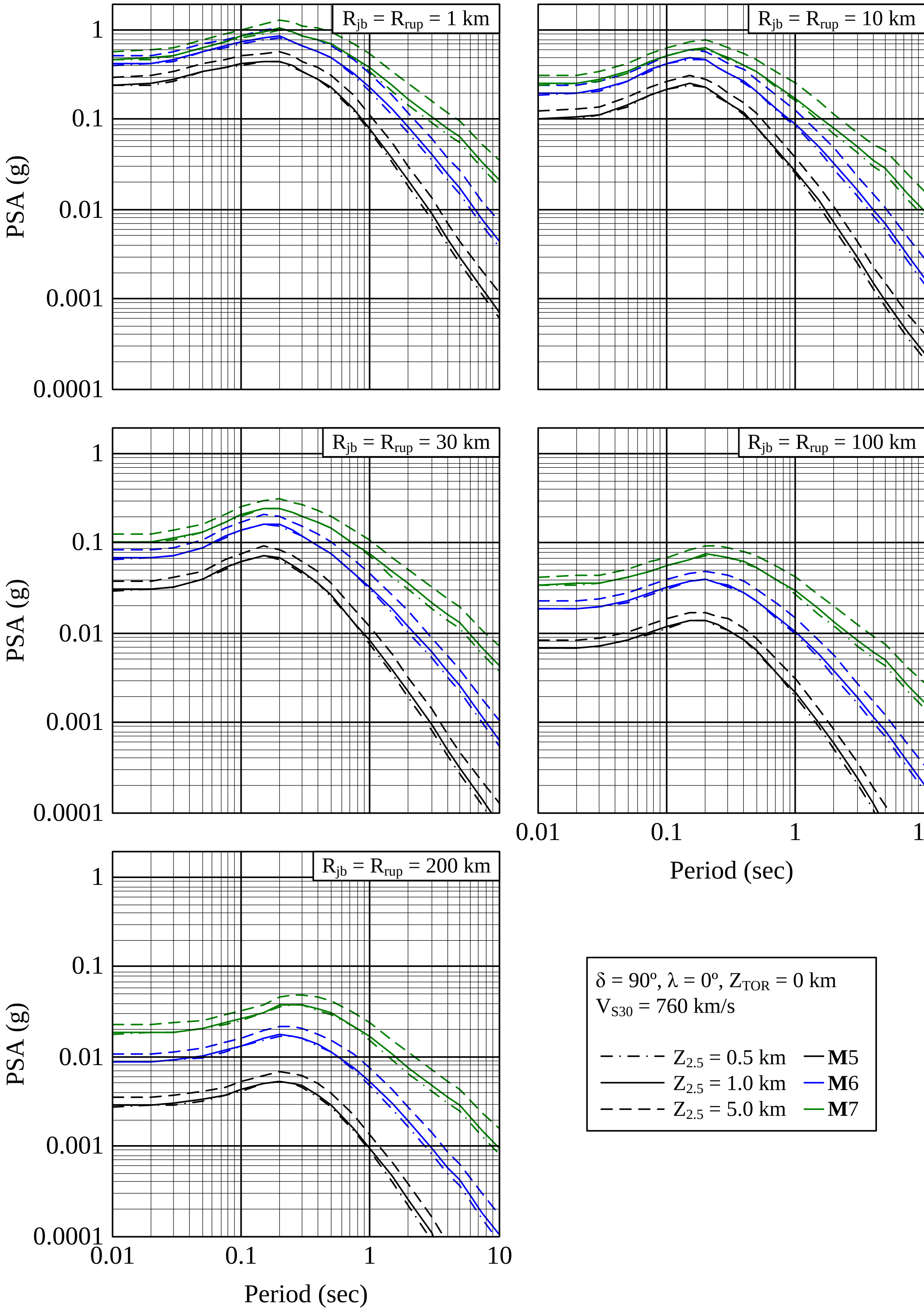


Figure 2-73. PSA as a function of period for different distances, magnitudes and hard rock depths. The relations shown are for a vertical strike-slip fault and V_{S30} = 760 km/s. Note that this takes into account variations in f_{mag}, f_{dis} and f_{sed}; f_{hng} and f_{flt} are equal to zero.

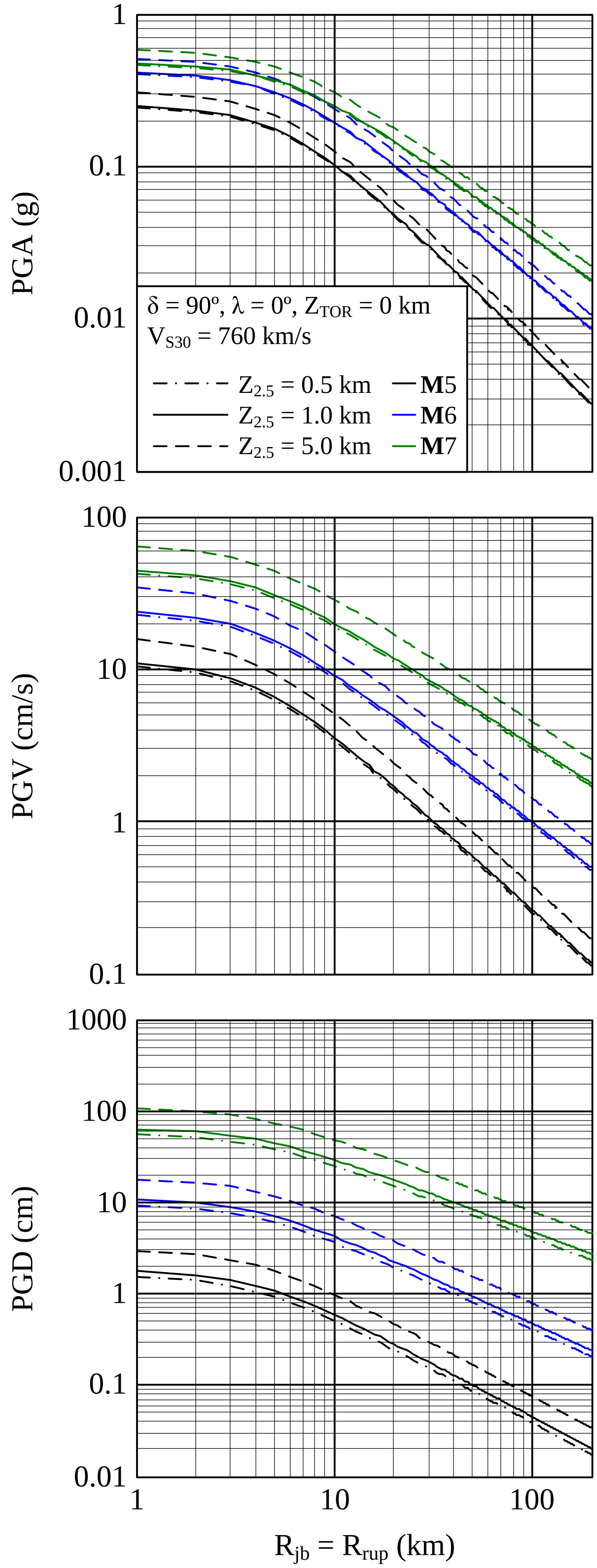


Figure 2-74. PGA, PGV and PGD as a function of distance for the same conditions as in Figure 2-73.

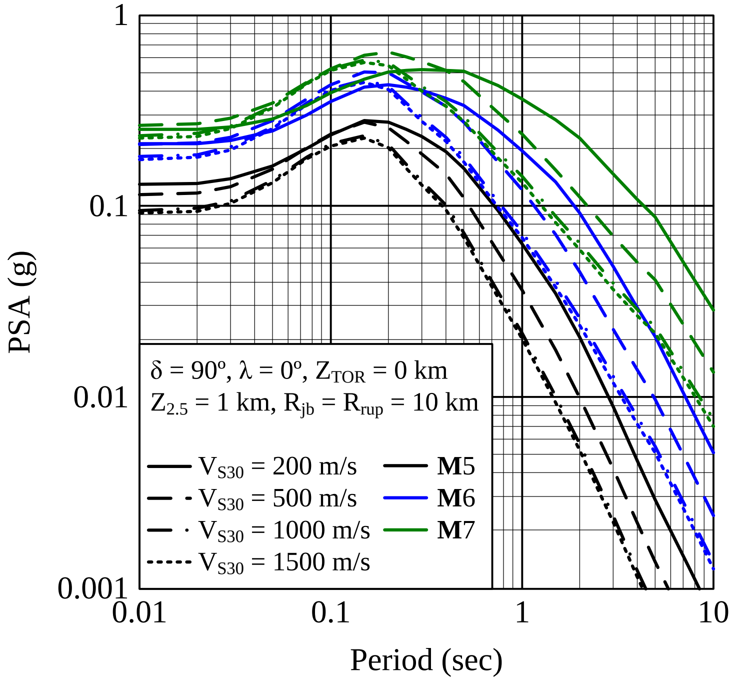


Figure 2-75. PSA as a function of period for given parameters. Note that this accounts for the variation in f_{site}; f_{hng}, f_{flt} and f_{sed} are equal to zero.

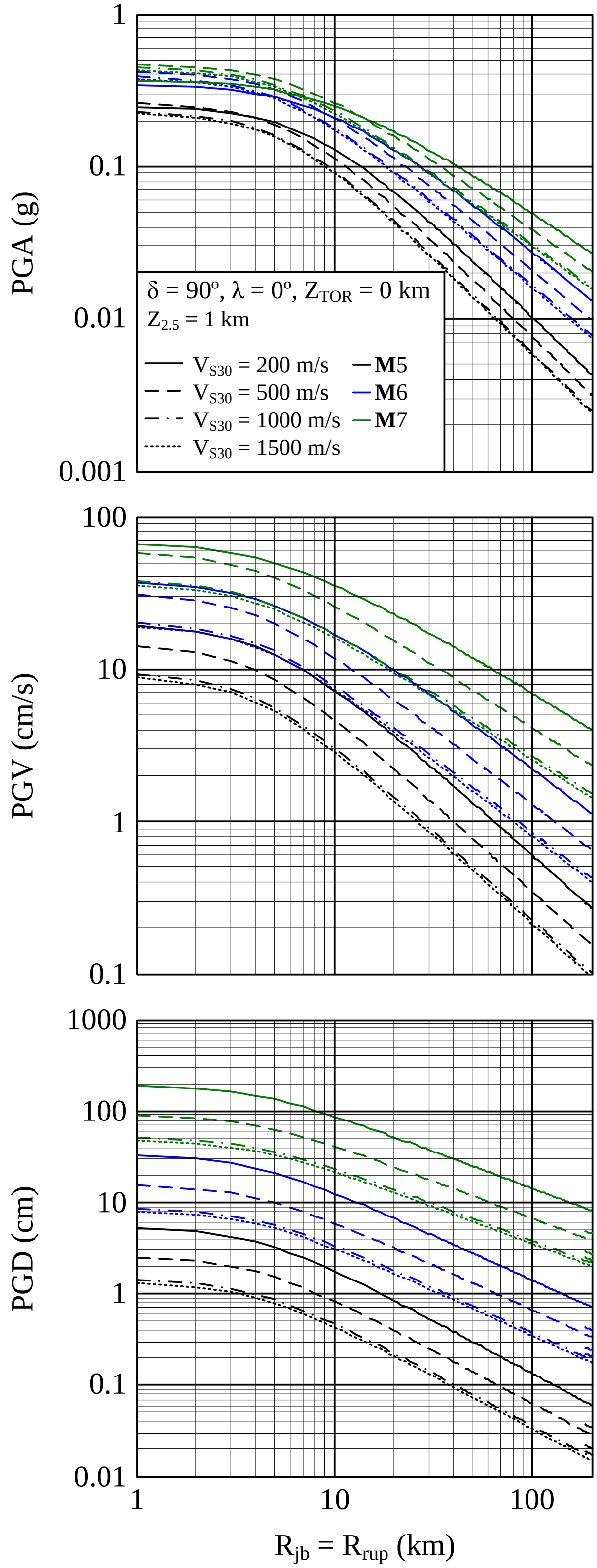
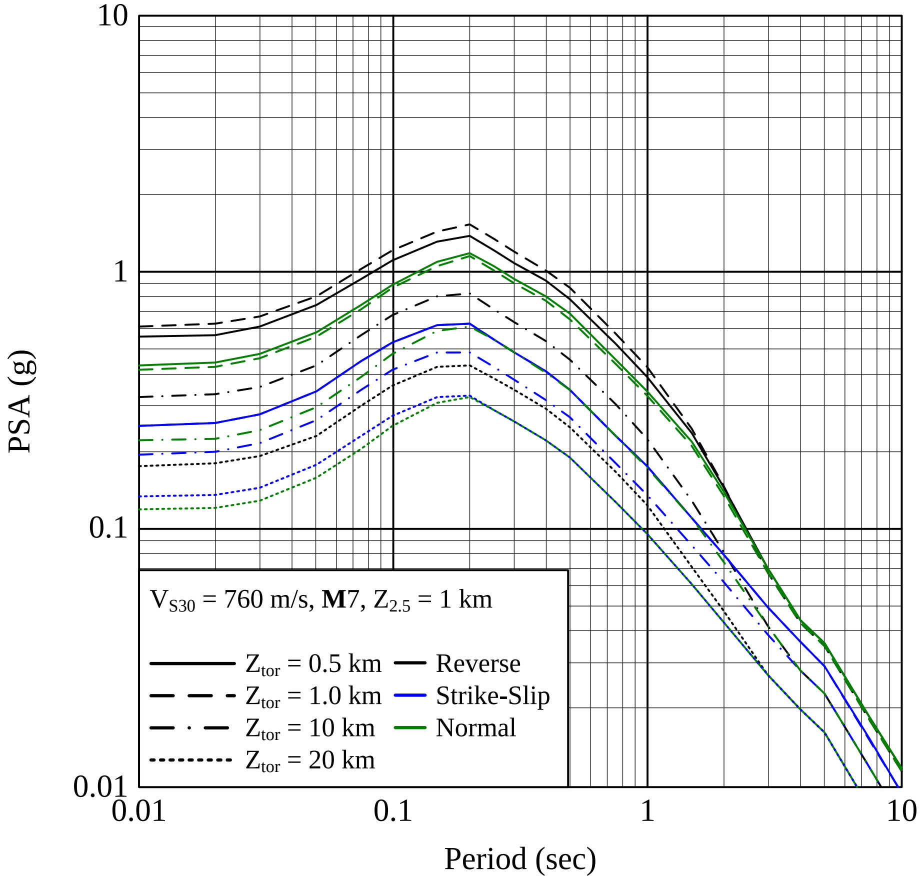


Figure 2-76. PGA, PGV and PGD as a function of distance for the same conditions as in Figure 2-75.



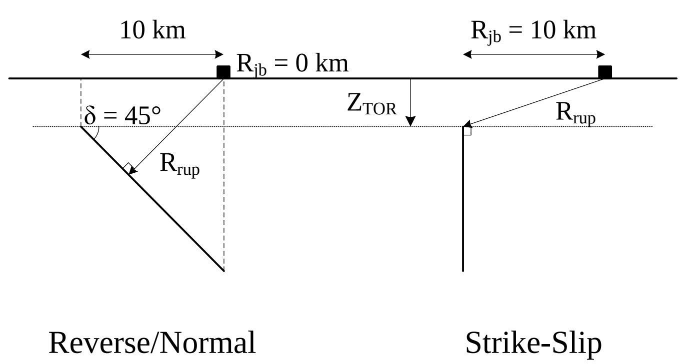


Figure 2-77. PSA as a function of period for various fault geometries. Note that this accounts for the variation in $f_{hng,Z}$ and f_{flt}; f_{sed} equals zero.

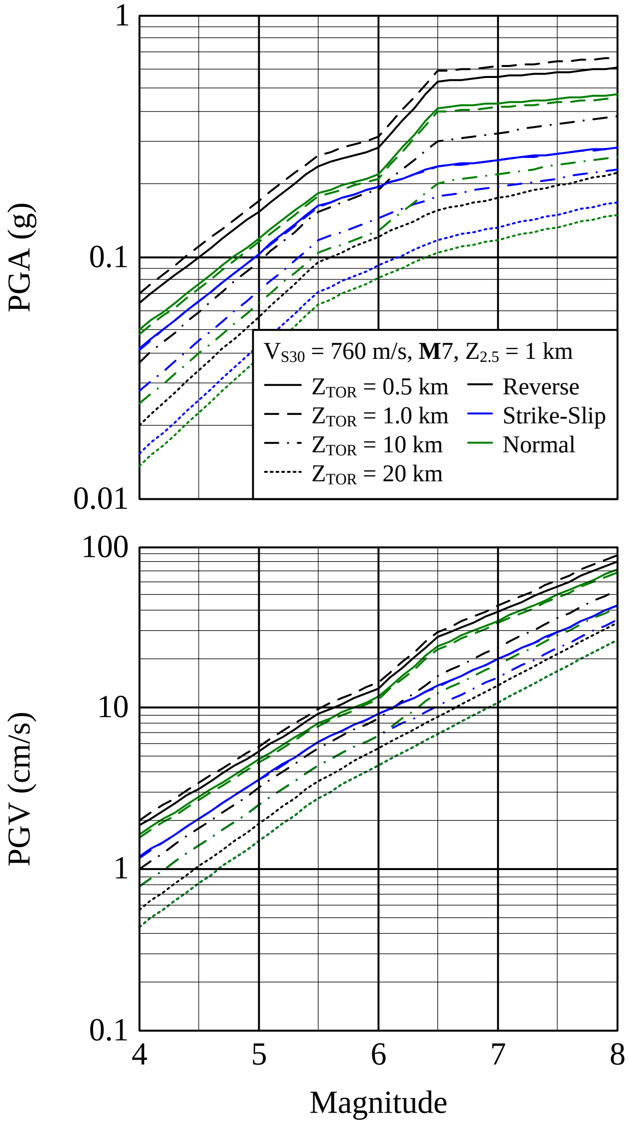


Figure 2-78. PGA and PGV as a function of magnitude. (PGD is not included because it is not dependant on f_{flt} or f_{hng}). Note that this takes into the same considerations and geometries as Figure 2-77 but also includes the effect of $f_{hng,M}$.

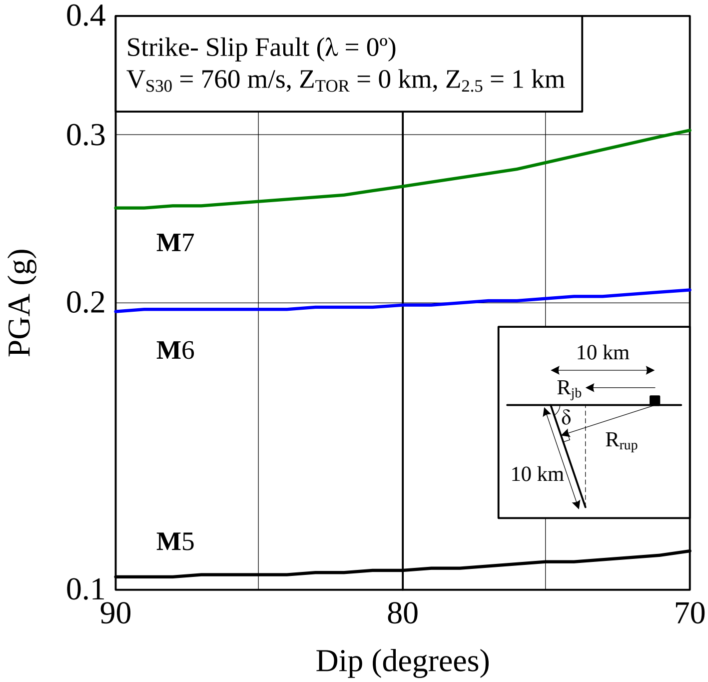


Figure 2-79. PGA as a function of dip angle. Note that this shows the effect of $f_{hng,\delta}$ (at lower dips, there is no change in $f_{hng,\delta}$); f_{flt} and f_{sed} are equal to zero.

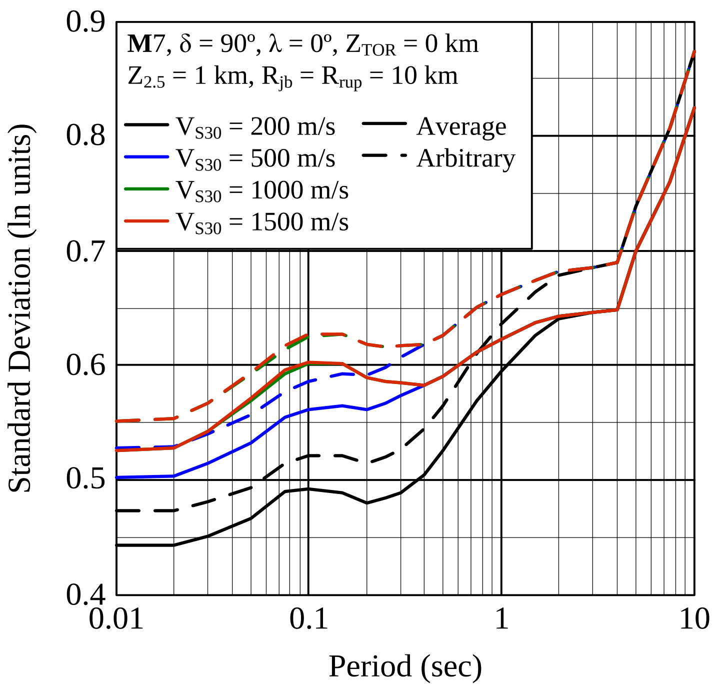


Figure 2-80. Arbitrary and average components as a function of period shown for various shear wave velocities and the conditions given.

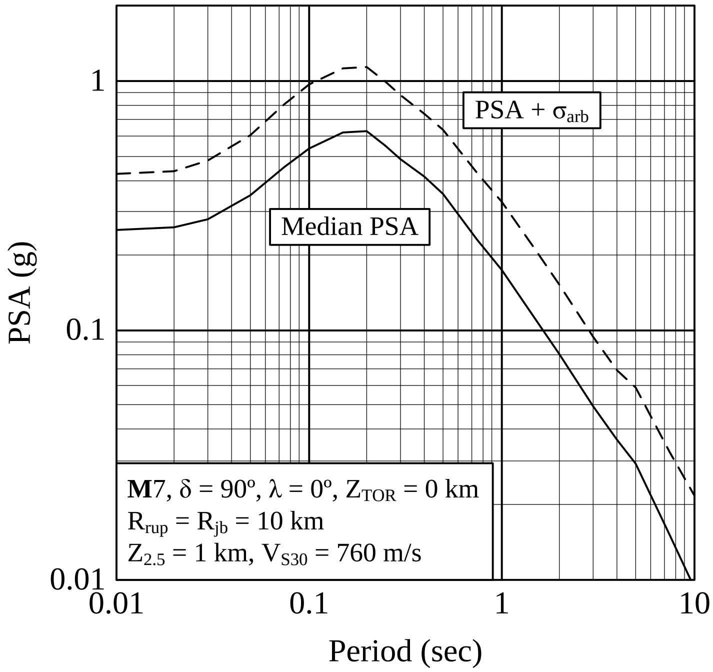


Figure 2-81. Example of application of median PSA plus one standard deviation.

2.10.5 Database

Strong motion database compiled by the "PEER NGA" (Pacific Earthquake Engineering Research Center's Next Generation Attenuation)

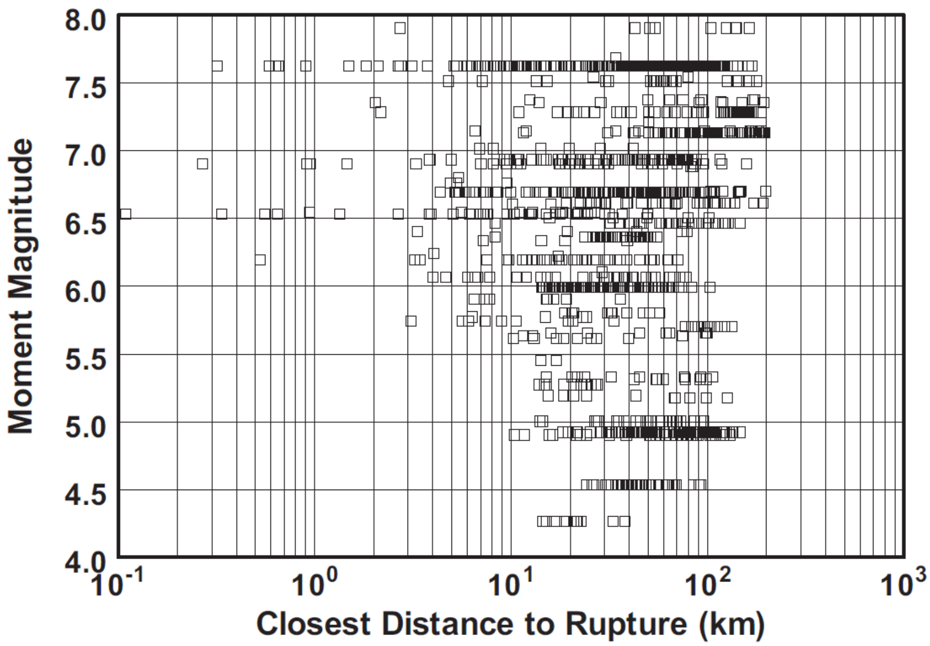


Figure 2-82. Distribution of recordings with respect to moment magnitude (**M**) and rupture distance (R_{RUP}) for the database used in this study.

2.10.6 MATLAB Code

```
% by Nirmal Jayaram, 6/21/07
% Stanford University
% nirmalj@stanford.edu
%
% edits:
% by Katyrn A. Gunberg, 11/10/08
% Virginia Tech
% kgunberg@vt.edu
%
% Campbell and Bozorgnia attenuation equation, 2008
% edited from: Campbell and Bozorgnia, 2007
%
% The edits by Gunberg take into account the new evaluation procedure for
% the standard deviation.
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T             = Period (sec), 0 for PGA, -1 for PGV, -10 for PGD
% M             = Moment magnitude
% delta         = Dip angle (degree)
% lambda        = Rake angle (degree)
% Ztor          = Depth to the top of the rupture plane (km)
% Rrup          = Closest distance to rupture plane (km)
% Rjb           = Joyner-Boore distance (km)
% Z25           = Depth to the 2.5 km/s shear-wave velocity horizon (km)
% Vs30          = Shear wave velocity averaged over top 30 m (m/s)
% arb           = Error type: 1 for arbitrary, 0 for average
%---------------------------------------------------------------------------
% Output Variables
% Sa            = Median spectral acceleration, PGV or PGD prediction
%                 (g, cm/s or cm)
% sigma         = logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = CB_2008_nga (T, M, delta, lambda, Ztor, Rrup, Rjb, Z25, Vs30, arb)
% Coefficients
period  =  [0.01    0.02    0.03    0.05    0.075   0.1     0.15    0.2     ...
    0.25    0.3     0.4     0.5     0.75    1       1.5     2       3       ...
    4       5       7.5     10      0       -1      -10];
c0      =  [-1.715  -1.68   -1.552  -1.209  -0.657  -0.314  -0.133  -0.486  ...
    -0.89   -1.171  -1.466  -2.569  -4.844  -6.406  -8.692  -9.701  -10.556 ...
    -11.212 -11.684 -12.505 -13.087 -1.715  0.954   -5.27];
c1      =  [0.5     0.5     0.5     0.5     0.5     0.5     0.5     0.5     ...
    0.5     0.5     0.5     0.656   0.972   1.196   1.513   1.6     1.6     ...
    1.6     1.6     1.6     1.6     0.5     0.696   1.6];
c2      =  [-0.53   -0.53   -0.53   -0.53   -0.53   -0.53   -0.53   -0.446  ...
    -0.362  -0.294  -0.186  -0.304  -0.578  -0.772  -1.046  -0.978  -0.638  ...
    -0.316  -0.07   -0.07   -0.07   -0.53   -0.309  -0.07];
c3      =  [-0.262  -0.262  -0.262  -0.267  -0.302  -0.324  -0.339  -0.398  ...
    -0.458  -0.511  -0.592  -0.536  -0.406  -0.314  -0.185  -0.236  -0.491  ...
    -0.77   -0.986  -0.656  -0.422  -0.262  -0.019  0];
c4      =  [-2.118  -2.123  -2.145  -2.199  -2.277  -2.318  -2.309  -2.22   ...
    -2.146  -2.095  -2.066  -2.041  -2      -2      -2      -2      -2      ...
    -2      -2      -2      -2      -2.118  -2.016  -2];
c5      =  [0.17    0.17    0.17    0.17    0.17    0.17    0.17    0.17    ...
    0.17    0.17    0.17    0.17    0.17    0.17    0.17    0.17    0.17    ...
    0.17    0.17    0.17    0.17    0.17    0.17    0.17];
c6      =  [5.6     5.6     5.6     5.74    7.09    8.05    8.79    7.6     ...
    6.58    6.04    5.3     4.73    4       4       4       4       4       ...
    4       4       4       5.6     4       4];
c7      =  [0.28    0.28    0.28    0.28    0.28    0.28    0.28    0.28    ...
    0.28    0.28    0.28    0.28    0.28    0.255   0.161   0.094   0       ...
    0       0       0       0       0.28    0.245   0];
c8      =  [-0.12   -0.12   -0.12   -0.12   -0.12   -0.099  -0.048  -0.012  ...
    0       0       0       0       0       0       0       0       0       ...
    0       0       0       0       -0.12   0       0];
c9      =  [0.49    0.49    0.49    0.49    0.49    0.49    0.49    0.49    ...
    0.49    0.49    0.49    0.49    0.49    0.49    0.49    0.371   0.154   ...
    0       0       0       0       0.49    0.358   0];
c10     =  [1.058   1.102   1.174   1.272   1.438   1.604   1.928   2.194   ...
    2.351   2.46    2.587   2.544   2.133   1.571   0.406   -0.456  -0.82   ...
```

```
    -0.82   -0.82   -0.82   -0.82   1.058   1.694   -0.82];
c11     =  [0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    ...
    0.04    0.04    0.04    0.04    0.077   0.15    0.253   0.3     0.3     ...
    0.3     0.3     0.3     0.3     0.04    0.092   0.3];
c12     =  [0.61    0.61    0.61    0.61    0.61    0.61    0.61    0.61    ...
    0.70    0.75    0.85    0.883   1       1       1       1       1       ...
    1       1       1       1       0.61    1       1];
k1      =  [865     865     908     1054    1086    1032    878     748     ...
    654     587     503     457     410     400     400     400     400     ...
    400     400     400     400     865     400     400];
k2      =  [-1.186  -1.219  -1.273  -1.346  -1.471  -1.624  -1.931  -2.188  ...
    -2.381  -2.518  -2.657  -2.669  -2.401  -1.955  -1.025  -0.299  0       ...
    0       0       0       0       -1.186  -1.955  0];
k3      =  [1.839   1.84    1.841   1.843   1.845   1.847   1.852   1.856   ...
    1.861   1.865   1.874   1.883   1.906   1.929   1.974   2.019   2.11    ...
    2.2     2.291   2.517   2.744   1.839   1.929   2.744];
slny    =  [0.478   0.48    0.489   0.51    0.52    0.531   0.532   0.534   ...
    0.534   0.544   0.541   0.55    0.568   0.568   0.564   0.571   0.558   ...
    0.576   0.601   0.628   0.667   0.478   0.484   0.667];
tlny    =  [0.219   0.219   0.235   0.258   0.292   0.286   0.28    0.249   ...
    0.24    0.215   0.217   0.214   0.227   0.255   0.296   0.296   0.326   ...
    0.297   0.359   0.428   0.485   0.219   0.203   0.485];
sig_c   =  [0.166   0.166   0.165   0.162   0.158   0.17    0.18    0.186   ...
    0.191   0.198   0.206   0.208   0.221   0.225   0.222   0.226   0.229   ...
    0.237   0.237   0.271   0.29    0.166   0.19    0.29];
sig_t   =  [0.526   0.528   0.543   0.572   0.596   0.603   0.601   0.589   ...
    0.585   0.585   0.583   0.590   0.612   0.623   0.637   0.643   0.646   ...
    0.648   0.700   0.760   0.825   0.526   0.525   0.825];
sig_arb =  [0.551   0.553   0.567   0.594   0.617   0.627   0.628   0.618   ...
    0.616   0.618   0.618   0.626   0.650   0.662   0.675   0.682   0.686   ...
    0.690   0.739   0.807   0.874   0.551   0.558   0.874];
rho     =  [1       0.999   0.989   0.963   0.922   0.898   0.89    0.871   ...
    0.852   0.831   0.785   0.735   0.628   0.534   0.411   0.331   0.289   ...
    0.261   0.2     0.174   0.174   1       0.691   0.174];
c = 1.88;
n = 1.18;
% interpolate between periods if neccesary
if (length(find(period == T)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low sigma_low] = CB_2008_nga (T_low, M, delta, lambda, Ztor, Rrup, Rjb, Z25, Vs30, arb);
    [sa_hi  sigma_hi]  = CB_2008_nga (T_hi,  M, delta, lambda, Ztor, Rrup, Rjb, Z25, Vs30, arb);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    y = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(period == T);
    % Magnitude dependence
    if M <= 5.5
        fmag = c0(i) + c1(i) * M;
    else if M<=6.5
            fmag = c0(i) + c1(i) * M + c2(i) * (M - 5.5);
        else
            fmag = c0(i) + c1(i) * M + c2(i) * (M - 5.5) + c3(i) * (M - 6.5);
        end
    end
    % Distance dependence
    fdis = (c4(i) + c5(i) * M) * log(sqrt(Rrup^2 + c6(i)^2));
    % Style of faulting
    if Ztor < 1
        ffltz = Ztor;
    else
        ffltz = 1;
    end
    Frv = (lambda > 30 & lambda < 150);
    Fnm = (lambda > -150 & lambda < -30);
    fflt = c7(i) * Frv * ffltz + c8(i) * Fnm;
    % Hanging-wall effects
    if Rjb == 0
        fhngr = 1;
    else
        if Ztor < 1
```

```
            fhngr = (max(Rrup,sqrt(Rjb^2+1))-Rjb)/max(Rrup,sqrt(Rjb^2+1));
        else
            fhngr = (Rrup - Rjb)/Rrup;
        end
    end
    if M <= 6
        fhngm = 0;
    else if M < 6.5
            fhngm = 2 * (M - 6);
        else
            fhngm = 1;
        end
    end
    fhngz = ((20 - Ztor)/20) * (Ztor >= 0 & Ztor < 20);
    fhngdelta = (delta <= 70) + ((90 - delta)/20) * (delta > 70);
    fhng = c9(i) * fhngr * fhngm * fhngz * fhngdelta;
    % Site conditions
    if Vs30 < k1(i)
        A1100 = CB_2008_nga (0, M, Rjb, Rrup, Ztor, Z25, 1100, lambda, delta, arb);
        fsite = c10(i)*log(Vs30/k1(i)) + k2(i)*(log(A1100 + c*(Vs30/k1(i))^n) - log(A1100 + c));
    else
        fsite = (c10(i) + k2(i) * n) * log(min(Vs30,1100)/k1(i));
    end
    % Sediment effects
    if Z25 < 1
        fsed = c11(i) * (Z25 - 1);
    elseif Z25 <= 3
        fsed = 0;
    else
        fsed = c12(i) * k3(i) * exp(-0.75) * (1 - exp(-0.25 * (Z25 - 3)));
    end
    % Median value
    Sa = exp(fmag + fdis + fflt + fhng + fsite + fsed);
    % Standard deviation computations
    if (Vs30 < k1(i))
        alpha1 = k2(i) * A1100 * ((A1100 + c*(Vs30/k1(i))^n)^(-1) - (A1100+c)^(-1));
    else
        alpha1 = 0;
    end
    slnAF = 0.3;
    slnYB = sqrt(slny(i)^2 - slnAF^2);
    slnAB = sqrt(slny(find(period==0))^2 - slnAF^2);
    sigma_sq = slnYB^2 + slnAF^2 + alpha1^2 * slnAB^2 + 2 * alpha1 * rho(i) * slnYB * slnAB;
    if arb == 0
        sigma = sqrt(sigma_sq + tlny(i)^2);
    else
        sigma = sqrt(sigma_sq + tlny(i)^2 + sig_c(i)^2);
    end
end
```

2.11 Chiou and Youngs – 2008

2.11.1 Reference

Chiou, B. S.-J., and R. R. Youngs (2008). An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra, *Earthquake Spectra* **24**, 173-215.

Youngs, R. R. (2009). AMEC Geomatrix, Oakland, CA. Written communication.

2.11.2 Abstract

Using a subset of the PEER NGA database (1950 recordings from 125 earthquakes), an empirical ground-motion model for the average horizontal component was developed. The model predicts peak ground velocity (PGV, in cm/s), peak ground acceleration (PGA, in g) and 5%-damped spectral values (in g) for periods ranging from 0.01 to 10 s. The model is applicable for earthquakes of M4.0 – M8.0 for reverse and normal faults, M4.0 – M8.5 for strike-slip faults, distances from 0 – 200 km, and average shear wave velocity in the upper 30 meters from 150 – 1500 m/s. Please note that during the development of this document, one of the figures in the original source could not be recreated. The authors were notified and the issue has not been fully resolved.

2.11.3 Attenuation Relationship

The predicted ground motion parameters are a function of:

- T – Period (sec), use 0 for PGA, -1 for PGV
- **M** – Moment magnitude
- δ – Average dip (degree)
- λ – Rake angle (degree)
- Z_{TOR} – Depth to the top of the rupture plane (km)
- F_{AS} – 1 for aftershock, 0 otherwise
- R_{rup} – Closest distance to rupture plane (km)
- R_{jb} – Joyner-Boore distance (km)
- R_x – Horizontal distance from the top of the rupture plane, measured perpendicular to the fault strike (km) with the down-dip direction being positive
- $Z_{1.0}$ – Depth to shear wave velocity of 1.0 km/s (m)
- V_{S30} – Shear wave velocity (m/s) averaged over top 30 m
- E – 1 if V_{S30} inferred from geology, 0 if measured

$$
\begin{aligned}
\ln(Sa) = \ln(y_{ref}) + \phi_1 \min\left(\ln\left(\frac{V_{S30}}{1130}\right), 0\right) \\
+ \phi_2\left\{e^{\phi_3(\min(V_{S30},1130)-360)} - e^{\phi_3(1130-360)}\right\} \ln\left(\frac{y_{ref}+\phi_4}{\phi_4}\right) \\
+ \phi_5\left(1 - \frac{1}{\cosh[\phi_6 \max(0, Z_{1.0}-\phi_7)]}\right) + \frac{\phi_8}{\cosh[0.15 \max(0, Z_{1.0}-15)]}
\end{aligned}
$$

where:

$$
\begin{aligned}
\ln(y_{ref}) = {} & c_1 + [c_{1a}F_{RV} + c_{1b}F_{NM} + c_7(Z_{TOR} - 4)](1 - \mathrm{F}_{AS}) + [c_{10} + c_{7a}(Z_{TOR} - 4)]\mathrm{F}_{AS} \\
& + c_2(\mathbf{M} - 6) + \frac{c_2 - c_3}{c_n}\ln\left(1 + e^{c_n(c_M - \mathbf{M})}\right) \\
& + c_4 \ln\left[R_{rup} + c_5 \cosh\{c_6 \max(\mathbf{M} - c_{HM}, 0)\}\right] \\
& + (c_{4a} - c_4)\ln\sqrt{{R_{rup}}^2 + {c_{RB}}^2} + \left\{c_{\gamma 1} + \frac{c_{\gamma 2}}{\cosh\left[\max\left(\mathbf{M} - c_{\gamma 3}, 0\right)\right]}\right\} R_{RUP} \\
& + c_9 F_{HW} \tanh\left(\frac{R_x \cos^2\delta}{c_{9a}}\right)\left\{1 - \sqrt{{R_{jb}}^2 + {Z_{TOR}}^2}/\left(R_{rup} + 0.001\right)\right\}
\end{aligned}
$$

where:

$$F_{HW} = \begin{cases} 1 & for\ R_x \geq 0 \\ 0 & for\ R_x < 0 \end{cases}$$

$$F_{RV} = \begin{cases} 1 & for\ 30° \leq \lambda \leq 150° \\ 0 & otherwise \end{cases}$$

$$F_{NM} = \begin{cases} 1 & for - 120° \leq \lambda \leq -60° \\ 0 & otherwise \end{cases}$$

Standard Deviation:

$$\sigma_T = \sqrt{(1 + NL_0)^2\tau^2 + \sigma^2}$$

where:

$$\tau = \tau_1 + \frac{\tau_2 - \tau_1}{2}[\min\{\max(\mathbf{M}, 5), 7\} - 5]$$

$$\sigma = \left[\sigma_1 + \frac{\sigma_2 - \sigma_1}{2}(\min\{\max(\mathbf{M}, 5), 7\} - 5) + \sigma_4 \mathrm{F}_{AS}\right] \times \sqrt{(\sigma_3 E_I + 0.7E_M) + (1 + NL_0)^2}$$

where:

$$E_I = \begin{cases} 1 & if\ V_{S30}\ is\ inferred\ from\ geometry \\ 0 & otherwise \end{cases}$$

$$E_M = \begin{cases} 1 & if\ V_{S30} is\ measured \\ 0 & otherwise \end{cases}$$

$$NL_0 = \phi_2\left\{e^{\phi_3(\min(V_{S30}, 1130) - 360)} - e^{\phi_3(1130 - 360)}\right\}\frac{y_{ref}}{y_{ref} + \phi_4}$$

Constants:

Table 2-32. Period-independent coefficients of model for $\ln(y_{ref})$

c_2	c_3	c_4	c_{4a}	c_{RB}	c_{HM}	$c_{\gamma 3}$
1.06	3.45	-2.1	-0.5	50	3	4

Table 2-33. Period-dependent coefficients of model for $\ln(y_{ref})$

T (sec)	c_1	c_{1a}	c_{1b}	c_n	c_M	c_5	c_6	c_7	c_{7a}	c_9	c_{9a}	c_{10}	$c_{\gamma 1}$	$c_{\gamma 2}$
PGA	-1.2687	0.1000	-0.2550	2.996	4.1840	6.1600	0.4893	0.0512	0.0860	0.7900	1.5005	-0.3218	-0.00804	-0.00785
PGV	2.2884	0.1094	-0.6260	1.648	4.2979	5.1700	0.4407	0.0207	0.0437	0.3079	2.6690	-0.1166	-0.00275	-0.00625
0.010	-1.2687	0.1000	-0.2550	2.996	4.1840	6.1600	0.4893	0.0512	0.0860	0.7900	1.5005	-0.3218	-0.00804	-0.00785
0.020	-1.2515	0.1000	-0.2550	3.292	4.1879	6.1580	0.4892	0.0512	0.0860	0.8129	1.5028	-0.3323	-0.00811	-0.00792
0.030	-1.1744	0.1000	-0.2550	3.514	4.1556	6.1550	0.4890	0.0511	0.0860	0.8439	1.5071	-0.3394	-0.00839	-0.00819
0.040	-1.0671	0.1000	-0.2550	3.563	4.1226	6.1508	0.4888	0.0508	0.0860	0.8740	1.5138	-0.3453	-0.00875	-0.00855
0.050	-0.9464	0.1000	-0.2550	3.547	4.1011	6.1441	0.4884	0.0504	0.0860	0.8996	1.5230	-0.3502	-0.00912	-0.00891
0.075	-0.7051	0.1000	-0.2540	3.448	4.0860	6.1200	0.4872	0.0495	0.0860	0.9442	1.5597	-0.3579	-0.00973	-0.00950
0.10	-0.5747	0.1000	-0.2530	3.312	4.1030	6.0850	0.4854	0.0489	0.0860	0.9677	1.6104	-0.3604	-0.00975	-0.00952
0.15	-0.5309	0.1000	-0.2500	3.044	4.1717	5.9871	0.4808	0.0479	0.0860	0.9660	1.7549	-0.3565	-0.00883	-0.00862
0.20	-0.6352	0.1000	-0.2449	2.831	4.2476	5.8699	0.4755	0.0471	0.0860	0.9334	1.9157	-0.3470	-0.00778	-0.00759
0.25	-0.7766	0.1000	-0.2382	2.658	4.3184	5.7547	0.4706	0.0464	0.0860	0.8946	2.0709	-0.3379	-0.00688	-0.00671
0.30	-0.9278	0.0999	-0.2313	2.505	4.3844	5.6527	0.4665	0.0458	0.0860	0.8590	2.2005	-0.3314	-0.00612	-0.00598
0.40	-1.2176	0.0997	-0.2146	2.261	4.4979	5.4997	0.4607	0.0445	0.0850	0.8019	2.3886	-0.3256	-0.00498	-0.00486
0.50	-1.4695	0.0991	-0.1972	2.087	4.5881	5.4029	0.4571	0.0429	0.0830	0.7578	2.5000	-0.3189	-0.00420	-0.00410
0.75	-1.9278	0.0936	-0.1620	1.812	4.7571	5.2900	0.4531	0.0387	0.0690	0.6788	2.6224	-0.2702	-0.00308	-0.00301
1.0	-2.2453	0.0766	-0.1400	1.648	4.8820	5.2480	0.4517	0.0350	0.0450	0.6196	2.6690	-0.2059	-0.00246	-0.00241
1.5	-2.7307	0.0022	-0.1184	1.511	5.0697	5.2194	0.4507	0.0280	0.0134	0.5101	2.6985	-0.0852	-0.00180	-0.00176
2.0	-3.1413	-0.0591	-0.1100	1.470	5.2173	5.2099	0.4504	0.0213	0.0040	0.3917	2.7085	0.0160	-0.00147	-0.00143
3.0	-3.7413	-0.0931	-0.1040	1.456	5.4385	5.2040	0.4501	0.0106	0.0010	0.1244	2.7145	0.1876	-0.00117	-0.00115
4.0	-4.1814	-0.0982	-0.1020	1.465	5.5977	5.2020	0.4501	0.0041	0.0000	0.0086	2.7164	0.3378	-0.00107	-0.00104
5.0	-4.5187	-0.0994	-0.1010	1.478	5.7276	5.2010	0.4500	0.0010	0.0000	0.0000	2.7172	0.4579	-0.00102	-0.00099
7.5	-5.1224	-0.0999	-0.1010	1.498	5.9891	5.2000	0.4500	0.0000	0.0000	0.0000	2.7177	0.7514	-0.00096	-0.00094
10.0	-5.5872	-0.1000	-0.1000	1.502	6.1930	5.2000	0.4500	0.0000	0.0000	0.0000	2.7180	1.1856	-0.00094	-0.00091

Units are in g's for PGA and PSA, and cm/s for PGV

Table 2-34. Coefficients of site response model for ln(y).

T (sec)	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8
PGA	-0.4417	-0.1417	-0.007010	0.102151	0.2289	0.014996	580.0	0.0700
PGV	-0.7861	-0.0699	-0.008444	5.410000	0.2899	0.006718	459.0	0.1138
0.010	-0.4417	-0.1417	-0.007010	0.102151	0.2289	0.014996	580.0	0.0700
0.020	-0.4340	-0.1364	-0.007279	0.108360	0.2289	0.014996	580.0	0.0699
0.030	-0.4177	-0.1403	-0.007354	0.119888	0.2289	0.014996	580.0	0.0701
0.040	-0.4000	-0.1591	-0.006977	0.133641	0.2289	0.014996	579.9	0.0702
0.050	-0.3903	-0.1862	-0.006467	0.148927	0.2290	0.014996	579.9	0.0701
0.075	-0.4040	-0.2538	-0.005734	0.190596	0.2292	0.014996	579.6	0.0686
0.10	-0.4423	-0.2943	-0.005604	0.230662	0.2297	0.014996	579.2	0.0646
0.15	-0.5162	-0.3113	-0.005845	0.266468	0.2326	0.014988	577.2	0.0494
0.20	-0.5697	-0.2927	-0.006141	0.255253	0.2386	0.014964	573.9	-0.0019
0.25	-0.6109	-0.2662	-0.006439	0.231541	0.2497	0.014881	568.5	-0.0479
0.30	-0.6444	-0.2405	-0.006704	0.207277	0.2674	0.014639	560.5	-0.0765
0.40	-0.6931	-0.1975	-0.007125	0.165464	0.3120	0.013493	540.0	-0.0960
0.50	-0.7246	-0.1633	-0.007435	0.133828	0.3610	0.011133	512.9	-0.0998
0.75	-0.7708	-0.1028	-0.008120	0.085153	0.4353	0.006739	441.9	-0.0765
1.0	-0.7990	-0.0699	-0.008444	0.058595	0.4629	0.005749	391.8	-0.0412
1.5	-0.8382	-0.0425	-0.007707	0.031787	0.4756	0.005544	348.1	0.0140
2.0	-0.8663	-0.0302	-0.004792	0.019716	0.4785	0.005521	332.5	0.0544
3.0	-0.9032	-0.0129	-0.001828	0.009643	0.4796	0.005517	324.1	0.1232
4.0	-0.9231	-0.0016	-0.001523	0.005379	0.4799	0.005517	321.7	0.1859
5.0	-0.9222	0.0000	-0.001440	0.003223	0.4799	0.005517	320.9	0.2295
7.5	-0.8346	0.0000	-0.001369	0.001134	0.4800	0.005517	320.3	0.2660
10.0	-0.7332	0.0000	-0.001361	0.000515	0.4800	0.005517	320.1	0.2682

Table 2-35. Coefficients of variance model

T (sec)	τ_1	τ_2	σ_1	σ_2	σ_3	σ_4
PGA	0.3437	0.2637	0.4458	0.3459	0.8000	0.0663
PGV	0.2539	0.2381	0.4496	0.3554	0.7504	0.0133
0.010	0.3437	0.2637	0.4458	0.3459	0.8000	0.0663
0.020	0.3471	0.2671	0.4458	0.3459	0.8000	0.0663
0.030	0.3603	0.2803	0.4535	0.3537	0.8000	0.0663
0.040	0.3718	0.2918	0.4589	0.3592	0.8000	0.0663
0.050	0.3848	0.3048	0.4630	0.3635	0.8000	0.0663
0.075	0.3878	0.3129	0.4702	0.3713	0.8000	0.0663
0.10	0.3835	0.3152	0.4747	0.3769	0.8000	0.0663
0.15	0.3719	0.3128	0.4798	0.3847	0.8000	0.0612
0.20	0.3601	0.3076	0.4816	0.3902	0.8000	0.0530
0.25	0.3522	0.3047	0.4815	0.3946	0.7999	0.0457
0.30	0.3438	0.3005	0.4801	0.3981	0.7997	0.0398
0.40	0.3351	0.2984	0.4758	0.4036	0.7988	0.0312
0.50	0.3353	0.3036	0.4710	0.4079	0.7966	0.0255
0.75	0.3429	0.3205	0.4621	0.4157	0.7792	0.0175
1.0	0.3577	0.3419	0.4581	0.4213	0.7504	0.0133
1.5	0.3769	0.3703	0.4493	0.4213	0.7136	0.0090
2.0	0.4023	0.4023	0.4459	0.4213	0.7035	0.0068
3.0	0.4406	0.4406	0.4433	0.4213	0.7006	0.0045
4.0	0.4784	0.4784	0.4424	0.4213	0.7001	0.0034
5.0	0.5074	0.5074	0.4420	0.4213	0.7000	0.0027
7.5	0.5328	0.5328	0.4416	0.4213	0.7000	0.0018
10.0	0.5542	0.5542	0.4414	0.4213	0.7000	0.0014

2.11.4 Calibration Plots

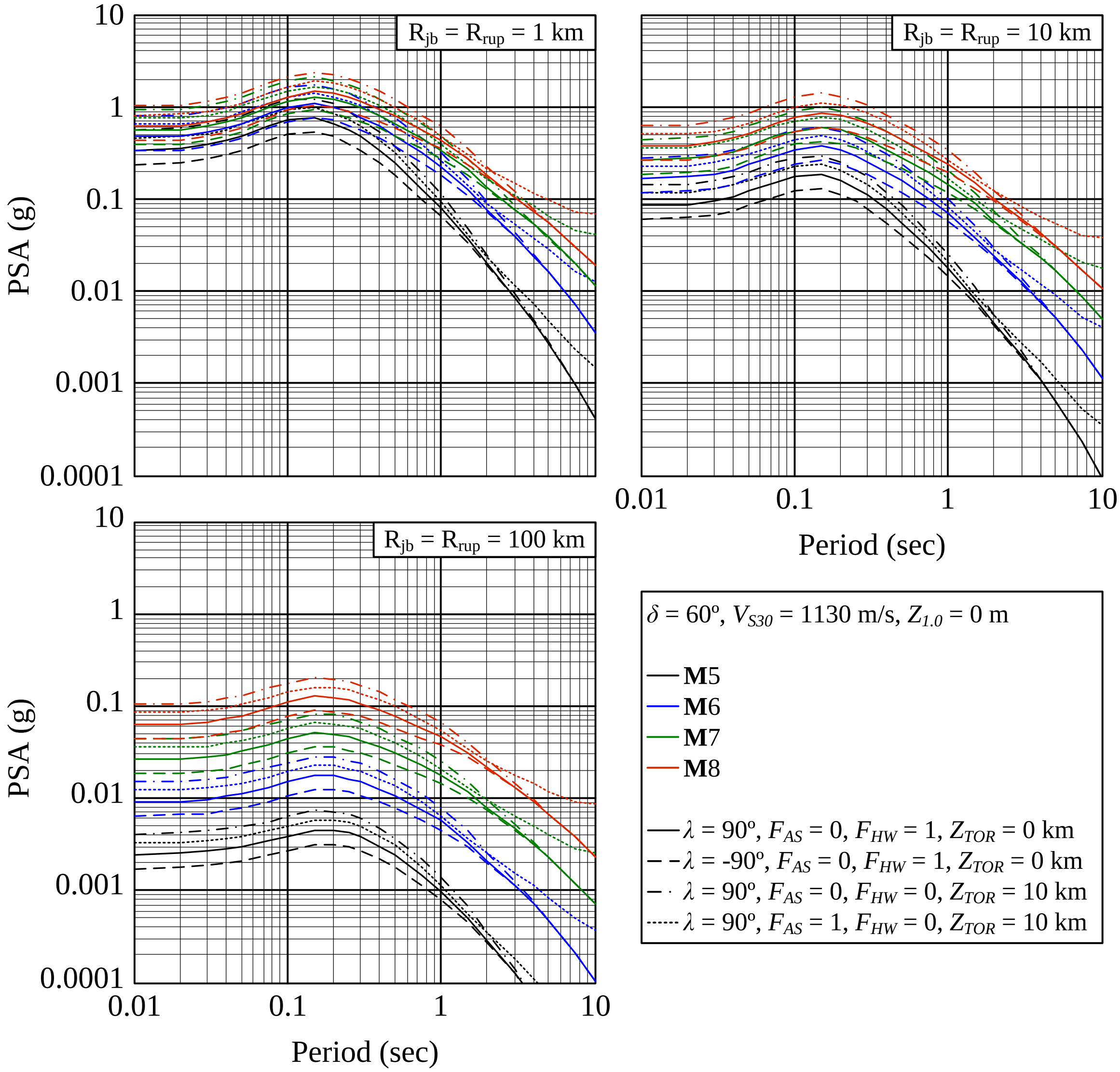


Figure 2-83. PSA as a function of period for different distances, magnitudes and geometric configurations. Please note that $R_x = R_{rup}$ for cases where $F_{HW} = 1$ and $R_x = -R_{rup}$ for cases where $F_{HW} = 0$.

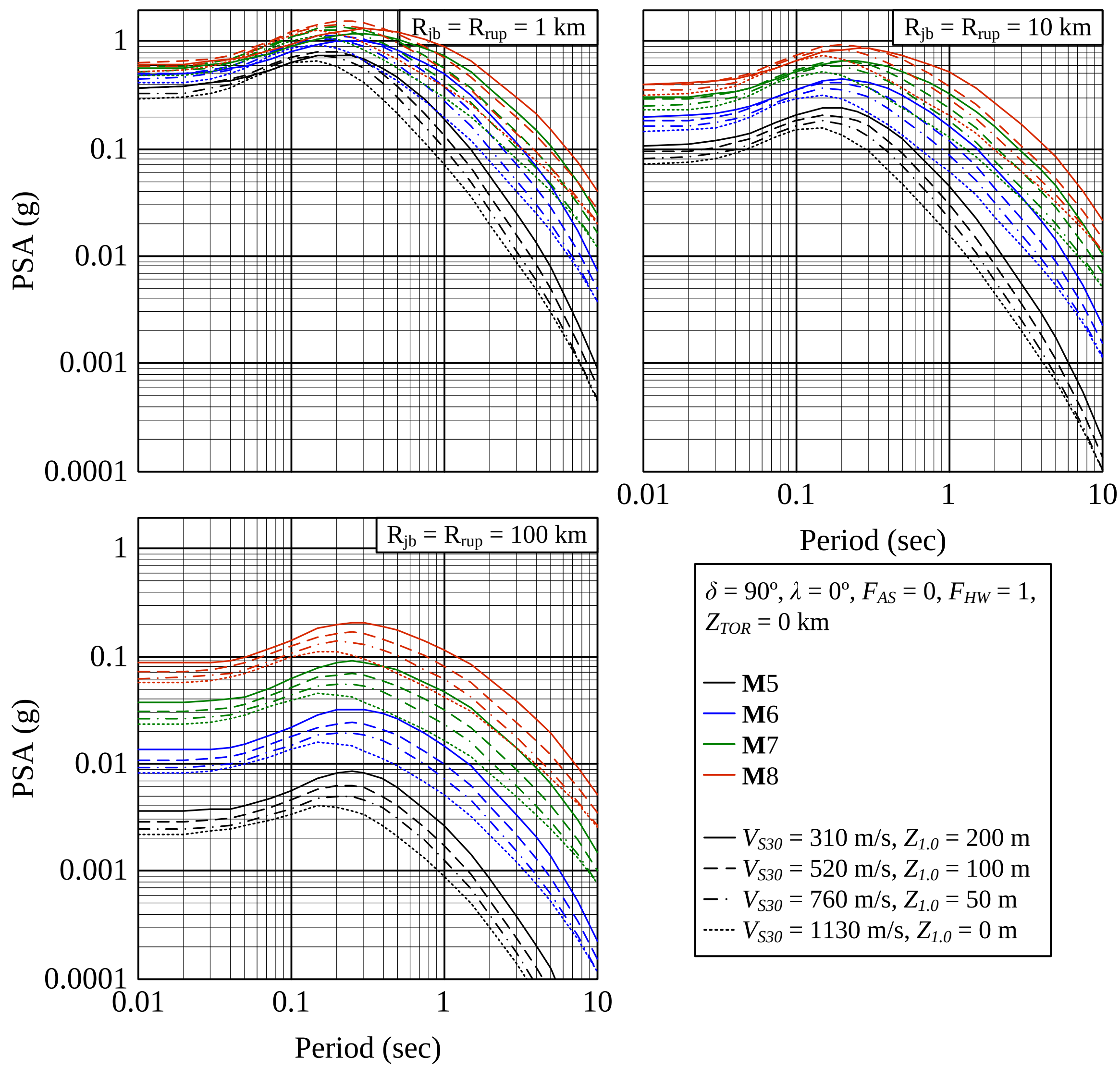


Figure 2-84. PSA as a function of period for different distances, magnitudes and ground conditions. Please note that since δ = 90 the hanging wall term is reduced to 0 which results in the value of R_x being insignificant.

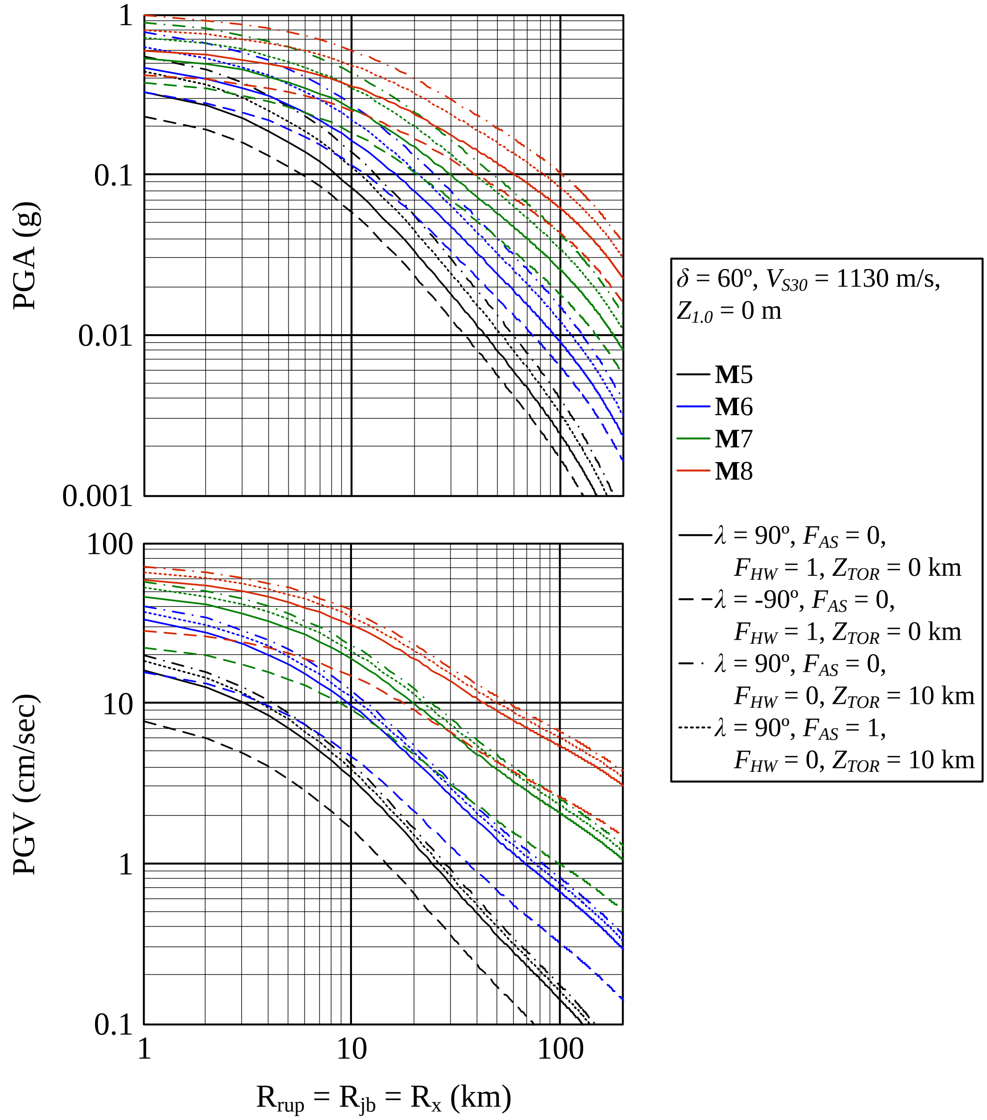


Figure 2-85. PGA and PGV as a function of period for different distances, magnitudes and geometric configurations. Please note that $R_x = R_{rup}$ for cases where $F_{HW} = 1$ and $R_x = -R_{rup}$ for cases where $F_{HW} = 0$.

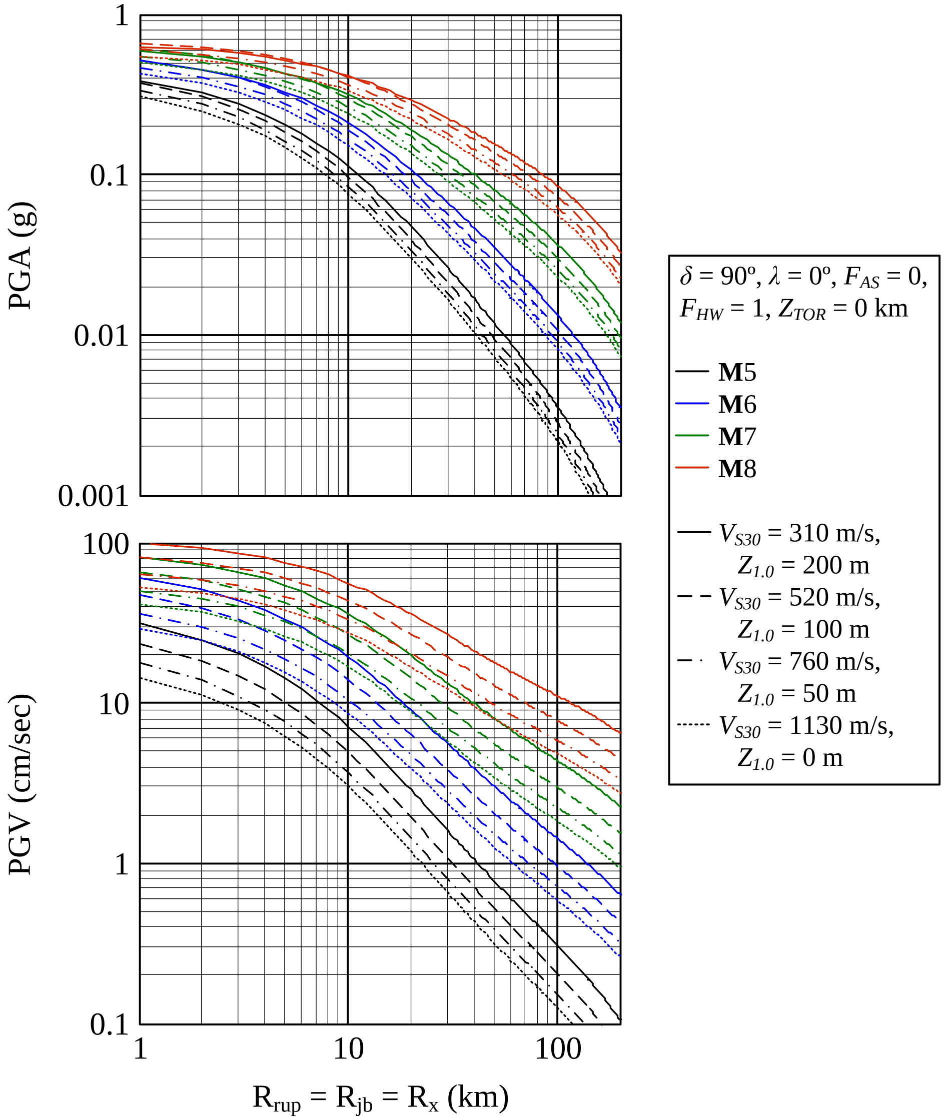


Figure 2-86. PGA and PGV as a function of period for different distances, magnitudes and ground conditions. Please note that since δ = 90 the hanging wall term is reduced to 0 which results in the value of R_x being insignificant.

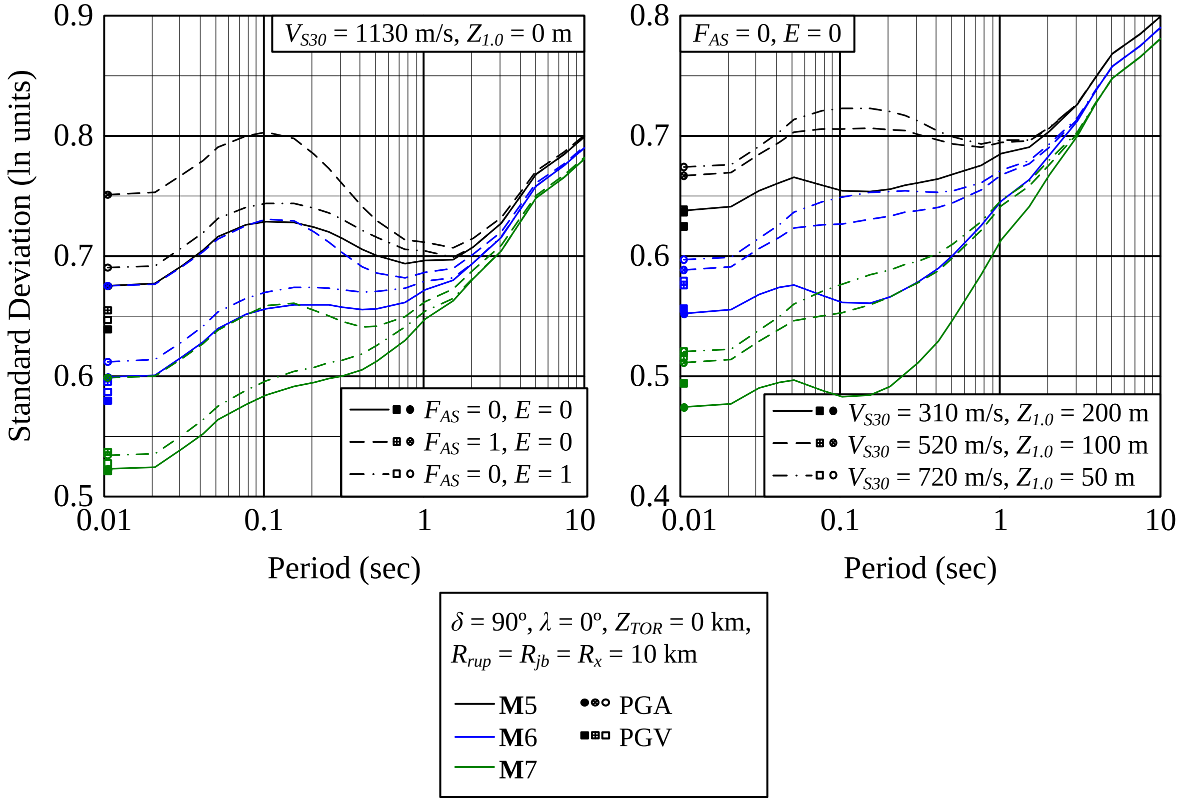


Figure 2-87. Standard deviations for PSA, PGA and PGV values for the given conditions.

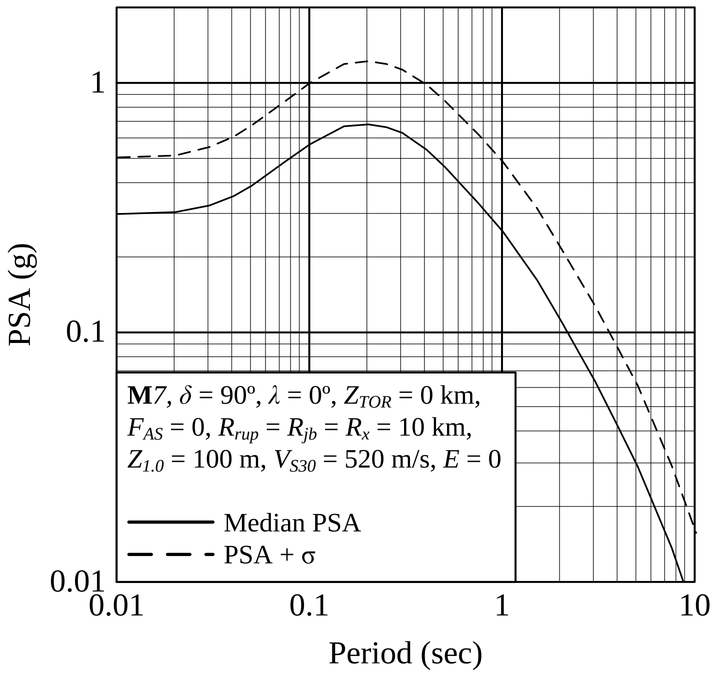


Figure 2-88. Example of application of median PSA plus one standard deviation.

2.11.5 Database

Strong motion database compiled by the "PEER NGA" (Pacific Earthquake Engineering Research Center's Next Generation Attenuation)

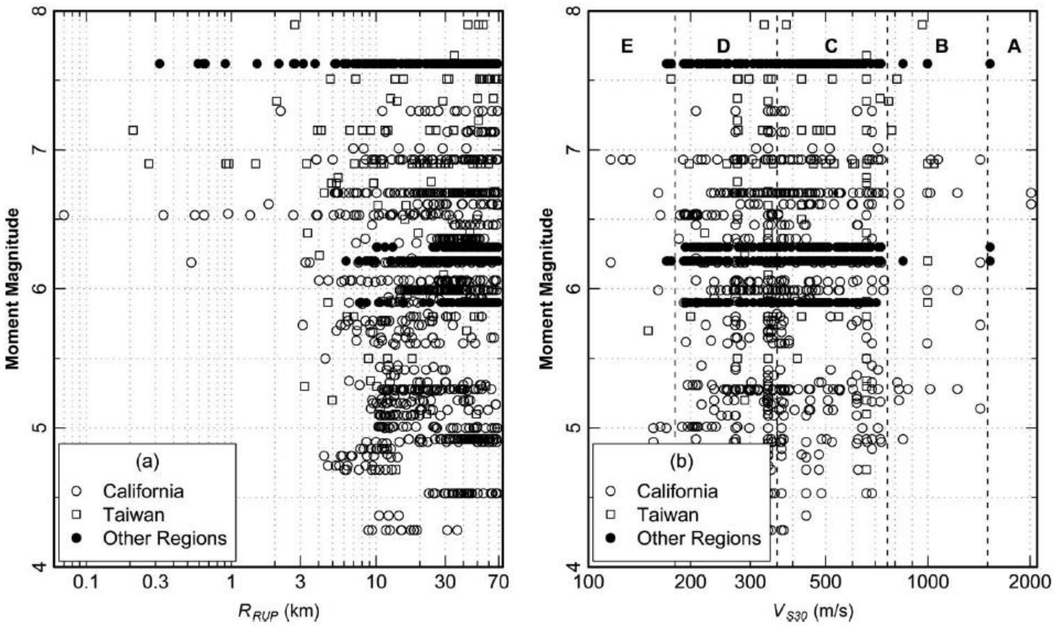


Figure 2-89. (a) Magnitude-distance-region distribution of selected recordings. (b) V_{S30}-magnitude-region distribution of selected recordings. V_{S30} ranges for NEHRP site classes are indicated by the vertical dashed lines.

2.11.6 MATLAB Code

```
% by Nirmal Jayaram, 4/27/07
% Stanford University
% nirmalj@stanford.edu
%
% edits:
% by Katyrn A. Gunberg, 12/29/08
% Virginia Tech
% kgunberg@vt.edu
%
% Chiou and Youngs attenuation equation, 2008
% edited from: Chiou and Youngs, 2007?
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0 for PGA, -1 for PGV
% M         = Moment magnitude
% delta     = Dip angle (degrees)
% lambda    = Rake angle (degrees)
% Ztor      = Depth to top of rupture (km)
% Fas       = Aftershock flag: 1 for aftershock, 0 otherwise
% Rrup      = Closest distance to rupture plane (km)
% Rjb       = Joyner-Boore distance (km)
% Rx        = Horizontal distance from the top of the rupture plane,
%             measured perpendicular to the fault strike (km),
%             with the downdip direction being positive
% Z1        = Depth to shear wave velocity of 1.0 km/s (m)
% Vs30      = Average shear velocity for top 30 m (m/s)
% E         = 1 if Vs30 inferred from geology, 0 if measured
%--------------------------------------------------------------------------
% Output variables
% Sa        = median spectral acceleration or PGV prediction (g or cm/s)
% sigma     = logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = CY_2008_nga(T,M,delta,lambda,Ztor,Fas,Rrup,Rjb,Rx,Z1,Vs30,E)
% Coefficients
c2      =   1.06;
c3      =   3.45;
c4      =  -2.1;
c4a     =  -0.5;
crb     =  50;
chm     =   3;
cy3     =   4;
period  =  [0           -1          0.01        0.02        0.03        0.04        ...
            0.05        0.075       0.1         0.15        0.2         0.25        ...
            0.3         0.4         0.5         0.75        1           1.5         ...
            2           3           4           5           7.5         10];
c1      =  [-1.2687     2.2884      -1.2687     -1.2515     -1.1744     -1.0671     ...
            -0.9464     -0.7051     -0.5747     -0.5309     -0.6352     -0.7766     ...
            -0.9278     -1.2176     -1.4695     -1.9278     -2.2453     -2.7307     ...
            -3.1413     -3.7413     -4.1814     -4.5187     -5.1224     -5.5872];
c1a     =  [0.1         0.1094      0.1         0.1         0.1         0.1         ...
            0.1         0.1         0.1         0.1         0.1         0.1         ...
            0.0999      0.0997      0.0991      0.0936      0.0766      0.0022      ...
            -0.0591     -0.0931     -0.0982     -0.0994     -0.0999     -0.1];
c1b     =  [-0.2550     -0.626      -0.2550     -0.2550     -0.2550     -0.2550     ...
            -0.2550     -0.2540     -0.2530     -0.2500     -0.2449     -0.2382     ...
            -0.2313     -0.2146     -0.1972     -0.1620     -0.1400     -0.1184     ...
            -0.1100     -0.1040     -0.1020     -0.1010     -0.1010     -0.1000];
cn      =  [2.996       1.648       2.996       3.292       3.514       3.563       ...
            3.547       3.448       3.312       3.044       2.831       2.658       ...
            2.505       2.261       2.087       1.812       1.648       1.511       ...
            1.470       1.456       1.465       1.478       1.498       1.502];
cM      =  [4.1840      4.2979      4.1840      4.1879      4.1556      4.1226      ...
            4.1011      4.0860      4.1030      4.1717      4.2476      4.3184      ...
            4.3844      4.4979      4.5881      4.7571      4.8820      5.0697      ...
            5.2173      5.4385      5.5977      5.7276      5.9891      6.1930];
c5      =  [6.1600      5.1700      6.1600      6.1580      6.1550      6.1508      ...
            6.1441      6.1200      6.0850      5.9871      5.8699      5.7547      ...
            5.6527      5.4997      5.4029      5.2900      5.2480      5.2194      ...
            5.2099      5.2040      5.2020      5.2010      5.2000      5.2000];
```

```
c6      =  [0.4893      0.4407      0.4893      0.4892      0.4890      0.4888      ...
            0.4884      0.4872      0.4854      0.4808      0.4755      0.4706      ...
            0.4665      0.4607      0.4571      0.4531      0.4517      0.4507      ...
            0.4504      0.4501      0.4501      0.4500      0.4500      0.4500];
c7      =  [0.0512      0.0207      0.0512      0.0512      0.0511      0.0508      ...
            0.0504      0.0495      0.0489      0.0479      0.0471      0.0464      ...
            0.0458      0.0445      0.0429      0.0387      0.0350      0.0280      ...
            0.0213      0.0106      0.0041      0.0010      0.0000      0.0000];
c7a     =  [0.0860      0.0437      0.0860      0.0860      0.0860      0.0860      ...
            0.0860      0.0860      0.0860      0.0860      0.0860      0.0860      ...
            0.0860      0.0850      0.0830      0.0690      0.0450      0.0134      ...
            0.0040      0.0010      0.0000      0.0000      0.0000      0.0000];
c9      =  [0.7900      0.3079      0.7900      0.8129      0.8439      0.8740      ...
            0.8996      0.9442      0.9677      0.9660      0.9334      0.8946      ...
            0.8590      0.8019      0.7578      0.6788      0.6196      0.5101      ...
            0.3917      0.1244      0.0086      0.0000      0.0000      0.0000];
c9a     =  [1.5005      2.6690      1.5005      1.5028      1.5071      1.5138      ...
            1.5230      1.5597      1.6104      1.7549      1.9157      2.0709      ...
            2.2005      2.3886      2.5000      2.6224      2.6690      2.6985      ...
            2.7085      2.7145      2.7164      2.7172      2.7177      2.7180];
c10     =  [-0.3218     -0.1166     -0.3218     -0.3323     -0.3394     -0.3453     ...
            -0.3502     -0.3579     -0.3604     -0.3565     -0.3470     -0.3379     ...
            -0.3314     -0.3256     -0.3189     -0.2702     -0.2059     -0.0852     ...
            0.0160      0.1876      0.3378      0.4579      0.7514      1.1856];
cy1     =  [-0.00804    -0.00275    -0.00804    -0.00811    -0.00839    -0.00875    ...
            -0.00912    -0.00973    -0.00975    -0.00883    -0.00778    -0.00688    ...
            -0.00612    -0.00498    -0.00420    -0.00308    -0.00246    -0.00180    ...
            -0.00147    -0.00117    -0.00107    -0.00102    -0.00096    -0.00094];
cy2     =  [-0.00785    -0.00625    -0.00785    -0.00792    -0.00819    -0.00855    ...
            -0.00891    -0.00950    -0.00952    -0.00862    -0.00759    -0.00671    ...
            -0.00598    -0.00486    -0.00410    -0.00301    -0.00241    -0.00176    ...
            -0.00143    -0.00115    -0.00104    -0.00099    -0.00094    -0.00091];
phi1    =  [-0.4417     -0.7861     -0.4417     -0.4340     -0.4177     -0.4000     ...
            -0.3903     -0.4040     -0.4423     -0.5162     -0.5697     -0.6109     ...
            -0.6444     -0.6931     -0.7246     -0.7708     -0.7990     -0.8382     ...
            -0.8663     -0.9032     -0.9231     -0.9222     -0.8346     -0.7332];
phi2    =  [-0.1417     -0.0699     -0.1417     -0.1364     -0.1403     -0.1591     ...
            -0.1862     -0.2538     -0.2943     -0.3113     -0.2927     -0.2662     ...
            -0.2405     -0.1975     -0.1633     -0.1028     -0.0699     -0.0425     ...
            -0.0302     -0.0129     -0.0016     0.0000      0.0000      0.0000];
phi3    =  [-0.007010   -0.008444   -0.007010   -0.007279   -0.007354   -0.006977   ...
            -0.006467   -0.005734   -0.005604   -0.005845   -0.006141   -0.006439   ...
            -0.006704   -0.007125   -0.007435   -0.008120   -0.008444   -0.007707   ...
            -0.004792   -0.001828   -0.001523   -0.001440   -0.001369   -0.001361];
phi4    =  [0.102151    5.410000    0.102151    0.108360    0.119888    0.133641    ...
            0.148927    0.190596    0.230662    0.266468    0.255253    0.231541    ...
            0.207277    0.165464    0.133828    0.085153    0.058595    0.031787    ...
            0.019716    0.009643    0.005379    0.003223    0.001134    0.000515];
phi5    =  [0.2289      0.2899      0.2289      0.2289      0.2289      0.2289      ...
            0.2290      0.2292      0.2297      0.2326      0.2386      0.2497      ...
            0.2674      0.3120      0.3610      0.4353      0.4629      0.4756      ...
            0.4785      0.4796      0.4799      0.4799      0.4800      0.4800];
phi6    =  [0.014996    0.006718    0.014996    0.014996    0.014996    0.014996    ...
            0.014996    0.014996    0.014996    0.014988    0.014964    0.014881    ...
            0.014639    0.013493    0.011133    0.006739    0.005749    0.005544    ...
            0.005521    0.005517    0.005517    0.005517    0.005517    0.005517];
phi7    =  [580.0       459.0       580.0       580.0       580.0       579.9       ...
            579.9       579.6       579.2       577.2       573.9       568.5       ...
            560.5       540.0       512.9       441.9       391.8       348.1       ...
            332.5       324.1       321.7       320.9       320.3       320.1];
phi8    =  [0.0700      0.1138      0.0700      0.0699      0.0701      0.0702      ...
            0.0701      0.0686      0.0646      0.0494      -0.0019     -0.0479     ...
            -0.0765     -0.0960     -0.0998     -0.0765     -0.0412     0.0140      ...
            0.0544      0.1232      0.1859      0.2295      0.2660      0.2682];
tau1    =  [0.3437      0.2539      0.3437      0.3471      0.3603      0.3718      ...
            0.3848      0.3878      0.3835      0.3719      0.3601      0.3522      ...
            0.3438      0.3351      0.3353      0.3429      0.3577      0.3769      ...
            0.4023      0.4406      0.4784      0.5074      0.5328      0.5542];
tau2    =  [0.2637      0.2381      0.2637      0.2671      0.2803      0.2918      ...
            0.3048      0.3129      0.3152      0.3128      0.3076      0.3047      ...
            0.3005      0.2984      0.3036      0.3205      0.3419      0.3703      ...
            0.4023      0.4406      0.4784      0.5074      0.5328      0.5542];
sigma1  =  [0.4458      0.4496      0.4458      0.4458      0.4535      0.4589      ...
            0.4630      0.4702      0.4747      0.4798      0.4816      0.4815      ...
```

```
            0.4801      0.4758      0.4710      0.4621      0.4581      0.4493      ...
            0.4459      0.4433      0.4424      0.4420      0.4416      0.4414];
sigma2  =  [0.3459      0.3554      0.3459      0.3459      0.3537      0.3592      ...
            0.3635      0.3713      0.3769      0.3847      0.3902      0.3946      ...
            0.3981      0.4036      0.4079      0.4157      0.4213      0.4213      ...
            0.4213      0.4213      0.4213      0.4213      0.4213      0.4213];
sigma3  =  [0.8000      0.7504      0.8000      0.8000      0.8000      0.8000      ...
            0.8000      0.8000      0.8000      0.8000      0.8000      0.7999      ...
            0.7997      0.7988      0.7966      0.7792      0.7504      0.7136      ...
            0.7035      0.7006      0.7001      0.7000      0.7000      0.7000];
sigma4  =  [0.0663      0.0133      0.0663      0.0663      0.0663      0.0663      ...
            0.0663      0.0663      0.0663      0.0612      0.0530      0.0457      ...
            0.0398      0.0312      0.0255      0.0175      0.0133      0.0090      ...
            0.0068      0.0045      0.0034      0.0027      0.0018      0.0014];
% interpolate between periods if neccesary
if (length(find(period == T)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, stdev_low] = CY_2008_nga (T_low,M,delta,lambda,Ztor,Fas,Rrup,Rjb,Rx,Z1,Vs30,E);
    [sa_hi, stdev_hi]   = CY_2008_nga (T_hi, M,delta,lambda,Ztor,Fas,Rrup,Rjb,Rx,Z1,Vs30,E);
    x       = [log(T_low) log(T_hi)];
    Y_sa    = [log(sa_low) log(sa_hi)];
    Y_stdev = [stdev_low stdev_hi];
    Sa      = exp(interp1(x,Y_sa,log(T)));
    sigma   = interp1(x,Y_stdev,log(T));
else
    i = find(period == T); % Identify the period
    fhw = Rx >= 0; % fhw: 1 for Rx greater than or equal to 0 km, 0 otherwise
    frv = lambda >= 30 & lambda <= 150; % frv: 1 for lambda between 30 and 150, 0 otherwise
    fnm = lambda >= -120 & lambda <= -60; % fnm: 1 for lambda between -120 and -60, 0 otherwise
    lnyref = c1(i) + (c1a(i)*frv + c1b(i)*fnm + c7(i)*(Ztor - 4))*(1 - Fas) + (c10(i) + ...
        c7a(i)*(Ztor - 4))*Fas + c2*(M - 6) + ((c2 - c3)/cn(i))*log (1 + exp(cn(i)*...
        (cM(i) - M))) + c4*log(Rrup + c5(i)*cosh(c6(i)*max(M - chm,0))) + (c4a - c4)*...
        log(sqrt(Rrup^2 + crb^2)) + (cy1(i) + cy2(i)/cosh(max(M-cy3,0)))*Rrup + c9(i)*...
        fhw*tanh(Rx*cosd(delta)^2/c9a(i))*(1 - sqrt(Rjb^2 + Ztor^2)/(Rrup + 0.001));
    yref   = exp(lnyref);
    extra  = phi1(i)*min(log(Vs30/1130),0) + phi2(i)*(exp(phi3(i)*(min(Vs30,1130) - 360)) - ...
        exp(phi3(i)*(1130 - 360)))*log((yref + phi4(i))/phi4(i)) + phi5(i)*...
        (1 - 1/cosh(phi6(i)*max(0,Z1 - phi7(i)))) + phi8(i)/cosh(0.15*max(0,Z1 - 15));
    % Compute median
    Sa = exp(lnyref + extra);
    % Compute standard deviation
    Finf    = E == 1; % Finf:  1 for inferred Vs30, 0 otherwise
    Fmeas   = E == 0; % Fmeas: 1 for measured Vs30, 0 otherwise
    NL0     = phi2(i)*(exp(phi3(i)*(min(Vs30,1130) - 360)) - exp(phi3(i)*(1130 - 360)))*...
        yref/(yref + phi4(i));
    sig   = (sigma1(i) + (sigma2(i) - sigma1(i))/2*(min(max(M,5),7) - 5) + ...
        sigma4(i)*Fas)*sqrt((sigma3(i)*Finf + 0.7*Fmeas) + (1 + NL0)^2);
    tau   = tau1(i) + (tau2(i) - tau1(i))/2*(min(max(M,5),7)-5);
    sigma = sqrt((1 + NL0)^2 * tau^2 + sig^2);
end
```

2.12 Idriss – 2008

2.12.1 Reference

Idriss, I. M. (2008). An NGA Empirical model for Estimating the Horizontal Spectral Values Generated by Shallow Crustal Earthquakes, *Earthquake Spectra* **24**, 217–241.

2.12.2 Abstract

Using a subset of the PEER NGA database (942 recordings from 72 earthquakes), an empirical ground-motion model for the average horizontal component was developed. The model predicts peak ground acceleration (PGA, in g) and 5%-damped spectral values (PSA, in g) for periods ranging from 0.02 to 10 s. The model is applicable for magnitudes of M5.0 – M8.0 for reverse and normal faults, M5.0 – M8.5 for strike-slip faults, distances from 0 – 200 km and average shear wave velocity in the upper 30 meters greater than 450 m/s. Relationships for lower velocities have yet to be published.

2.12.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0.01 s for PGA
- **M** – Moment magnitude
- F – Fault type: 0 for strike-slip and normal faults, 1 for reverse or oblique faults
- R_{rup} – Closest distance to rupture plane (km)
- V_{S30} – Shear wave velocity (m/s) averaged over top 30 m

$$\ln(PSA) = \alpha_1 + \alpha_2 M - [\beta_1 + \beta_2 M] \ln\left(R_{rup} + 10\right) + \gamma R_{rup} + \varphi F + \begin{cases} 0 & for\ 450 \le V_{S30} \le 900 \\ \Delta\alpha_1 & for\ V_{S30} > 900 \end{cases}$$

Standard Error

$$\sigma = 1.28 + 0.05 \ln(T) - 0.08M$$

Notes on σ:

- If M < 5, use M = 5
- If M > 7.5, use M = 7.5
- If T < 0.05 sec, use T = 0.05 sec
- If T > 3 sec, use T = 3 sec.

Alternate form for σ:

$$\sigma = 1.28 + 0.05 \ln[\max(\min(T, 3), 0.05)] - 0.08[\max(\min(M, 7.5), 5)]$$

Coefficients

Table 2-36. Derived parameters

T (sec)	$M \leq 6.75$				$6.75 < M \leq 8.5$				γ	ϕ	$\Delta\alpha_1$
	α_1	α_2	β_1	β_2	α_1	α_2	β_1	β_2			
0.01	3.7066	-0.1252	2.9832	-0.2339	5.6315	-0.4104	2.9832	-0.2339	0.00047	0.12	-0.1492
0.02	3.7066	-0.1252	2.9832	-0.2339	5.6315	-0.4104	2.9832	-0.2339	0.00047	0.12	-0.1492
0.03	3.7566	-0.1252	2.9832	-0.2339	5.6815	-0.4104	2.9832	-0.2339	0.00047	0.12	-0.1492
0.04	3.8066	-0.1252	2.9832	-0.2339	5.7315	-0.4104	2.9832	-0.2339	0.00047	0.12	-0.1492
0.05	4.1248	-0.1781	3.0156	-0.2445	5.8447	-0.4329	2.9487	-0.2346	0.00000	0.12	-0.1492
0.06	4.4681	-0.2228	3.0708	-0.2536	6.0362	-0.4551	2.9494	-0.2356	0.00000	0.12	-0.1657
0.08	4.4853	-0.1949	3.1071	-0.2576	6.4307	-0.4831	2.9788	-0.2386	0.00000	0.12	-0.1922
0.10	4.4592	-0.1624	3.1212	-0.2570	6.3053	-0.4359	2.9153	-0.2265	0.00000	0.12	-0.2126
0.15	3.4793	-0.0188	2.8609	-0.2267	5.0845	-0.2566	2.4829	-0.1707	0.00000	0.12	-0.2475
0.20	3.2354	0.0346	2.8739	-0.2282	5.0842	-0.2393	2.5066	-0.1738	0.00000	0.12	-0.2693
0.25	2.7628	0.0791	2.8203	-0.2292	4.5453	-0.1850	2.3687	-0.1623	-0.00049	0.12	-0.2842
0.30	2.3813	0.1187	2.8126	-0.2301	4.2719	-0.1614	2.3475	-0.1612	0.00052	0.12	-0.2948
0.35	2.0302	0.1545	2.8056	-0.2309	4.0174	-0.1399	2.3284	-0.1602	0.00099	0.12	-0.3028
0.40	1.7037	0.1873	2.7992	-0.2317	3.7792	-0.1202	2.3105	-0.1593	0.00112	0.12	-0.3088
0.45	1.3940	0.2177	2.7932	-0.2324	3.5519	-0.1020	2.2937	-0.1584	0.00114	0.12	-0.3136
0.50	1.0893	0.2461	2.7876	-0.2330	3.3235	-0.0849	2.2793	-0.1577	0.00132	0.12	-0.3173
0.60	0.5308	0.2979	2.7772	-0.2342	2.9047	-0.0538	2.2507	-0.1562	0.00154	0.12	-0.3227
0.70	0.0240	0.3443	2.7677	-0.2353	2.5222	-0.0258	2.2250	-0.1549	0.00170	0.12	-0.3262
0.80	-0.4141	0.3866	2.7590	-0.2363	2.1972	-0.0003	2.2014	-0.1537	0.00152	0.12	-0.3285
0.90	-0.8184	0.4255	2.7510	-0.2373	1.8971	0.0232	2.1786	-0.1525	0.00157	0.11	-0.3299
1.0	-1.2290	0.4615	2.7434	-0.2381	1.5822	0.0450	2.1588	-0.1515	0.00188	0.10	-0.3308
1.5	-2.9168	0.6103	2.7112	-0.2418	0.2888	0.1354	2.0720	-0.1471	0.00250	0.06	-0.3297
2.0	-4.2783	0.7246	2.6851	-0.2447	-0.7737	0.2054	2.0027	-0.1436	0.00268	0.04	-0.3248
3.0	-6.2431	0.8935	2.6437	-0.2493	-2.3037	0.3099	1.8938	-0.1382	0.00050	0.00	-0.3110
4.0	-7.6967	1.0137	2.6110	-0.2529	-3.4564	0.3855	1.8091	-0.1341	-0.00248	0.00	-0.2956
5.0	-8.8110	1.1027	2.5839	-0.2558	-4.3563	0.4427	1.7401	-0.1308	-0.00453	0.00	-0.2797
6.0	-9.7232	1.1696	2.5607	-0.2582	-5.1145	0.4868	1.6825	-0.1281	-0.00566	0.00	-0.2638
7.0	-10.4706	1.2197	2.5406	-0.2603	-5.7538	0.5209	1.6327	-0.1258	-0.00633	0.00	-0.2481
8.0	-11.0814	1.2566	2.5228	-0.2621	-6.2921	0.5471	1.5900	-0.1239	-0.00671	0.00	-0.2327
9.0	-11.5896	1.2826	2.5070	-0.2636	-6.7588	0.5669	1.5532	-0.1223	-0.00689	0.00	-0.2175
10.0	-12.0149	1.2995	2.4928	-0.2650	-7.1679	0.5814	1.5201	-0.1209	-0.00709	0.00	-0.2026

2.12.4 Calibration Plots

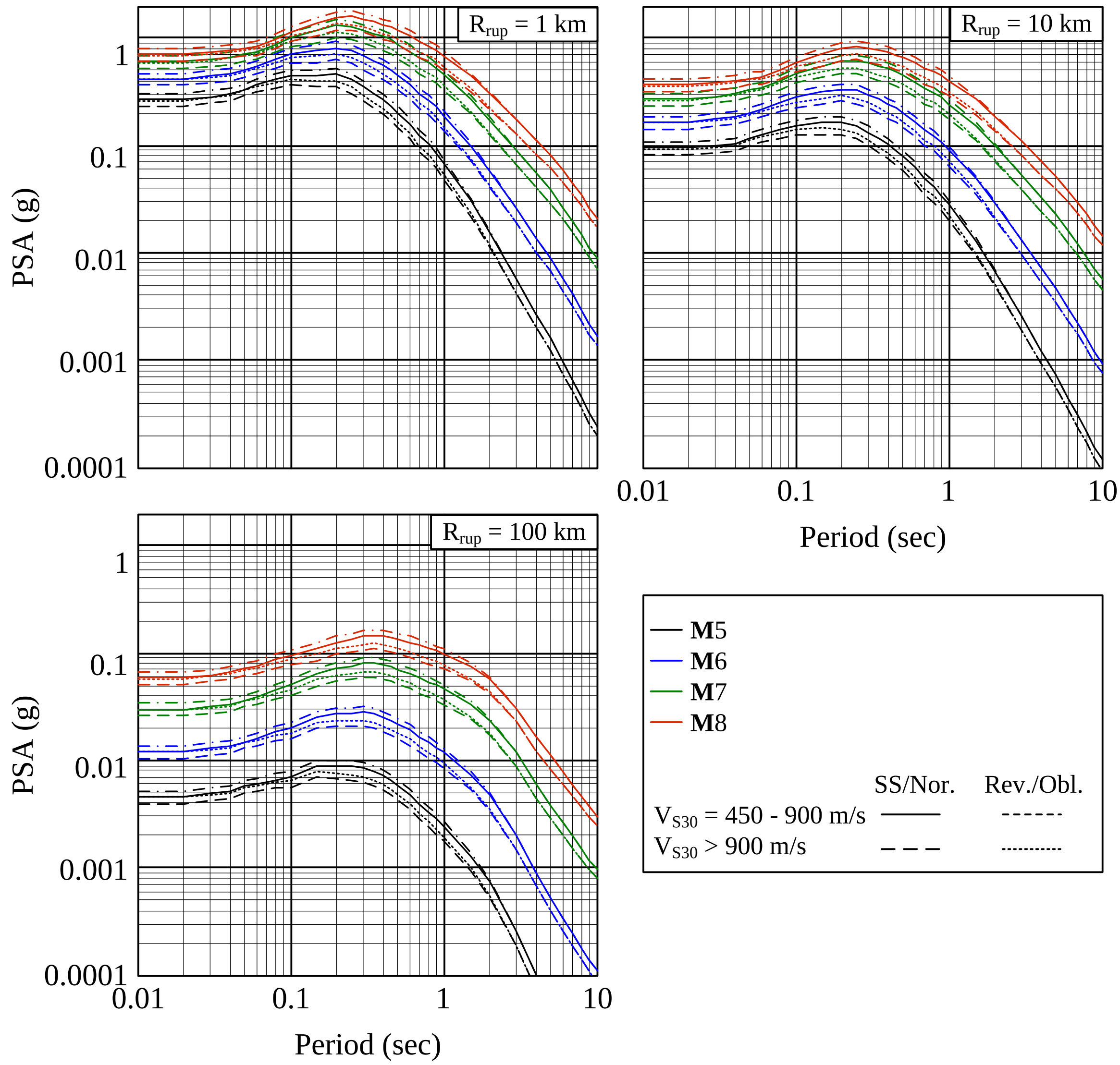


Figure 2-90. PSA as a function of period for the conditions given.

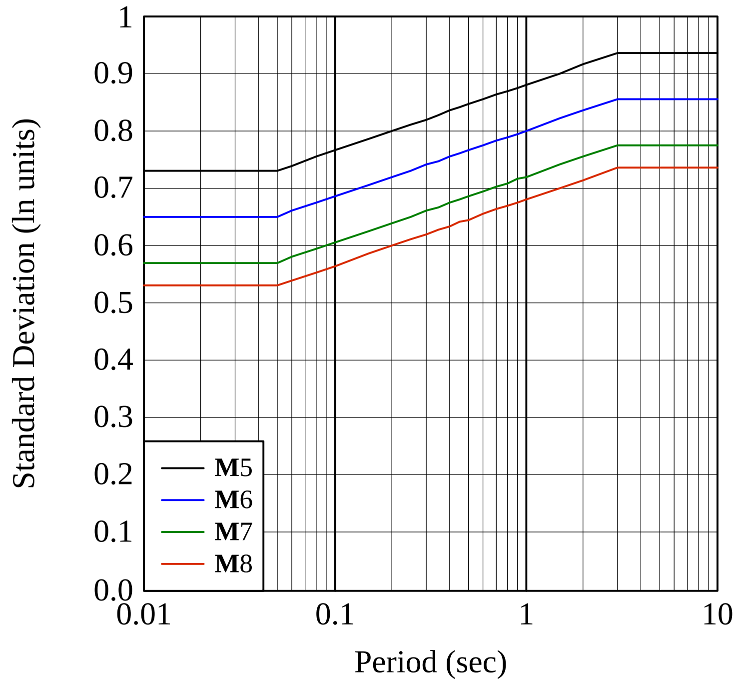


Figure 2-91. Standard deviations as a function of period for different magnitudes (not dependant on distance, fault type and shear wave velocity).

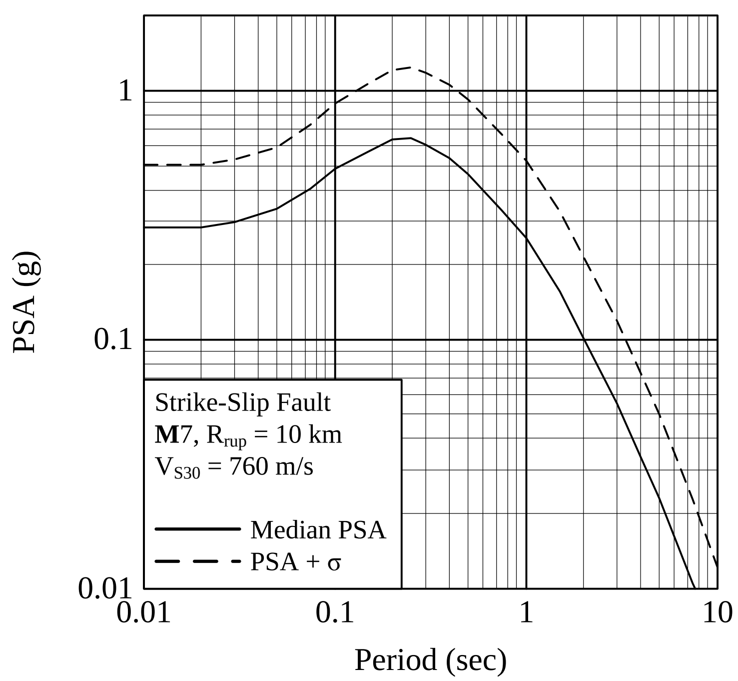


Figure 2-92. Example of application of median PSA plus one standard deviation.

2.12.5 Database

Strong motion database compiled by the "PEER NGA" (Pacific Earthquake Engineering Research Center's Next Generation Attenuation)

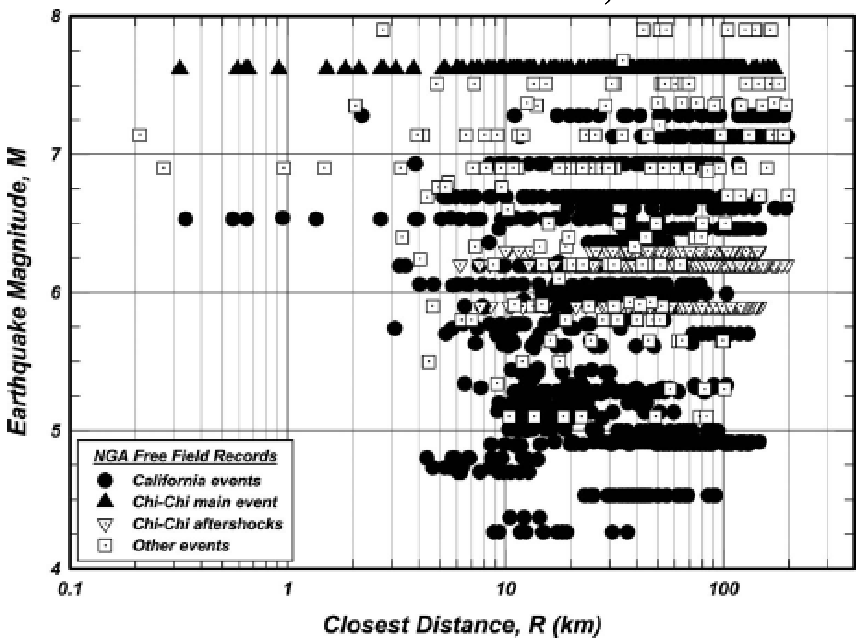


Figure 2-93. Magnitude-distance distribution of free-field records included in the PEER Flatfile.

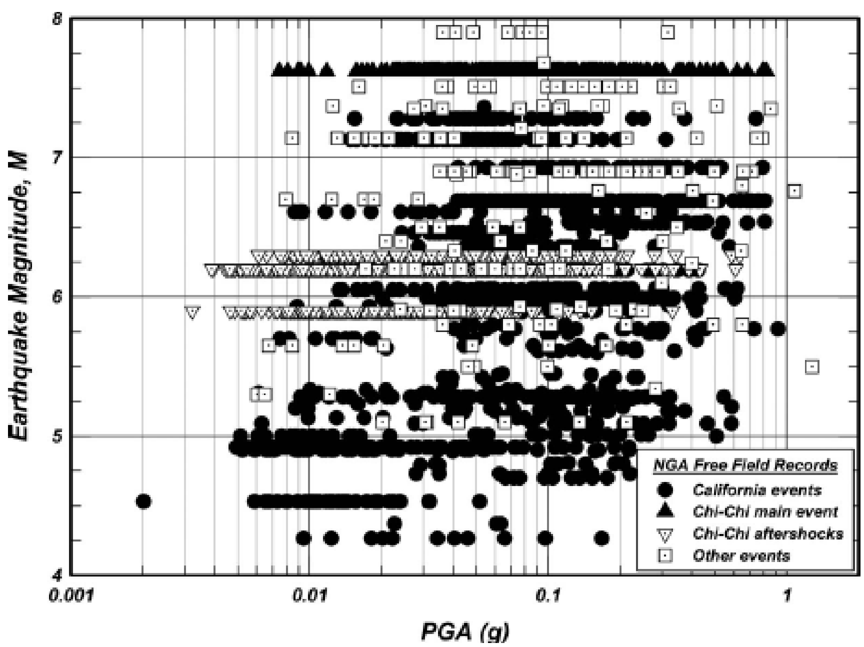


Figure 2-94. Magnitude-PGA distribution of free-field records included in the PEER Flatfile.

2.12.6 MATLAB Code

```
% by Kathryn A. Gunberg 1/7/2008
% Virginia Tech
% kgunberg@vt.edu
%
% Idriss attenuation equation, 2008
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0.01 for PGA
% M         = Moment magnitude
% F         = Fault type: 0 for strike-slip/normal, 1 for reverse/oblique
% Rrup      = Closest distance to rupture plane (km)
% Vs30      = Shear wave velocity (m/s) averaged over top 30 m
% ---------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = I_2008_nga(T, M, F, Rrup, Vs30)
% Coefficients

period   = [0.01       0.02       0.03       0.04       0.05       0.06       0.08...
            0.10       0.15       0.20       0.25       0.30       0.35       0.40...
            0.45       0.50       0.60       0.70       0.80       0.90       1.00...
            1.50       2.00       3.00       4.00       5.00       6.00       7.00...
            8.00       9.00       10];
gamma    = [0.00047    0.00047    0.00047    0.00047    0          0          0 ...
            0          0          0          -0.00049   0.00052    0.00099    0.00112...
            0.00114    0.00132    0.00154    0.00170    0.00152    0.00157    0.00188...
            0.00250    0.00268    0.00050    -0.00248   -0.00453   -0.00566   -0.00633...
            -0.00671   -0.00689   -0.00709];
phi      = [0.12       0.12       0.12       0.12       0.12       0.12       0.12...
            0.12       0.12       0.12       0.12       0.12       0.12       0.12...
            0.12       0.12       0.12       0.12       0.12       0.11       0.10...
            0.06       0.04       0          0          0          0          0 ...
            0          0          0];
da       = [-0.1492    -0.1492    -0.1492    -0.1492    -0.1492    -0.1657    -0.1922...
            -0.2126    -0.2475    -0.2693    -0.2842    -0.2948    -0.3028    -0.3088...
            -0.3136    -0.3173    -0.3227    -0.3262    -0.3285    -0.3299    -0.3308...
            -0.3297    -0.3248    -0.3110    -0.2956    -0.2797    -0.2638    -0.2481...
            -0.2327    -0.2175    -0.2026];
if M <= 6.75
    a1   = [3.7066     3.7066     3.7566     3.8066     4.1248     4.4681     4.4853...
            4.4592     3.4793     3.2354     2.7628     2.3813     2.0302     1.7037...
            1.3940     1.0893     0.5308     0.0240     -0.4141    -0.8184    -1.2290...
            -2.9168    -4.2783    -6.2431    -7.6967    -8.8110    -9.7232    -10.4706...
            -11.0814   -11.5896   -12.0149];
    a2   = [-0.1252    -0.1252    -0.1252    -0.1252    -0.1781    -0.2228    -0.1949...
            -0.1624    -0.0188    0.0346     0.0791     0.1187     0.1545     0.1873...
            0.2177     0.2461     0.2979     0.3443     0.3866     0.4255     0.4615...
            0.6103     0.7246     0.8935     1.0137     1.1027     1.1696     1.2197...
            1.2566     1.2826     1.2995];
    b1   = [2.9832     2.9832     2.9832     2.9832     3.0156     3.0708     3.1071...
            3.1212     2.8609     2.8739     2.8203     2.8126     2.8056     2.7992...
            2.7932     2.7876     2.7772     2.7677     2.7590     2.7510     2.7434...
            2.7112     2.6851     2.6437     2.6110     2.5839     2.5607     2.5406...
            2.5228     2.5070     2.4928];
    b2   = [-0.2339    -0.2339    -0.2339    -0.2339    -0.2445    -0.2536    -0.2576...
            -0.2570    -0.2267    -0.2282    -0.2292    -0.2301    -0.2309    -0.2317...
            -0.2324    -0.2330    -0.2342    -0.2353    -0.2363    -0.2373    -0.2381...
            -0.2418    -0.2447    -0.2493    -0.2529    -0.2558    -0.2582    -0.2603...
            -0.2621    -0.2636    -0.2650];
elseif and(M > 6.75, M <= 8.5)
    a1   = [5.6315     5.6315     5.6815     5.7315     5.8447     6.0362     6.4307...
            6.3053     5.0845     5.0842     4.5453     4.2719     4.0174     3.7792...
            3.5519     3.3235     2.9047     2.5222     2.1972     1.8971     1.5822...
            0.2888     -0.7737    -2.3037    -3.4564    -4.3563    -5.1145    -5.7538...
            -6.2921    -6.7588 -7.1679];
    a2   = [-0.4104    -0.4104    -0.4104    -0.4104    -0.4329    -0.4551    -0.4831...
            -0.4359    -0.2566    -0.2393    -0.1850    -0.1614    -0.1399    -0.1202...
```

```
            -0.1020      -0.0849      -0.0538      -0.0258      -0.0003      0.0232       0.0450...
            0.1354       0.2054       0.3099       0.3855       0.4427       0.4868       0.5209...
            0.5471       0.5669       0.5814];
    b1   = [2.9832       2.9832       2.9832       2.9832       2.9487       2.9494       2.9788...
            2.9153       2.4829       2.5066       2.3687       2.3475       2.3284       2.3105...
            2.2937       2.2793       2.2507       2.2250       2.2014       2.1786       2.1588...
            2.0720       2.0027       1.8938       1.8091       1.7401       1.6825       1.6327...
            1.5900       1.5532       1.5201];
    b2   = [-0.2339      -0.2339      -0.2339      -0.2339      -0.2346      -0.2356      -0.2386...
            -0.2265      -0.1707      -0.1738      -0.1623      -0.1612      -0.1602      -0.1593...
            -0.1584      -0.1577      -0.1562      -0.1549      -0.1537      -0.1525      -0.1515...
            -0.1471      -0.1436      -0.1382      -0.1341      -0.1308      -0.1281      -0.1258...
            -0.1239      -0.1223      -0.1209];
end
if Vs30 > 900
    a1 = a1 + da;
end
% interpolate between periods if neccesary
if T == 0
    T = min(period);
end
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, SE_low] = I_2008_nga(T_low, M, Rrup, F, Vs30);
    [sa_hi,  SE_hi]  = I_2008_nga(T_hi,  M, Rrup, F, Vs30);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_SE = [SE_low SE_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_SE,log(T));
else
    i = find(period == T);
    Sa= exp(a1(i) + a2(i)*M - (b1(i) + b2(i)*M)*log(Rrup + 10) + gamma(i)*Rrup + phi(i)*F);
    M = max(min(7.5,M),5);
    T = max(min(3,T),0.05);
    sigma = 1.28 + 0.05 * log(T) - 0.08 * M;
end
```

2.13 Graizer and Kalkan – 2009

2.13.1 References

Graizer, V. and E. Kalkan (2009). Prediction of Spectral Acceleration Response Ordinates Based on PGA Attenuation, *Earthquake Spectra* **25**, 39–69.

Graizer, V. and E. Kalkan (2007). Ground Motion Attenuation Model for Peak Horizontal Acceleration from Shallow Crustal Earthquakes, *Earthquake Spectra* **23**, 585–613.

Graizer, V. (2009). U.S. Nuclear Regulatory Commission, Washington, DC. Written communication.

Kalkan, E. (2009). U.S. Geological Survey, Menlo Park, CA. Written communication.

2.13.2 Abstract

Using 2583 data points from 47 earthquakes in shallow crustal tectonic regimes, an empirical ground-motion model for peak horizontal ground acceleration (PGA, in g) was developed (Graizer and Kalkan, 2007). In addition, using the NGA database with the addition of more recent events, a PGA based predictive model for 5%-damped spectral acceleration (Sa, in g) was developed for periods from 0.01 to 5 seconds (Graizer and Kalkan, 2009). The model is applicable for earthquakes between M4.9 and M7.9, and distances up to 200 km. Since the spectral accelerations relations were PGA based, any PGA estimate can be used for Sa prediction. (Note: Despite attempts to address the issue, Figure 11a using this code, does not match the paper for basin effect sites.)

2.13.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA
- **M** – Moment magnitude
- F – Fault type: 1 for strike-slip, 1.28 for reverse
- R_{rup} – closest distance to rupture plane (km)
- V_{S30} – Shear wave velocity (m/s) averaged over top 30 m
- D_1 – 0.35 for basin effect (sediment depth greater than 1 km), 0.65 for no basin effect

$$\ln(PGA) = G1 + G2 + G3 + G4$$

where:

$$G1 = \ln[A(M,F)]$$

where:

$$A(M,F) = F[c_1 \arctan(M + c_2) + c_3]$$

$$G2 = -0.5 \ln \left[\left(1 - R_{rup}/R_0\right)^2 + 4{D_0}^2 \, R_{rup}/R_0 \right]$$

where:

$$R_0 = c_4 M + c_5$$
$$D_0 = c_6 \cos[c_7(M + c_8)] + c_9$$

$$G3 = -0.5 \ln \left[\left(1 - \sqrt{R_{rup}/R_1}\right)^2 + 4{D_1}^2 \sqrt{R_{rup}/R_1} \right]$$

$$G4 = b_v \ln(V_{S30}/VA)$$

$$Sa = PGA \times Sa_{norm}$$

where:

PGA is either the Graizer and Kalkan 2007 PGA or a PGA from another relationship

$$Sa_{norm} = F1 + F2$$

where:

$$F1 = I\left(M, R_{rup}\right) \exp\left\{- {}^1\!/_2 \left[\left(\ln(T) + \mu\left(M, R_{rup}, V_{S30}\right)\right) / S\left(M, R_{rup}\right)\right]^2 \right\}$$

where:

$$I\left(M, R_{rup}\right) = (a_1 M + a_2) \exp\left(a_3 R_{rup}\right)$$
$$\mu\left(M, R_{rup}, V_{S30}\right) = m_1 R_{rup} + m_2 M + m_3 V_{S30} + m_4$$
$$S\left(M, R_{rup}\right) = s_1 R_{rup} - (s_2 M + s_3)$$

$$F2 = \left[\left(1 - \left(T/T_{sp,0}\right)^\zeta\right)^2 + 4{D_{sp}}^2 \left(T/T_{sp,0}\right)^\zeta \right]^{-\frac{1}{2}}$$

where:

$$T_{sp,0}\left(M, R_{rup}, V_{S30}\right) = t_1 R_{rup} + t_2 M + t_3 V_{S30} + t_4$$

Standard Error

$$\sigma_{\ln(PGA)} = 0.552$$

If Graizer and Kalkan 2007 PGA estimate used: $\sigma_{\ln(Sa)} = {\sigma_{\ln(Sa)}}^b$

If other PGA estimate used: $\sigma_{\ln(Sa)} = \sigma_{\ln(PGA)} \frac{{\sigma_{\ln(Sa)}}^a}{0.092 \ln(T) + 0.404}$

Coefficients

Table 2-37. Coefficients for PGA relation.

c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	b_v	VA	R_1
0.14	-6.25	0.37	2.237	-7.542	-0.125	1.19	-6.15	0.525	-0.24	484.5	100

Table 2-38. Coefficients for Sa relation.

m_1	m_2	m_3	m_4	a_1	a_2	a_3	D_{sp}
-0.0012	-0.4087	0.0006	3.63	0.017	1.27	0.0001	0.75

t_1	t_2	t_3	t_4	s_1	s_2	s_3	ζ
0.0022	0.63	-0.0005	-2.1	0.001	0.077	0.3251	1.5

Table 2-39. Standard Error coefficients.

T (sec)	$\sigma_{\ln(Sa)}{}^{a}$	$\sigma_{\ln(Sa)}{}^{b}$	T (sec)	$\sigma_{\ln(Sa)}{}^{a}$	$\sigma_{\ln(Sa)}{}^{b}$	T (sec)	$\sigma_{\ln(Sa)}{}^{a}$	$\sigma_{\ln(Sa)}{}^{b}$
PGA	-	0.552	0.140	0.223	0.563	0.800	0.467	0.672
0.010	0.036	0.544	0.150	0.226	0.567	0.850	0.477	0.671
0.020	0.044	0.540	0.160	0.230	0.571	0.900	0.491	0.672
0.022	0.053	0.540	0.170	0.230	0.575	0.950	0.506	0.675
0.025	0.063	0.541	0.180	0.231	0.579	1.000	0.519	0.675
0.029	0.073	0.542	0.190	0.236	0.585	1.100	0.531	0.675
0.030	0.081	0.543	0.200	0.242	0.591	1.200	0.542	0.676
0.032	0.088	0.544	0.220	0.249	0.597	1.300	0.553	0.675
0.035	0.096	0.546	0.240	0.257	0.603	1.400	0.564	0.675
0.036	0.102	0.547	0.250	0.266	0.609	1.500	0.577	0.676
0.040	0.108	0.549	0.260	0.275	0.615	1.600	0.591	0.683
0.042	0.114	0.550	0.280	0.286	0.621	1.700	0.602	0.687
0.044	0.119	0.551	0.290	0.296	0.626	1.800	0.615	0.695
0.045	0.125	0.551	0.300	0.305	0.630	1.900	0.631	0.705
0.046	0.132	0.550	0.320	0.314	0.633	2.000	0.646	0.715
0.048	0.139	0.549	0.340	0.323	0.636	2.200	0.661	0.726
0.050	0.145	0.549	0.350	0.328	0.637	2.400	0.679	0.740
0.055	0.152	0.549	0.360	0.334	0.638	2.500	0.704	0.764
0.060	0.160	0.549	0.380	0.342	0.640	2.600	0.728	0.783
0.065	0.167	0.548	0.400	0.348	0.641	2.800	0.749	0.796
0.067	0.176	0.547	0.420	0.353	0.641	3.000	0.754	0.794
0.070	0.184	0.547	0.440	0.359	0.641	3.200	0.754	0.788
0.075	0.192	0.548	0.450	0.365	0.643	3.400	0.753	0.781
0.080	0.198	0.549	0.460	0.370	0.645	3.500	0.754	0.776
0.085	0.202	0.549	0.480	0.376	0.648	3.600	0.756	0.771
0.090	0.205	0.550	0.500	0.383	0.651	3.800	0.759	0.769
0.095	0.209	0.550	0.550	0.391	0.653	4.000	0.755	0.759
0.100	0.212	0.551	0.600	0.401	0.656	4.200	0.751	0.750
0.110	0.216	0.553	0.650	0.413	0.659	4.400	0.758	0.753
0.120	0.217	0.555	0.667	0.426	0.662	4.600	0.765	0.758
0.130	0.219	0.557	0.700	0.441	0.667	4.800	0.779	0.765
0.133	0.221	0.560	0.750	0.454	0.670	5.000	0.801	0.781

2.13.4 Calibration Plots

(NOTE: Because PSA is a function of PGA, separate calibration plots for PGA are not required.)

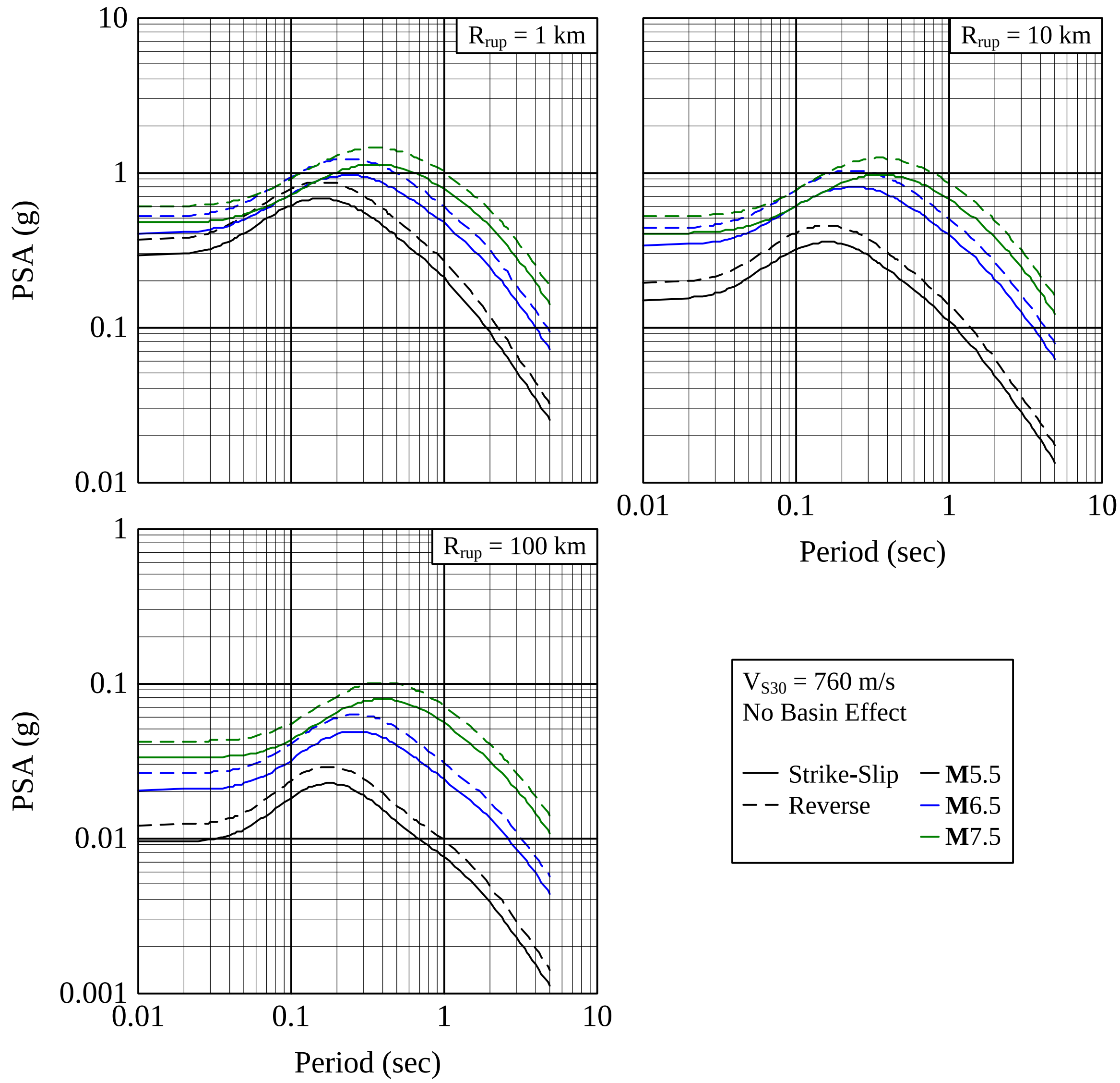


Figure 2-95. Shows changes in magnitude, distance and fault type.

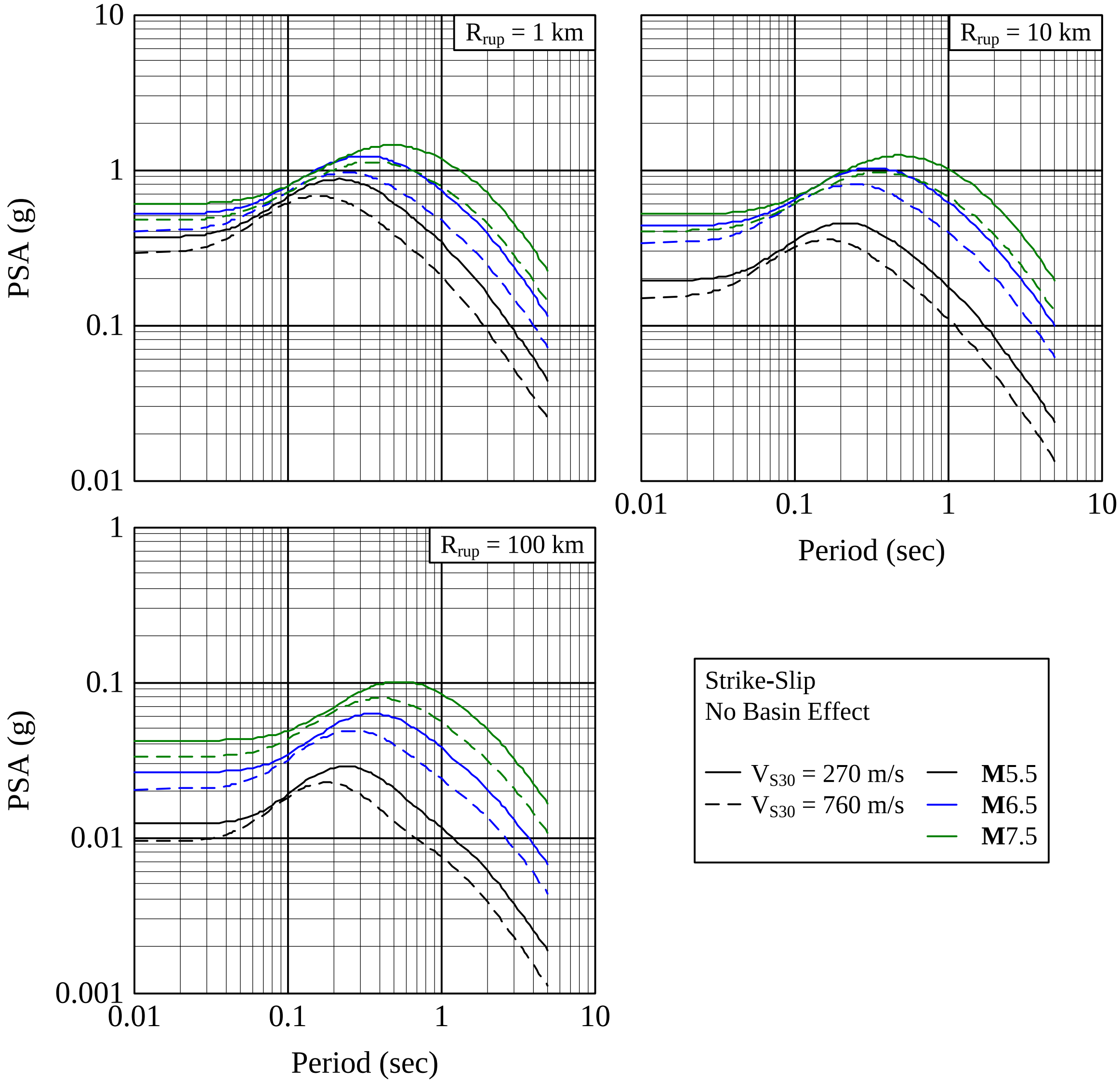


Figure 2-96. Shows changes in magnitude, distance and shear wave velocity.

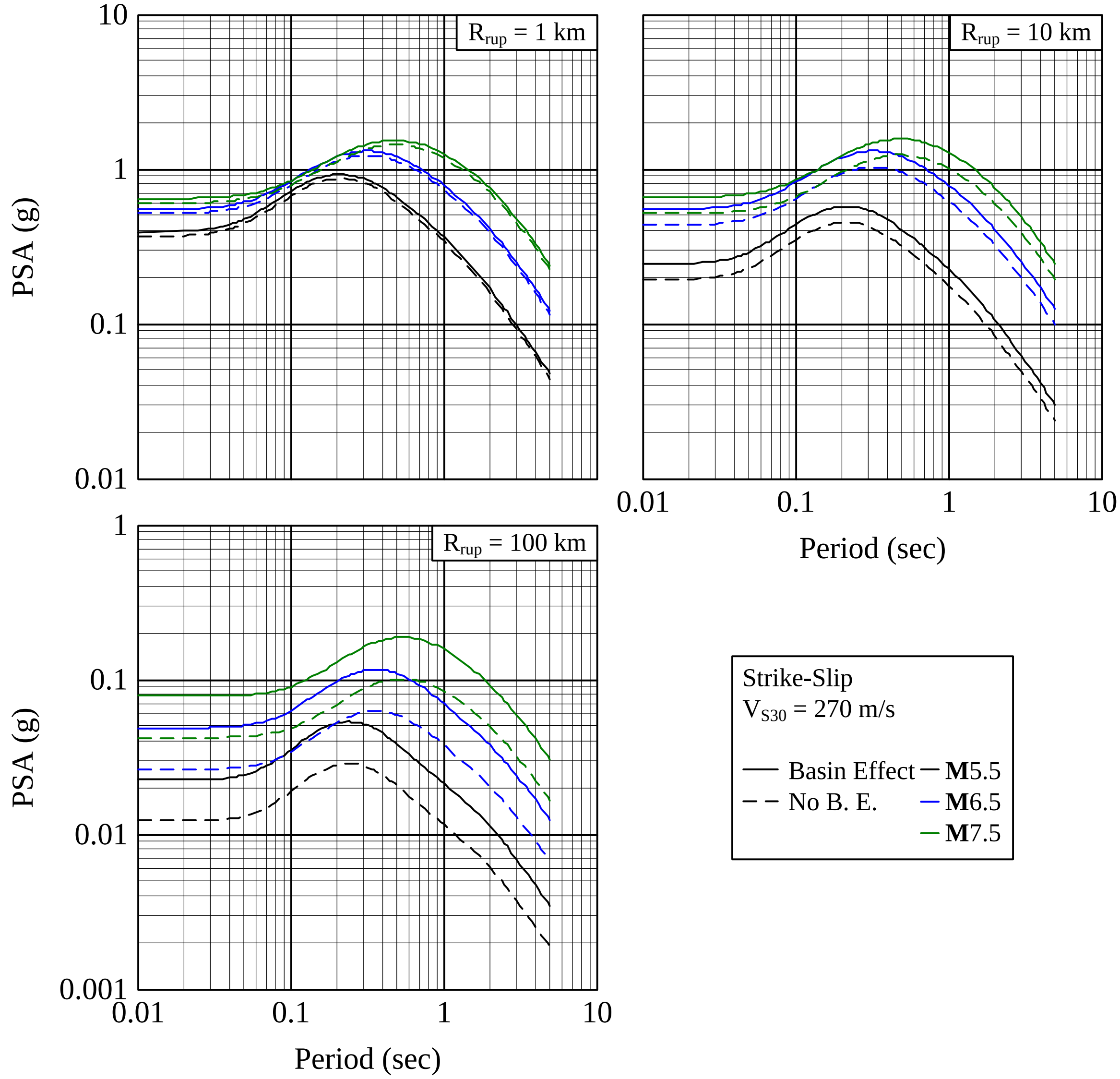


Figure 2-97. Shows changes in magnitude, distance and basin effect.

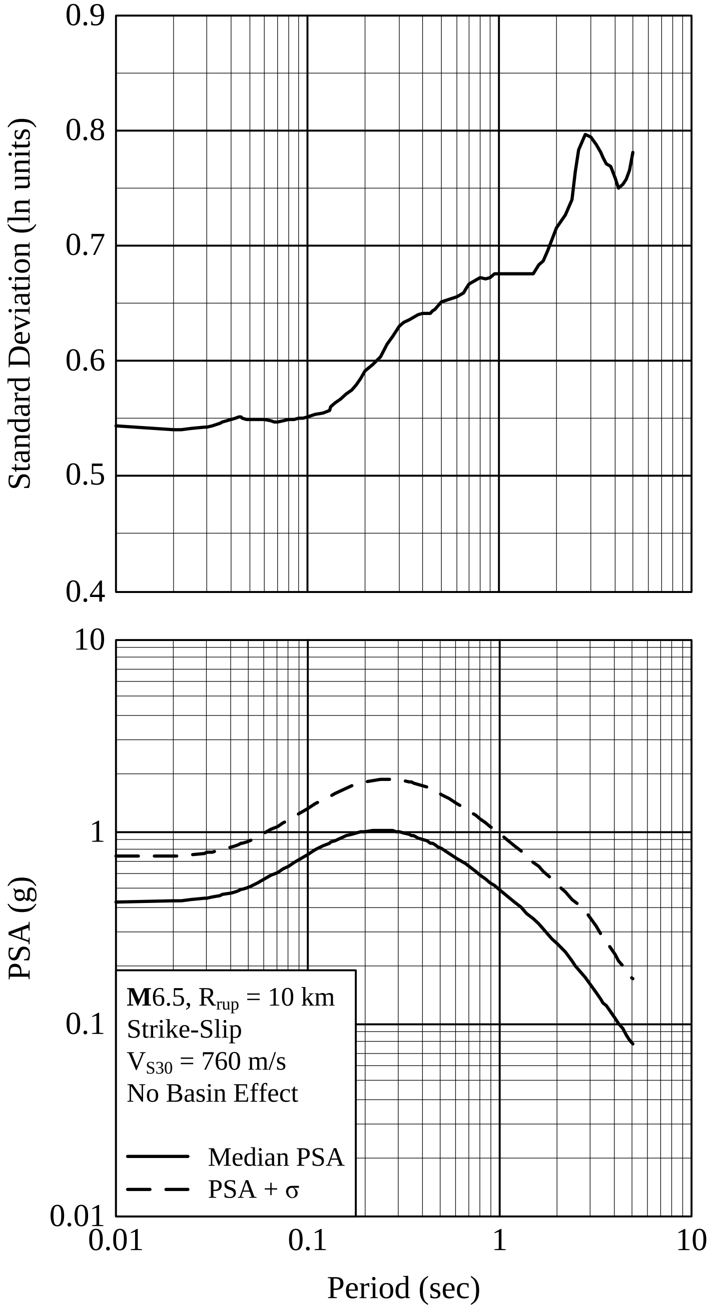


Figure 2-98. Above: Standard deviation as a function of magnitude. Note that this is only dependant on period. Below: Example of application of median PSA plus one standard deviation.

2.13.5 Database

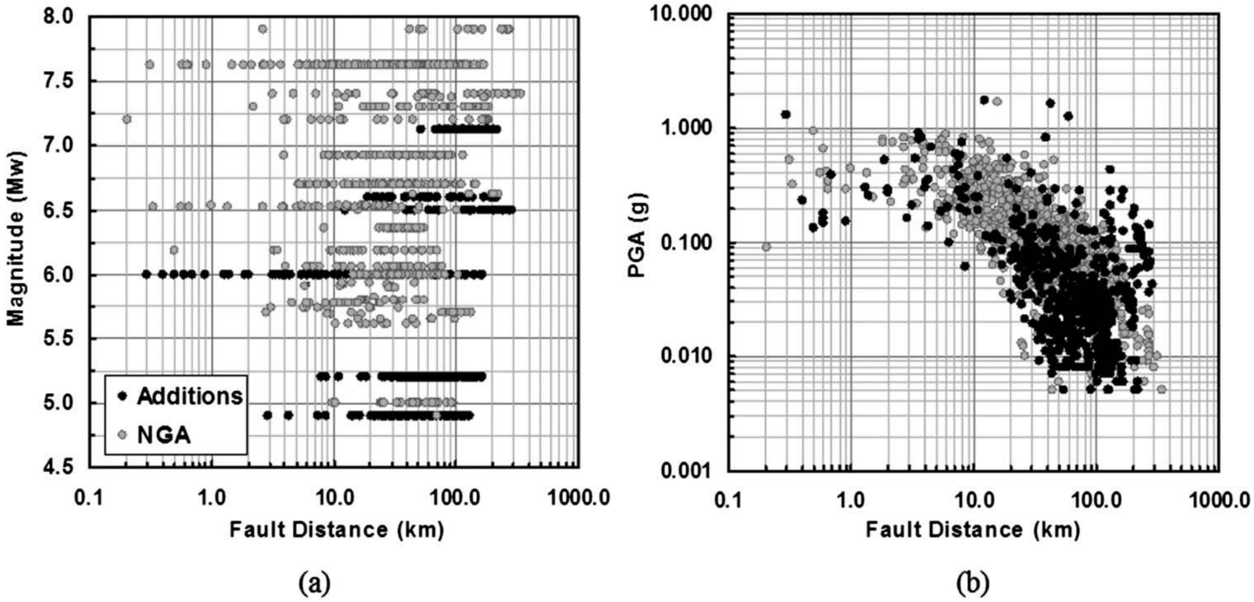


Figure 2-99. Earthquake data distribution with respect to (a) moment magnitude and (b) PGA of records in the database.

2.13.6 MATLAB Code

```
% by Kathryn A. Gunberg 4/14/09
% Virginia Tech
% kgunberg@vt.edu
%
% Graizer and Kalkan attenuation equation, 2007 and 2009
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T              = Period (sec), 0 for PGA
% M              = Moment magnitude
% Rrup           = Closest distance to fault plane (km)
% F              = 1 for strike-slip, 1.28 for reverse
% Vs30           = Shear wave velocity in upper 30 m (m/s)
% D1             = Basin Effect: 0.35 for basin effect
%                  (sediment depth > 1 km),0.65 otherwise
% --------------------------------------------------------------------------
% Output Variables
% Sa:            Median spectral acceleration prediction (g)
% sigma:         logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = GK_2009(T,M,F,Rrup,Vs30,D1)
period=[0.010   0.020   0.022   0.025   0.029   0.030   0.032   0.035   0.036   0.040   0.042...
        0.044   0.045   0.046   0.048   0.050   0.055   0.060   0.065   0.067   0.070   0.075...
        0.080   0.085   0.090   0.095   0.100   0.110   0.120   0.130   0.133   0.140   0.150...
        0.160   0.170   0.180   0.190   0.200   0.220   0.240   0.250   0.260   0.280   0.290...
        0.300   0.320   0.340   0.350   0.360   0.380   0.400   0.420   0.440   0.450   0.460...
        0.480   0.500   0.550   0.600   0.650   0.667   0.700   0.750   0.800   0.850   0.900...
        0.950   1.000   1.100   1.200   1.300   1.400   1.500   1.600   1.700   1.800   1.900...
        2.000   2.200   2.400   2.500   2.600   2.800   3.000   3.200   3.400   3.500   3.600...
        3.800   4.000   4.200   4.400   4.600   4.800   5.000];
siga = [0.036   0.044   0.053   0.063   0.073   0.081   0.088   0.096   0.102   0.108   0.114...
        0.119   0.125   0.132   0.139   0.145   0.152   0.160   0.167   0.176   0.184   0.192...
        0.198   0.202   0.205   0.209   0.212   0.216   0.217   0.219   0.221   0.223   0.226...
        0.230   0.230   0.231   0.236   0.242   0.249   0.257   0.266   0.275   0.286   0.296...
        0.305   0.314   0.323   0.328   0.334   0.342   0.348   0.353   0.359   0.365   0.370...
        0.376   0.383   0.391   0.401   0.413   0.426   0.441   0.454   0.467   0.477   0.491...
        0.506   0.519   0.531   0.542   0.553   0.564   0.577   0.591   0.602   0.615   0.631...
        0.646   0.661   0.679   0.704   0.728   0.749   0.754   0.754   0.753   0.754   0.756...
        0.759   0.755   0.751   0.758   0.765   0.779   0.801];
sigb = [0.544   0.540   0.540   0.541   0.542   0.543   0.544   0.546   0.547   0.549   0.550...
        0.551   0.551   0.550   0.549   0.549   0.549   0.549   0.548   0.547   0.547   0.548...
        0.549   0.549   0.550   0.550   0.551   0.553   0.555   0.557   0.560   0.563   0.567...
        0.571   0.575   0.579   0.585   0.591   0.597   0.603   0.609   0.615   0.621   0.626...
        0.630   0.633   0.636   0.637   0.638   0.640   0.641   0.641   0.641   0.643   0.645...
        0.648   0.651   0.653   0.656   0.659   0.662   0.667   0.670   0.672   0.671   0.672...
        0.675   0.675   0.675   0.676   0.675   0.675   0.676   0.683   0.687   0.695   0.705...
        0.715   0.726   0.740   0.764   0.783   0.796   0.794   0.788   0.781   0.776   0.771...
        0.769   0.759   0.750   0.753   0.758   0.765   0.781];
% Coefficients for PGA
c1 =  0.14;
c2 = -6.25;
c3 =  0.37;
c4 =  2.237;
c5 = -7.542;
c6 = -0.125;
c7 =  1.19;
c8 = -6.15;
c9 =  0.525;
bv = -0.24;
VA = 484.5;
R1 = 100;
A  = F * (c1*atan(M + c2) + c3);
R0 = c4*M + c5;
D0 = c6*cos(c7*(M + c8)) + c9;
G1 = log(A);
G2 = -0.5*log((1-Rrup/R0)^2 + 4*D0^2*(Rrup/R0));
G3 = -0.5*log((1-sqrt(Rrup/R1))^2 + 4*D1^2*sqrt(Rrup/R1));
```

```
G4 = bv*log(Vs30/VA);
PGA = exp(G1 + G2 + G3 + G4);
sigmaPGA = 0.552;
if T == 0
    Sa = PGA;
    sigma = sigmaPGA;
    return
end
% Coefficients for SA_norm
m1   = -0.0012;
m2   = -0.4087;
m3   =  0.0006;
m4   =  3.63;
a1   =  0.017;
a2   =  1.27;
a3   =  0.0001;
Dsp  =  0.75;
t1   =  0.0022;
t2   =  0.63;
t3   = -0.0005;
t4   = -2.1;
s1   =  0.001;
s2   =  0.077;
s3   =  0.3251;
zeta =  1.5;
mu  = m1*Rrup + m2*M + m3*Vs30 + m4;
I   = (a1*M + a2)*exp(a3*Rrup);
S   = s1*Rrup - (s2*M + s3);
Tsp = t1*Rrup + t2*M + t3*Vs30 + t4;
F1 = I*exp(-1/2*((log(T) + mu)/S)^2);
F2 = ((1 - (T/Tsp)^zeta)^2 + 4*Dsp^2*(T/Tsp)^zeta)^(-1/2);
Sa_norm = F1 + F2;
Sa = PGA*Sa_norm;
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi  = min(period(find(period>T)));
    i_low = find(abs((period - T_low)) < 0.0001); % Identify the period index
    i_hi  = find(abs((period - T_hi))  < 0.0001); % Identify the period index
    sigma = sigb(i_hi) - (T_hi-T)*((sigb(i_hi) - sigb(i_low))/(T_hi - T_low));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    sigma = sigb(i);
end
```

3 SHALLOW STABLE TECTONIC REGIONS

The attenuation relations in this section apply to shallow stable tectonic regions such as the central and eastern United States (CEUS).

Table 3-1. List of parameters used in this section by each relationship. Definitions below.

Input Parameter	TAS97	SCAGS01	C03	SGD03 & SGL04	AB06	A08
T	●	●	●	●	●	●
M	●	●	●	●	●	●
C		●				
G	●			●		
rift		●				
F						●
R_{rup}	●		●		●	
R_{jb}	●	●		●		●
S					●	
V_{S30}					●	●
SE	●			●		
CM				●		
SD_{level}				●		
SD_{type}				●		
SAF					●	
SMM						●

T – Period (sec), PGA, PGV or PGD
M – Moment magnitude
C – Component indicator (0 for horizontal, 1 for vertical)
G – Crustal region indicator (1 for mid-continent, 0 for gulf coast, 2 for South Carolina)
rift – Rift zone indicator (1 for rift zone, 0 for nonrift zone)
F – Fault type indicator
R_{rup} – Closest distance to rupture plane (km)
R_{jb} – Joyner-Boore distance (i.e. closest horizontal distance to surface projection of fault rupture) (km)
S – Soil condition indicator (0 for rock: V_{S30} > 2000 m/s or NEHRP site class A, 1 for soil)
V_{S30} – Shear wave velocity (m/s) averaged over top 30 m if VS30 < 2000 m/s
SE – Saturation effect indicator (1 to include saturation effect, 0 otherwise)
CM – Corner model type indicator (1 for single, 2 for double)
SD_{level} – Stress drop level indicator (0 for low, 1 for medium, 2 for high)
SD_{type} – Stress drop type indicator (0 for variable, 1 for constant)
SAF – Stress Adjustment Factor (enter 0 for stress drop of 140 bars, or log(stress drop/140)/log(2))
SMM – Small-to-moderate magnitude adjustment

Table 3-2. List of parameters provided by relationships in this section. Definitions below.

Output Parameter	TAS97	SCAGS01	C03	SGD03 & SGL04	AB06	A08
PSA	●	●	●	●	●	●
PGA	●	●	●	●	●	●
PGV				●	●	●

PSA – 5%-damped pseudo-spectral acceleration (g)
PGA – Peak ground acceleration (g)
PGV – Peak ground velocity (cm/s)

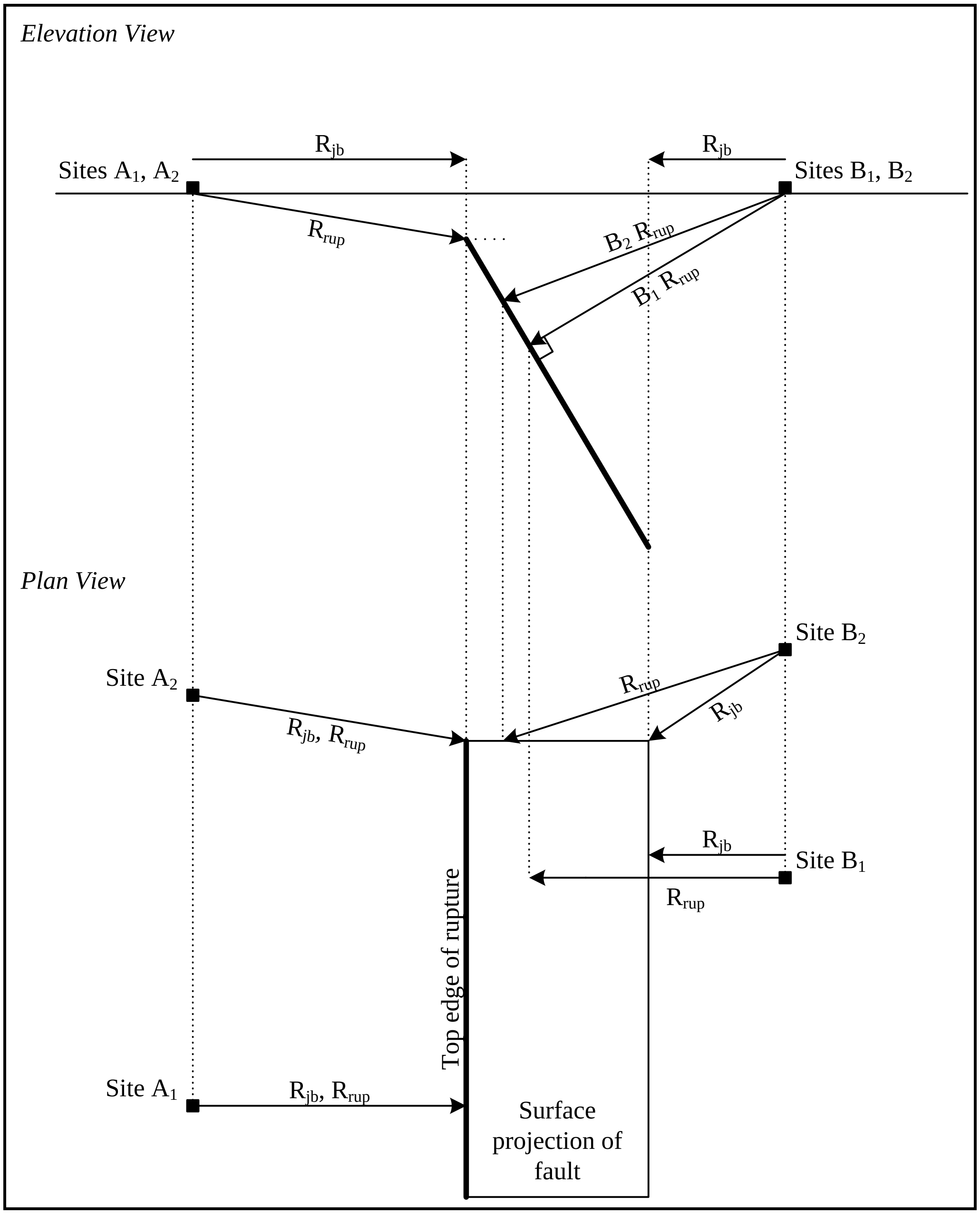


Figure 3-1. Fault geometry graphical definitions.

3.1 Toro, Abrahamson and Schneider - 1997

3.1.1 References

Toro, G. R., N. A. Abrahamson, and J. F. Schneider (1997). Model of Strong Ground Motions from Earthquakes in Central and Eastern North America: Best Estimates and Uncertainties, *Seismological Research Letters* **68**, 41-57.

Toro, G. R. (2002). Modification of the Toro et al. (1997) Attenuation Equations for Large Magnitudes and Short Distances, Risk Engineering, Inc.

Toro, G. R. (2009). Risk Engineering, Inc., Acton MA. Written communication.

3.1.2 Abstract

Using the predictions of a stochastic ground-motion model, empirical ground-motion attenuation equations were developed for two crustal regions and with Toro (2002) can include the effect of saturation. The model predicts peak ground acceleration (PGA, in g) and 5%-damped spectral values (in g) for frequencies ranging from 0.5 to 35 Hz. The model is applicable for earthquakes between M5 and M8, distances up to 500 km, and hard rock conditions (shear wave velocity of 1830 m/s or greater at the surface).

3.1.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA
- **M** – Moment magnitude
- G – 1 for mid-continent crustal region, 0 for gulf crustal region
- R_{rup} – Shortest distance to the rupture plane (km)
- R_{jb} – Joyner-Boore distance (km)
- SE – 1 for saturation effect, 0 for no saturation

$$\ln(Sa) = c_1 + c_2(M-6) + c_3(M-6)^2 - c_4\ln(R_M) - (c_5 - c_4)\max\left[\ln\left(\frac{R_M}{100}\right), 0\right] - c_6 R_M$$

where:

$$R_M = \sqrt{{R_{jb}}^2 + {c_7}^2}$$

With saturation:

$$\ln(Sa) = 0.2\ln\big(Sa(R_M)\big) + 0.4\ln\Big(Sa\big(R_{M,empirical}\big)\Big) + 0.4\ln\Big(Sa\big(R_{M,modeling}\big)\Big)$$

where:

$$R_{M,empirical} = \sqrt{{R_{jb}}^2 + {c_7}^2[\exp(-1.25 + 0.227M)]^2}$$

$$R_{M,modeling} = R_{rup} + 0.089\exp(0.6M)$$

Standard Deviation

$$\sigma_T = \sqrt{\sigma_a(M, R_{jb})^2 + \sigma_e(M)^2}$$

where:

$$\sigma_a(M, R) = \sqrt{\sigma_{a,modeling+\Delta\sigma}(M)^2 + \sigma_{a,depth+Q+\kappa}(R_{jb})^2}$$

$$\sigma_e(M) = \begin{cases} 0.34 + 0.06(M-6) & for\ T = 2\ sec \\ 0.36 + 0.07(M-6) & for\ T \leq 1\ sec\ and\ PGA \end{cases}$$

Coefficients

Table 3-3. Coefficients for regional and magnitude scale combinations.

Mid-Continent, Moment Magnitude Scale

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7
2.0	-0.74	1.86	-0.31	0.92	0.46	0.0017	6.9
1.0	0.09	1.42	-0.20	0.90	0.49	0.0023	6.8
0.4	1.07	1.05	-0.10	0.93	0.56	0.0033	7.1
0.2	1.73	0.84	0.00	0.98	0.66	0.0042	7.5
0.1	2.37	0.81	0.00	1.10	1.02	0.0040	8.3
0.04	3.68	0.80	0.00	1.46	1.77	0.0013	10.5
0.0286	4.00	0.79	0.00	1.57	1.83	0.0008	11.1
0	2.20	0.81	0.00	1.27	1.16	0.0021	9.3

Gulf Coast, Moment Magnitude Scale

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7
2.0	-0.81	1.72	-0.26	0.74	0.71	0.0025	6.6
1.0	0.24	1.31	-0.15	0.79	0.82	0.0034	7.2
0.4	1.64	1.06	-0.08	0.99	1.27	0.0036	8.9
0.2	3.10	0.92	0.00	1.34	1.95	0.0017	11.4
0.1	5.08	1.00	0.00	1.87	2.52	0.0002	14.1
0.04	5.19	0.91	0.00	1.96	1.96	0.0004	12.9
0.0286	4.81	0.91	0.00	1.89	1.80	0.0008	11.9
0	2.91	0.92	0.00	1.49	1.61	0.0014	10.9

Table 3-4. Coefficients for standard deviation equations. For values in between, use linear interpolation.

$\sigma_{a,modeling+\Delta\sigma}$

T (sec)	M-based equations		
	M 5	M 5.5	M 8
2.0	0.61	0.62	0.66
1.0	0.63	0.64	0.97
0.4	0.63	0.68	0.64
0.2	0.60	0.64	0.56
0.1	0.59	0.61	0.50
0.04	0.62	0.63	0.50
0.0286	0.62	0.63	0.50
0	0.55	0.59	0.50

$\sigma_{a,depth+Q+K}$

T (sec)	Mid-Continent		Gulf Coast	
	< 5 km	> 20 km	< 5 km	> 20 km
2.0	0.45	0.12	0.54	0.39
1.0	0.45	0.12	0.51	0.39
0.4	0.45	0.12	0.50	0.34
0.2	0.45	0.12	0.50	0.33
0.1	0.50	0.17	0.53	0.38
0.04	0.57	0.29	0.63	0.47
0.0286	0.62	0.35	0.68	0.47
0	0.54	0.20	0.48	0.30

3.1.4 Calibration Plots

(NOTE: Fault orientation and type, and depth to top of rupture are given for calculation of R_{rup} for saturation case.)

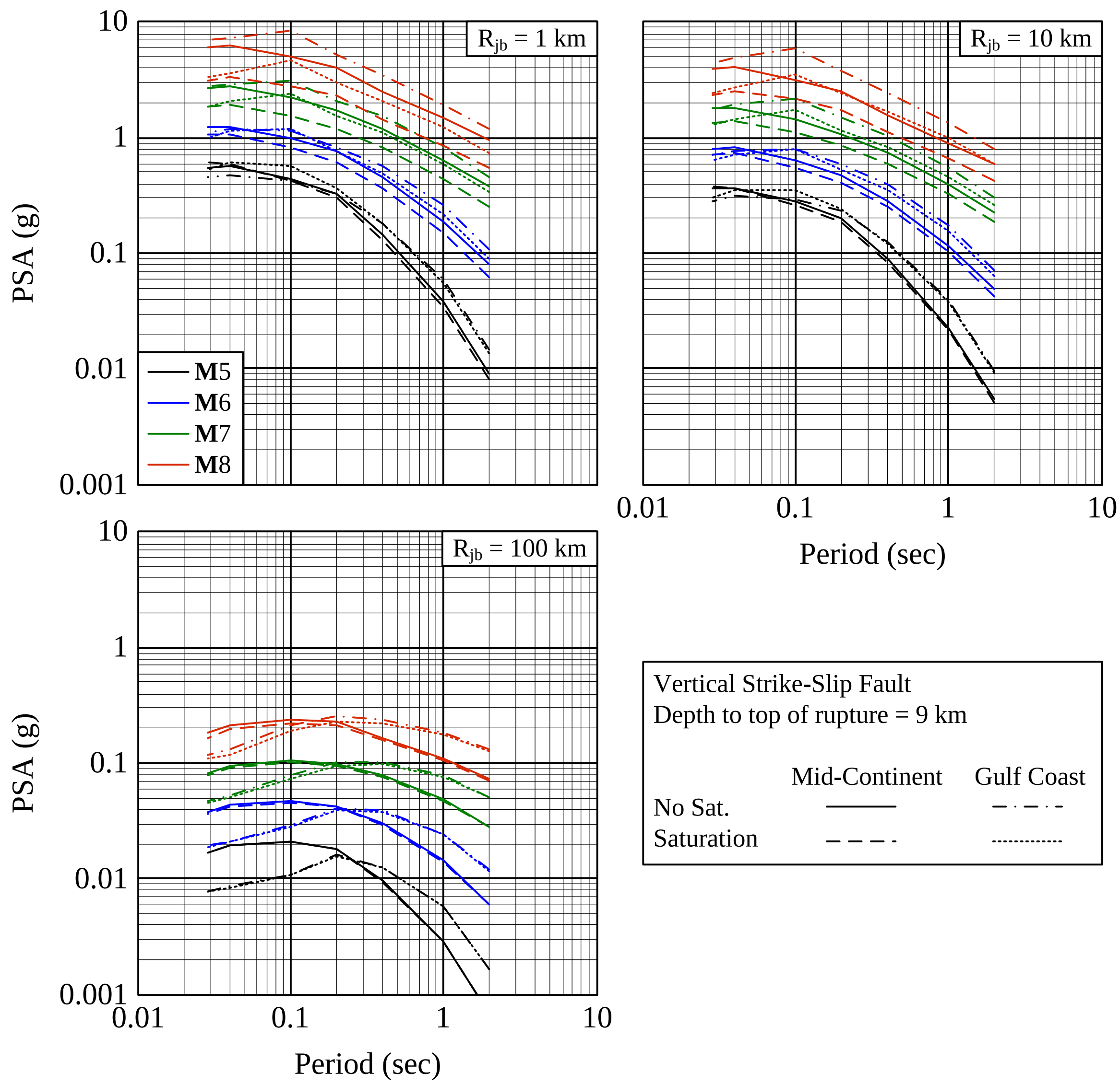


Figure 3-2. Shows variation in PSA for given parameters.

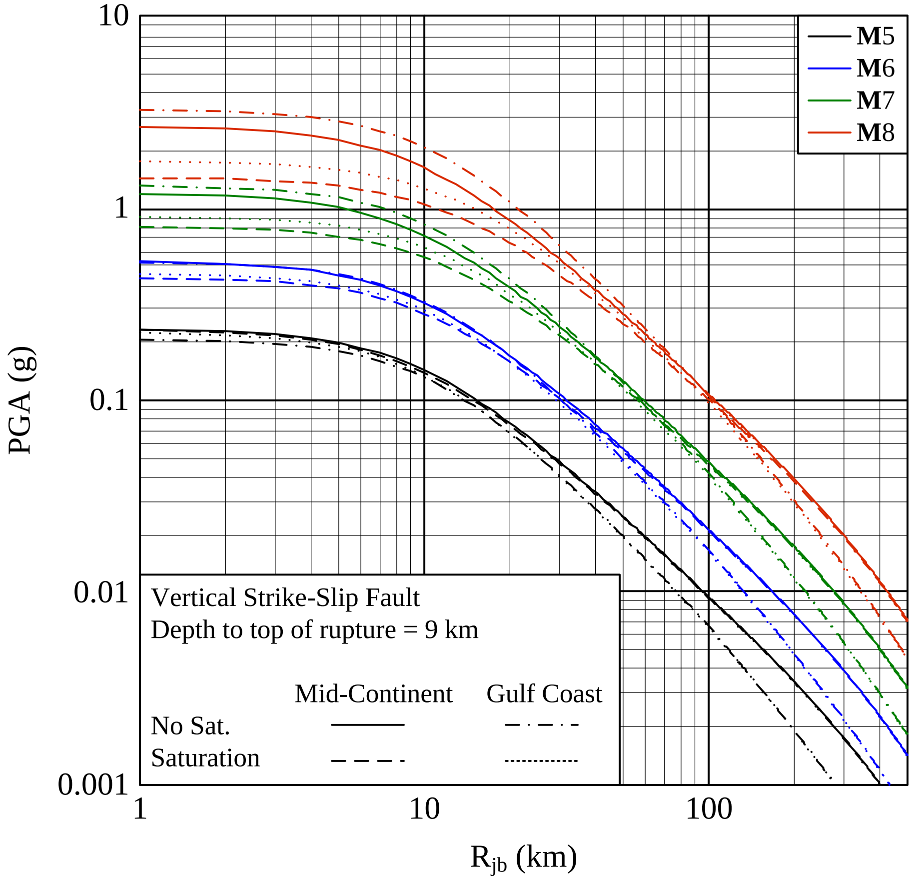


Figure 3-3. Shows variation in PGA for given input parameters.

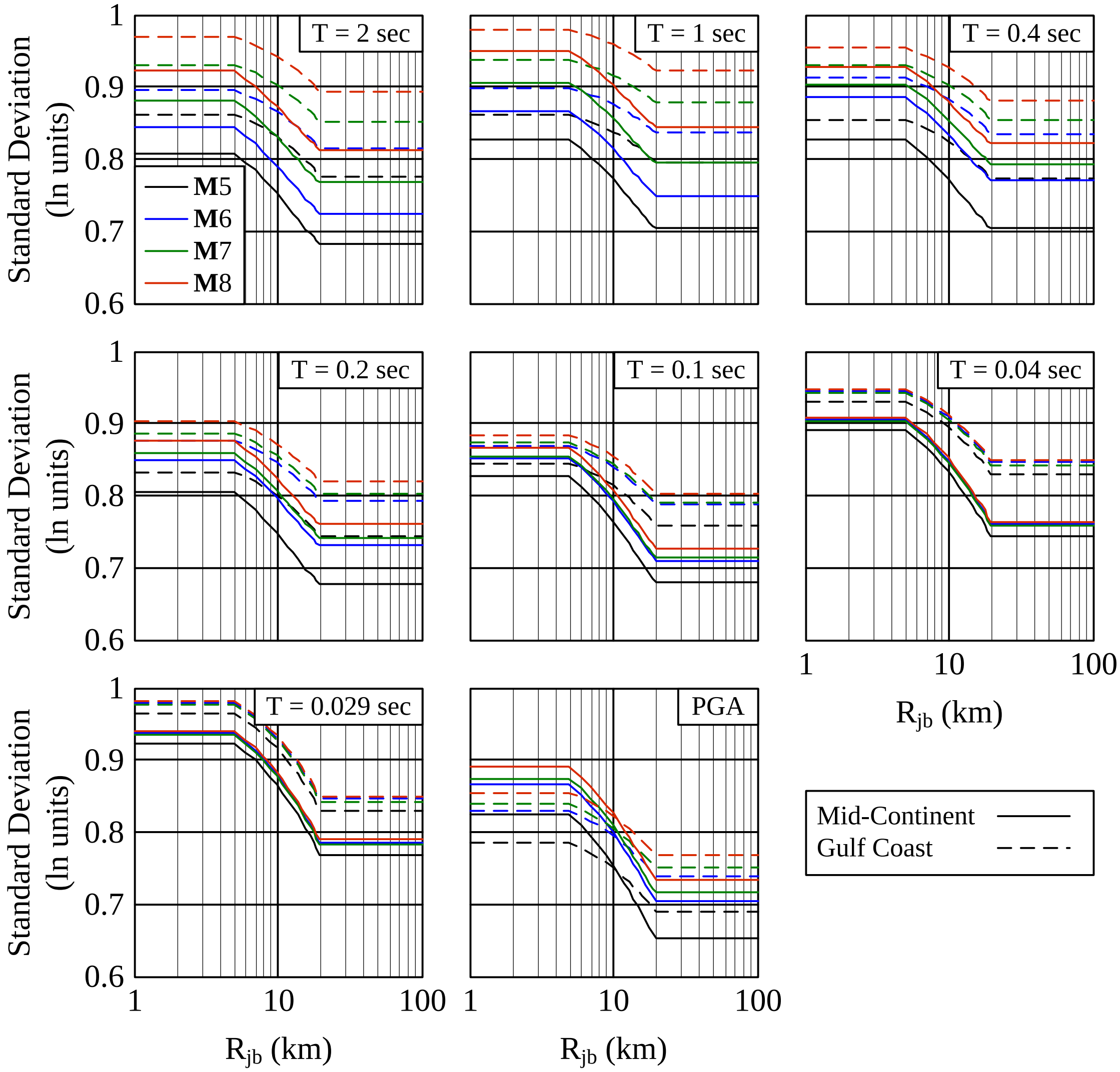


Figure 3-4. Shows variation in standard deviation. Note that effect of saturation is not significant.

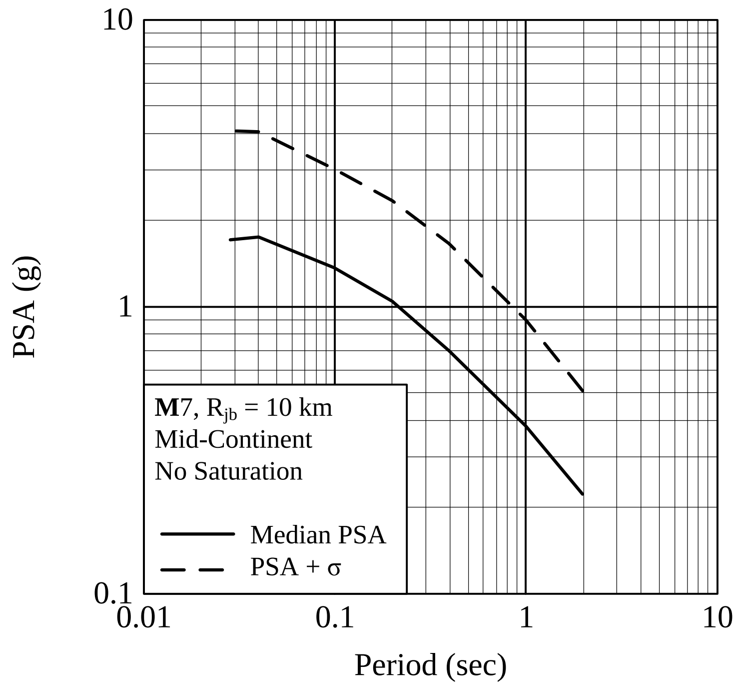


Figure 3-5. Example of application of median PSA plus one standard deviation.

3.1.5 Database

The database for this attenuation equation is based on predictions of a stochastic ground motion model. No graphs were provided.

3.1.6 MATLAB Code

```
% by Kathryn A. Gunberg 4/13/09
% Virginia Tech
% kgunberg@vt.edu
%
% Toro, Abrahamson & Schneider attenuation equation, 1997
%
% Includes update by Toro 2002
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T             = Period (sec), 0 for PGA
% M             = Moment magnitude
% G             = Crustal region: 1 for mid-continent, 0 for gulf coast
% Rrup          = Shortest distance to the rupture plane (km)
%                 (doesn't matter for SE = 0)
% Rjb           = Joyner-Boore distance (km)
% SE            = Saturation effect: 1 to include, 0 otherwise
% ---------------------------------------------------------------------------
% Output Variables
% Sa:           Median spectral acceleration prediction (g)
% sigma:        logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = TAS_1997(T,M,G,Rrup,Rjb,SE)
% Coefficients
period =   [2       1       0.4     0.2     0.1     0.04    1/35    0];
Mlow = 5;
Mmid = 5.5;
Mhi  = 8;
sigaMlow = [0.61    0.63    0.63    0.60    0.59    0.62    0.62    0.55];
sigaMmid = [0.62    0.64    0.68    0.64    0.61    0.63    0.63    0.59];
sigaMhi  = [0.66    0.67    0.64    0.56    0.50    0.50    0.50    0.50];
if G == 1
    c1 =   [-0.74   0.09    1.07    1.73    2.37    3.68    4.00    2.20];
    c2 =   [1.86    1.42    1.05    0.84    0.81    0.80    0.79    0.81];
    c3 =   [-0.31   -0.20   -0.10   0       0       0       0       0];
    c4 =   [0.92    0.90    0.93    0.98    1.10    1.46    1.57    1.27];
    c5 =   [0.46    0.49    0.56    0.66    1.02    1.77    1.83    1.16];
    c6 =   [0.0017  0.0023  0.0033  0.0042  0.0040  0.0013  0.0008  0.0021];
    c7 =   [6.9     6.8     7.1     7.5     8.3     10.5    11.1    9.3];
    sigaDlow = [0.45    0.45    0.45    0.45    0.50    0.57    0.62    0.54];
    sigaDhi  = [0.12    0.12    0.12    0.12    0.17    0.29    0.35    0.20];
else
    c1 =   [-0.81   0.24    1.64    3.10    5.08    5.19    4.81    2.91];
    c2 =   [1.72    1.31    1.06    0.92    1.00    0.91    0.91    0.92];
    c3 =   [-0.26   -0.15   -0.08   0       0       0       0       0];
    c4 =   [0.74    0.79    0.99    1.34    1.87    1.96    1.89    1.49];
    c5 =   [0.71    0.82    1.27    1.95    2.52    1.96    1.80    1.61];
    c6 =   [0.0025  0.0034  0.0036  0.0017  0.0002  0.0004  0.0008  0.0014];
    c7 =   [6.6     7.2     8.9     11.4    14.1    12.9    11.9    10.9];
    sigaDlow = [0.54    0.51    0.50    0.50    0.53    0.63    0.68    0.48];
    sigaDhi  = [0.39    0.39    0.34    0.33    0.38    0.47    0.47    0.30];
end
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = TAS_1997(T_low,M,G,Rrup,Rjb,SE);
    [sa_hi, sigma_hi] = TAS_1997(T_hi,M,G,Rrup,Rjb,SE);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    RM_nosat = sqrt(Rjb^2 + c7(i)^2);
    Sa_nosat = exp(c1(i) + c2(i)*(M-6) + c3(i)*(M-6)^2 - c4(i)*log(RM_nosat) - ...
```

```
        (c5(i)-c4(i))*max(log(RM_nosat/100),0) - c6(i)*RM_nosat);
    if SE == 0
        Sa = Sa_nosat;
    else
        RM_emp = sqrt(Rjb^2 + c7(i)^2*exp(-1.25+0.227*M)^2);
        Sa_emp = exp(c1(i) + c2(i)*(M-6) + c3(i)*(M-6)^2 - c4(i)*log(RM_emp) - ...
            (c5(i)-c4(i))*max(log(RM_emp/100),0) - c6(i)*RM_emp);
        RM_mod = Rrup + 0.089*exp(0.6*M);
        Sa_mod = exp(c1(i) + c2(i)*(M-6) + c3(i)*(M-6)^2 - c4(i)*log(RM_mod) - ...
            (c5(i)-c4(i))*max(log(RM_mod/100),0) - c6(i)*RM_mod);
        Sa = 0.2*Sa_nosat + 0.4*Sa_emp + 0.4*Sa_mod;
    end
    if M < Mlow
        sigaM = sigaMlow(i);
    elseif M < Mmid
        sigaM = sigaMmid(i) - (Mmid-M)*(sigaMmid(i)-sigaMlow(i))/(Mmid-Mlow);
    elseif M < Mhi
        sigaM = sigaMhi(i) - (Mhi-M)*(sigaMhi(i)-sigaMmid(i))/(Mhi-Mmid);
    else
        sigaM = sigaMhi(i);
    end
    if Rjb < 5
        sigaD = sigaDlow(i);
    elseif Rjb > 20
        sigaD = sigaDhi(i);
    else
        sigaD = sigaDhi(i) - (20-Rjb)*(sigaDhi(i)-sigaDlow(i))/(20-5);
    end
    siga = sqrt(sigaM^2 + sigaD^2);
    if T == 2
        sige = 0.34 + 0.06*(M-6);
    else
        sige = 0.36 + 0.07*(M-6);
    end
    sigma = sqrt(siga^2 + sige^2);
end
```

3.2 Somerville, Collins, Abrahamson, Graves and Saikia – 2001

3.2.1 Reference

Somerville, P., N. Collins, N. Abrahamson, R. Graves, and C. Saikia (2001). "Ground Motion Attenuation Relations for the Central and Eastern United States." URS Group, Inc.

3.2.2 Abstract

Using generated suites of ground motion time histories from source scaling relations derived from slip models of three recent earthquakes in eastern Canada, an empirical ground-motion model for the average horizontal and vertical components were developed. The model predicts 5%-damped spectral values (in g) for periods ranging from 0.01 to 4 s (for peak ground acceleration, PGA, use 0.01 sec). The model is applicable for earthquakes between M6.0 and M7.5 for reverse faults in rifted and nonrifted zones, distances up to 500 km, and hard rock conditions.

3.2.3 Attenuation Relationship

The spectral acceleration is a function of:

T	– Period (sec), use 0.01 or 0 for PGA
M	– Moment magnitude
C	– Component indicator: 1 for vertical and 0 for horizontal
rift	– Rift zone indicator: 1 for rift zones, 0 for nonrift zones
R_{jb}	– Joyner-Boore distance (km)

$$\ln(Sa) = \begin{cases} c_1 + c_2(M - m_1) + c_3 \ln R + c_4(M - m_1)\ln R \\ \quad + c_5 R_{jb} + c_7(8.5 - M)^2 & for\ R_{jb} < r_1 \\ c_1 + c_2(M - m_1) + c_3 \ln R_1 + c_4(M - m_1)\ln R \\ \quad + c_5 R_{jb} + c_6(\ln R - \ln R_1) + c_7(8.5 - M)^2 & for\ R_{jb} \geq r_1 \end{cases}$$

where:

$$m_1 = 6.4$$
$$r_1 = 50\ km$$
$$h = 6km$$
$$R = \sqrt{{R_{jb}}^2 + h^2}$$
$$R_1 = \sqrt{{r_1}^2 + h^2}$$

Total standard deviation is given in the tables.

Coefficients

Table 3-5. Coefficients of ground motion attenuation relationship.

Nonrift Zone - Horizontal

Period	c_1	c_2	c_3	c_4	c_5	c_6	c_7	σ_{Total}
0.01	0.418	0.808	-0.728	0.0651	-0.00601	-0.301	0.0000	0.587
0.04	1.099	0.808	-0.728	0.0651	-0.00601	-0.301	0.0000	0.592
0.10	1.071	0.808	-0.728	0.0651	-0.00601	-0.301	0.0000	0.595
0.20	0.978	0.808	-0.728	0.0651	-0.00601	-0.301	0.0000	0.611
0.40	0.851	0.808	-0.728	0.0651	-0.00538	-0.423	-0.0518	0.602
1.00	-0.139	0.808	-0.739	0.0651	-0.00398	-0.659	-0.1020	0.693
2.00	-0.932	0.808	-0.754	0.0651	-0.00318	-0.702	-0.1400	0.824
4.00	-2.080	0.808	-0.686	0.0651	-0.00156	-0.762	-0.1956	0.909

Rift Zone - Horizontal

Period	c_1	c_2	c_3	c_4	c_5	c_6	c_7	σ_{Total}
0.01	0.239	0.805	-0.679	0.0861	-0.00498	-0.477	0.0000	0.587
0.04	0.926	0.805	-0.679	0.0861	-0.00498	-0.477	0.0000	0.592
0.10	0.888	0.805	-0.679	0.0861	-0.00498	-0.477	0.0000	0.595
0.20	0.793	0.805	-0.679	0.0861	-0.00498	-0.477	0.0000	0.611
0.40	0.622	0.805	-0.664	0.0861	-0.00468	-0.557	-0.0518	0.602
1.00	-0.307	0.805	-0.696	0.0861	-0.00362	-0.755	-0.1020	0.693
2.00	-1.132	0.805	-0.728	0.0861	-0.00221	-0.946	-0.1400	0.824
4.00	-2.282	0.805	-0.671	0.0861	-0.000381	-1.059	-0.1956	0.909

Nonrift Zone - Vertical

Period	c_1	c_2	c_3	c_4	c_5	c_6	c_7	σ_{Total}
0.01	-0.151	0.8535	-0.607	0.0905	-0.00536	-0.490	0.0000	0.618
0.04	0.518	0.8535	-0.607	0.0905	-0.00536	-0.490	0.0000	0.618
0.10	0.505	0.8535	-0.607	0.0905	-0.00536	-0.490	0.0000	0.622
0.20	0.536	0.8535	-0.607	0.0905	-0.00536	-0.490	0.0000	0.635
0.40	0.566	0.8535	-0.682	0.0905	-0.00480	-0.698	0.0000	0.680
1.00	-0.273	0.8535	-0.781	0.0905	-0.00405	-0.658	-0.0115	0.763
2.00	-1.314	0.8535	-0.767	0.0905	-0.00348	-0.570	-0.0240	0.858
4.00	-2.382	0.8535	-0.712	0.0905	-0.00207	-0.490	-0.0565	0.919

Rift Zone - Vertical

Period	c_1	c_2	c_3	c_4	c_5	c_6	c_7	σ_{Total}
0.01	-0.530	0.936	-0.500	0.0746	-0.00436	-0.642	0.0000	0.618
0.04	0.147	0.936	-0.500	0.0746	-0.00436	-0.642	0.0000	0.618
0.10	0.122	0.936	-0.500	0.0746	-0.00436	-0.642	0.0000	0.622
0.20	-0.050	0.936	-0.500	0.0746	-0.00436	-0.642	0.0000	0.635
0.40	-0.222	0.936	-0.512	0.0746	-0.00397	-0.732	0.0000	0.680
1.00	-1.030	0.936	-0.569	0.0746	-0.00357	-0.708	-0.0115	0.763
2.00	-1.693	0.936	-0.705	0.0746	-0.00295	-0.629	-0.0240	0.858
4.00	-2.430	0.936	-0.744	0.0746	-0.00152	-0.614	-0.0565	0.919

3.2.4 Calibration Plots

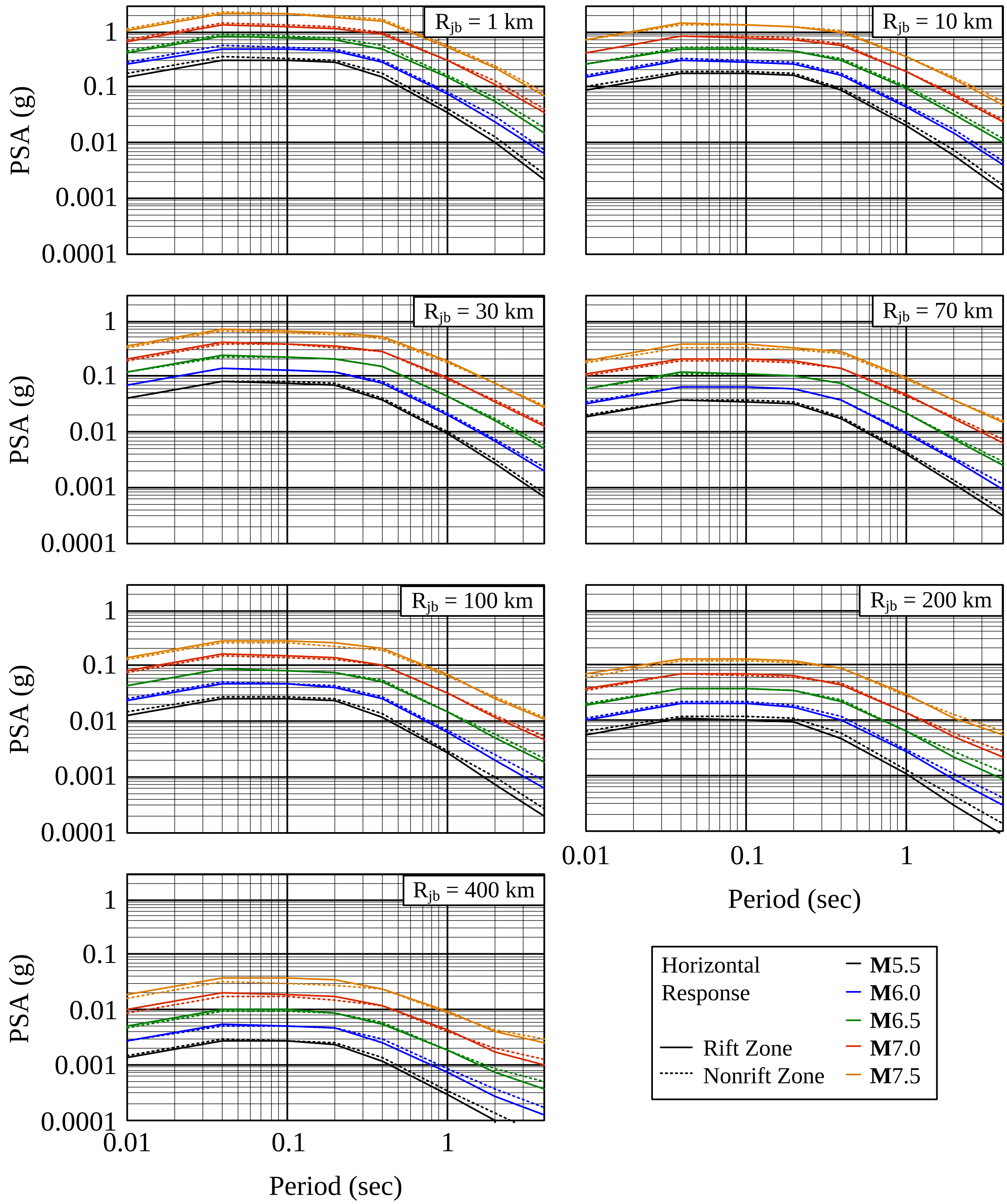


Figure 3-6. Horizontal response in rift and nonrift zones as a function on period for various magnitudes and distances.

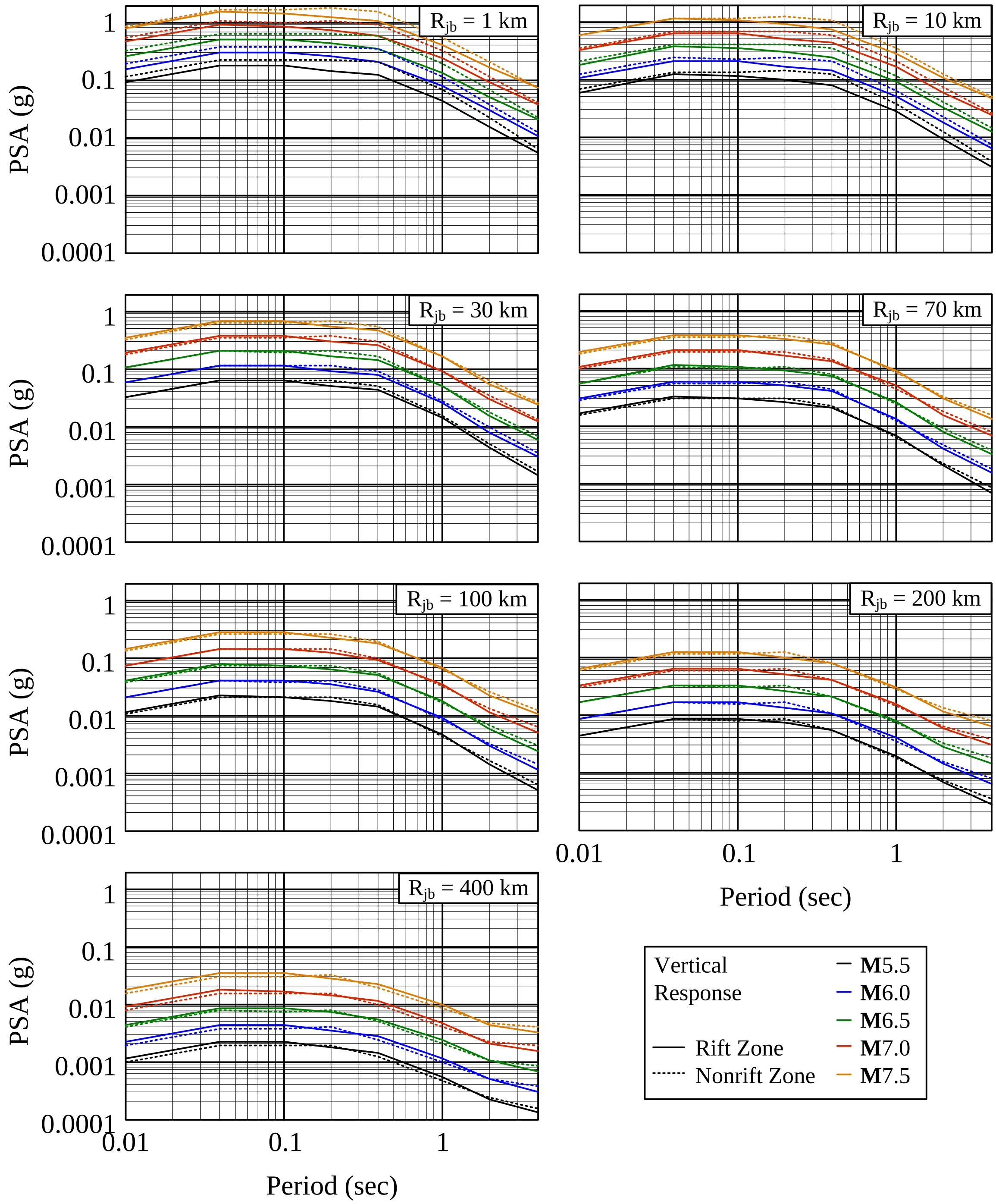


Figure 3-7. Vertical response in rift and nonrift zones as a function on period for various magnitudes and distances.

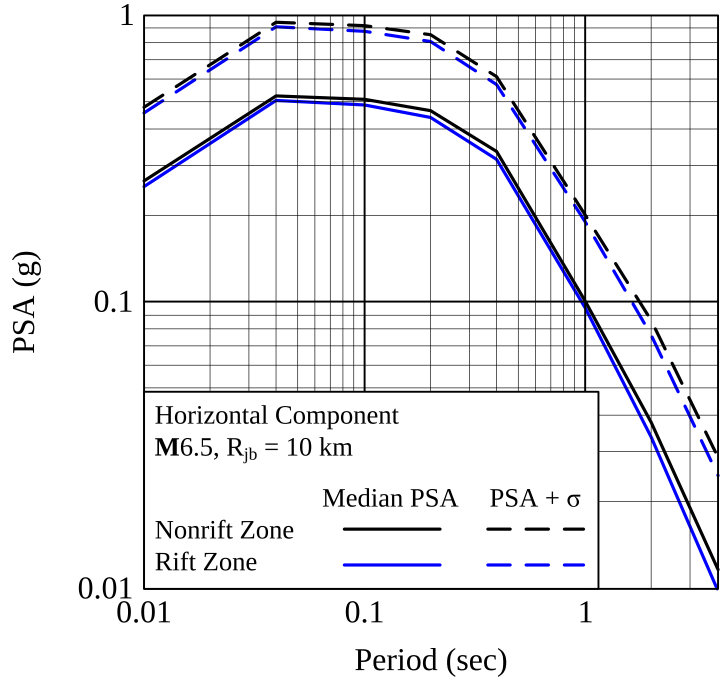


Figure 3-8. Example of application of median PSA plus one standard deviation.

3.2.5 Database

The attenuation relationship was based on simulations using source scaling relations from eastern North America (ENA) earthquakes.

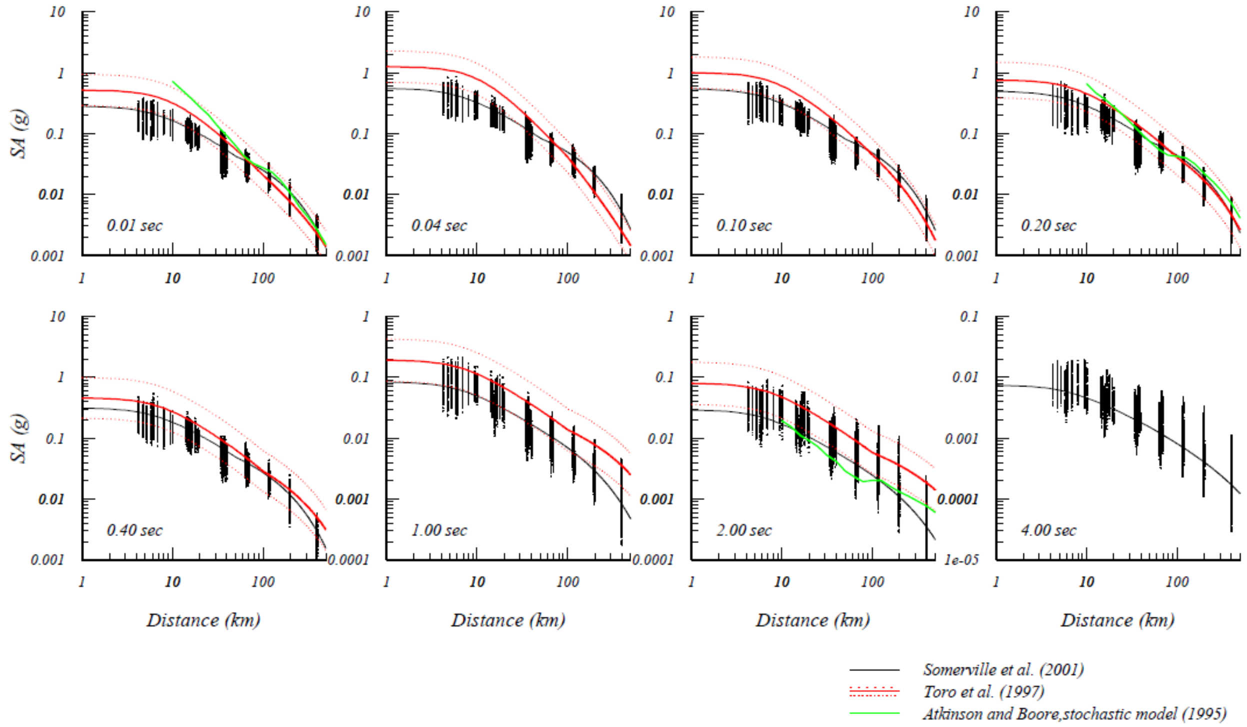


Figure 3-9. Horizontal ground motions model for non-rifted domains in ENA for a suite of periods for **M**6.0. The simulation values on which the model is based are shown by dots. For some periods the model is compared with Toro et al. (1997) and Atkinson and Boore (1995) models.

3.2.6 MATLAB Code

```
% by Kathryn A. Gunberg 2/22/09
% Virginia Tech
% kgunberg@vt.edu
%
% Somerville et al. attenuation equation, 2001
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T             = Period (sec), 0.01 or 0 for PGA
% M             = Moment magnitude
% C             = orientation: 1 vertical, 0 for horizontal
% rift          = 1 for rift zone, 0 for nonrift zone
% Rjb           = Joyner-Boore distance (km)
% ------------------------------------------------------------------------
% Output Variables
% Sa:           Median spectral acceleration prediction (g)
% sigma:        logarithmic standard deviation of SA prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = SCAGS_2001(T,M,C,rift,Rjb)
% Coefficients
R   = sqrt(Rjb^2+6^2);
period = [0.01 0.04 0.10 0.20 0.40 1.00 2.00 4.00];
if C == 0
    c7 =   [0       0       0       0       -0.0518 -0.1020 -0.1400 -0.1956];
    sig =  [0.587   0.592   0.595   0.611   0.602   0.693   0.824   0.909];
    if rift == 0
        c1 =   [0.418   1.099   1.071   0.978   0.851   -0.139  -0.932  -2.080];
        c2 =   [0.808   0.808   0.808   0.808   0.808   0.808   0.808   0.808];
        c3 =   [-0.728  -0.728  -0.728  -0.728  -0.728  -0.739  -0.754  -0.686];
        c4 =   [0.0651  0.0651  0.0651  0.0651  0.0651  0.0651  0.0651  0.0651];
        c5 =   [-0.00601 -0.00601 -0.00601 -0.00601 -0.00538 -0.00398 -0.00318 -0.00156];
        c6 =   [-0.301  -0.301  -0.301  -0.301  -0.423  -0.659  -0.702  -0.762];
    else
        c1 =   [0.239   0.926   0.888   0.793   0.622   -0.307  -1.132  -2.282];
        c2 =   [0.805   0.805   0.805   0.805   0.805   0.805   0.805   0.805];
        c3 =   [-0.679  -0.679  -0.679  -0.679  -0.664  -0.696  -0.728  -0.671];
        c4 =   [0.0861  0.0861  0.0861  0.0861  0.0861  0.0861  0.0861  0.0861];
        c5 =   [-0.00498 -0.00498 -0.00498 -0.00498 -0.00498 -0.00362 -0.00221 -0.000381];
        c6 =   [-0.477  -0.477  -0.477  -0.477  -0.557  -0.755  -0.946  -1.059];
    end
else
    c7 =   [0       0       0       0       0       -0.0115 -0.0240 -0.0565];
    sig =  [0.618   0.618   0.622   0.635   0.680   0.763   0.858   0.919];
    if rift == 0
        c1 =   [-0.151  0.518   0.505   0.536   0.566   -0.273  -1.314  -2.382];
        c2 =   [0.8535  0.8535  0.8535  0.8535  0.8535  0.8535  0.8535  0.8535];
        c3 =   [-0.607  -0.607  -0.607  -0.607  -0.682  -0.781  -0.767  -0.712];
        c4 =   [0.0905  0.0905  0.0905  0.0905  0.0905  0.0905  0.0905  0.0905];
        c5 =   [-0.00536 -0.00536 -0.00536 -0.00536 -0.00480 -0.00405 -0.00348 -0.00207];
        c6 =   [-0.490  -0.490  -0.490  -0.490  -0.698  -0.658  -0.570  -0.490];
    else
        c1 =   [-0.530  0.147   0.122   -0.050  -0.222  -1.030  -1.693  -2.430];
        c2 =   [0.936   0.936   0.936   0.936   0.936   0.936   0.936   0.936];
        c3 =   [-0.500  -0.500  -0.500  -0.500  -0.512  -0.569  -0.705  -0.744];
        c4 =   [0.0746  0.0746  0.0746  0.0746  0.0746  0.0746  0.0746  0.0746];
        c5 =   [-0.00436 -0.00436 -0.00436 -0.00436 -0.00397 -0.00357 -0.00295 -0.00152];
        c6 =   [-0.642  -0.642  -0.642  -0.642  -0.732  -0.708  -0.629  -0.614];
    end
end
% interpolate between periods if neccesary
if T == 0
    T = min(period);
end
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = SCAGS_2001(T_low,M,C,rift,Rjb);
```

```
    [sa_hi, sigma_hi] = SCAGS_2001(T_hi,M,C,rift,Rjb);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    Sa = exp(c1(i) + c2(i)*(M-6.4) + c3(i)*log(min(R,50.3587)) + c4(i)*(M-6.4)*log(R) + ...
        c5(i)*Rjb + c6(i)*(log(max(R,50.3587))-log(50.3587)) + c7(i)*(8.5-M)^2);
    sigma = sig(i);
end
```

3.3 Campbell – 2003

3.3.1 Reference

Campbell, K. W. (2003). Prediction of Strong Ground Motion Using the Hybrid Empirical method and its Use in the Development of Ground-Motion (Attenuation) Relations in Eastern North America, *Bulletin of the Seismological Society of America* **93**, 1012-1033.

3.3.2 Abstract

Using a hybrid empirical method that uses the ratio of stochastic or theoretical ground-motion estimates to adjust empirical ground-motion relations developed for one region to use in another region, an empirical ground-motion model for the average horizontal component was developed. The model predicts model predicts 5%-damped spectral values (in g) for periods ranging from 0.01 to 4 s (for peak ground acceleration, PGA, use 0.01 sec). The model is applicable for earthquakes between M5.0 and M8.2, distances up to 1000 km (most applicable at 70km or less), and hard rock sites (shear-wave velocity of 2800 m/s).

3.3.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0.01 or 0 for PGA
- M – Moment magnitude
- R_{rup} – Closest distance to rupture plane (km)

$$\ln(Sa) = c_1 + f_1(M) + f_2(M, R_{rup}) + f_3(R_{rup})$$

where:

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

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

where:

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

$$f_3(M) = \begin{cases} 0 & for\ R_{rup} \le R_1 \\ c_9(\ln R_{rup} - \ln R_1) & for\ R_1 < R_{rup} \le R_2 \\ c_9(\ln R_{rup} - \ln R_1) + c_{10}(\ln R_{rup} - \ln R_2) & for\ R_{rup} > R_2 \end{cases}$$

where:

$R_1 = 70\ km$
$R_2 = 130\ km$

Standard Deviation

$$\sigma_{\ln Y} = \begin{cases} c_{11} + c_{12}M & for\ M < M_1 \\ c_{13} & for\ M \geq M_1 \end{cases}$$

where:

$$M_1 = 7.16$$

Coefficients

Table 3-6. Regression coefficients.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}
0.010	0.0305	0.633	-0.0427	-1.591	-0.00428	0.000483	0.683	0.416	1.140	-0.873	1.030	-0.0860	0.414
0.020	1.3535	0.630	-0.0404	-1.787	-0.00388	0.000497	1.020	0.363	0.851	-0.715	1.030	-0.0860	0.414
0.030	1.1860	0.622	-0.0362	-1.691	-0.00367	0.000501	0.922	0.376	0.759	-0.922	1.030	-0.0860	0.414
0.050	0.3736	0.616	-0.0353	-1.469	-0.00378	0.000500	0.630	0.423	0.771	-1.239	1.042	-0.0838	0.443
0.075	-0.0395	0.615	-0.0353	-1.383	-0.00421	0.000486	0.491	0.463	0.955	-1.349	1.052	-0.0838	0.453
0.10	-0.1475	0.613	-0.0353	-1.369	-0.00454	0.000460	0.484	0.467	1.096	-1.284	1.059	-0.0838	0.460
0.15	-0.1901	0.616	-0.0478	-1.368	-0.00473	0.000393	0.461	0.478	1.239	-1.079	1.068	-0.0838	0.469
0.20	-0.4328	0.617	-0.0586	-1.320	-0.00460	0.000337	0.399	0.493	1.250	-0.928	1.077	-0.0838	0.478
0.30	-0.6906	0.609	-0.0786	-1.280	-0.00414	0.000263	0.349	0.502	1.241	-0.753	1.081	-0.0838	0.482
0.50	-0.5907	0.534	-0.1379	-1.216	-0.00341	0.000194	0.318	0.503	1.166	-0.606	1.098	-0.0824	0.508
0.75	-0.5429	0.480	-0.1806	-1.184	-0.00288	0.000160	0.304	0.504	1.110	-0.526	1.105	-0.0806	0.528
1.0	-0.6104	0.451	-0.2090	-1.158	-0.00255	0.000141	0.299	0.503	1.067	-0.482	1.110	-0.0793	0.543
1.5	-0.9666	0.441	-0.2405	-1.135	-0.00213	0.000119	0.304	0.500	1.029	-0.438	1.099	-0.0771	0.547
2.0	-1.4306	0.459	-0.2552	-1.124	-0.00187	0.000103	0.310	0.499	1.015	-0.417	1.093	-0.0758	0.551
3.0	-2.2331	0.492	-0.2646	-1.121	-0.00154	0.000084	0.310	0.499	1.014	-0.393	1.090	-0.0737	0.562
4.0	-2.7975	0.507	-0.2738	-1.119	-0.00135	0.000074	0.294	0.506	1.018	-0.386	1.092	-0.0722	0.575

3.3.4 Calibration Plots

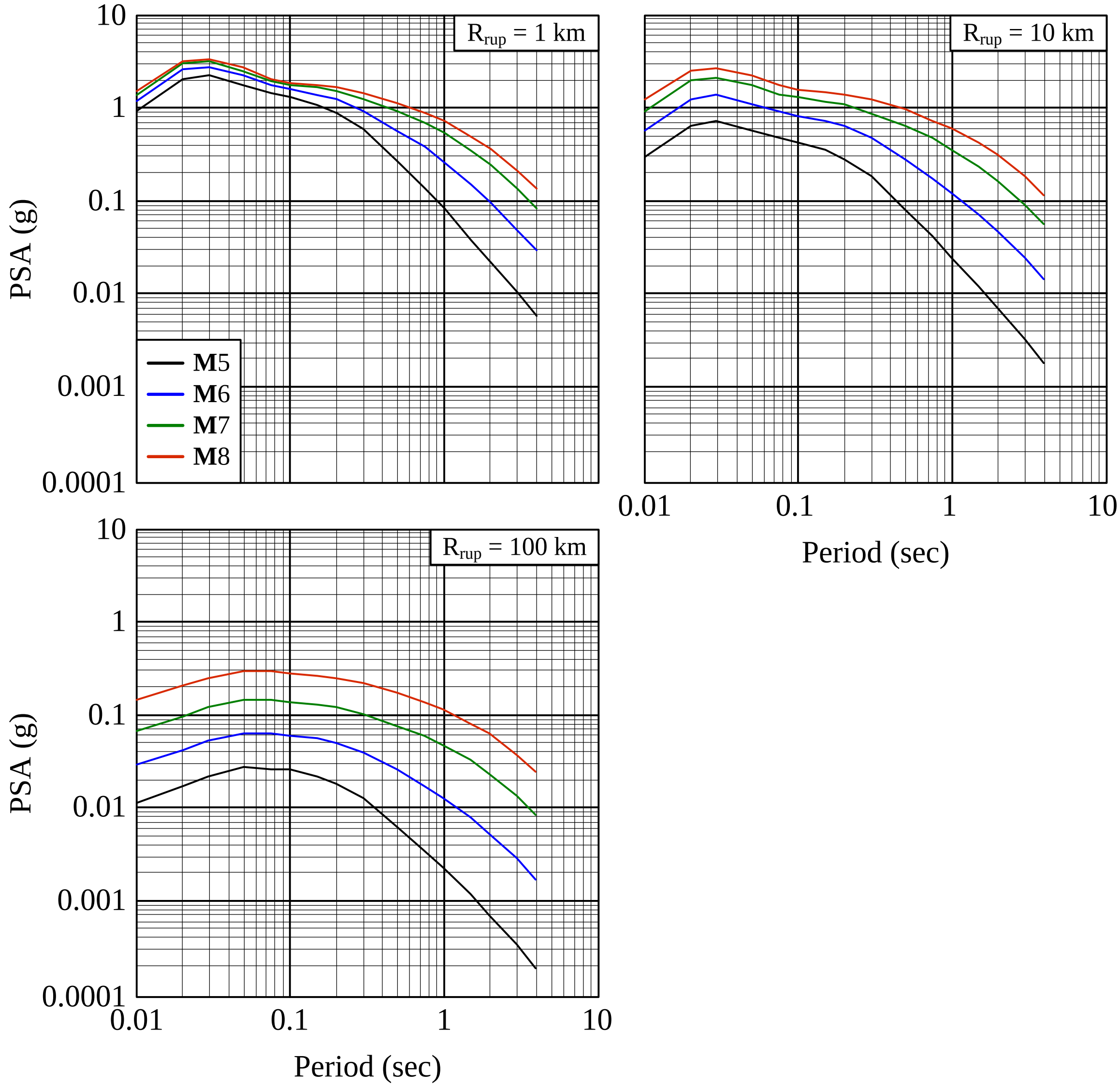


Figure 3-10. PSA as a function of period for various magnitudes and distances.

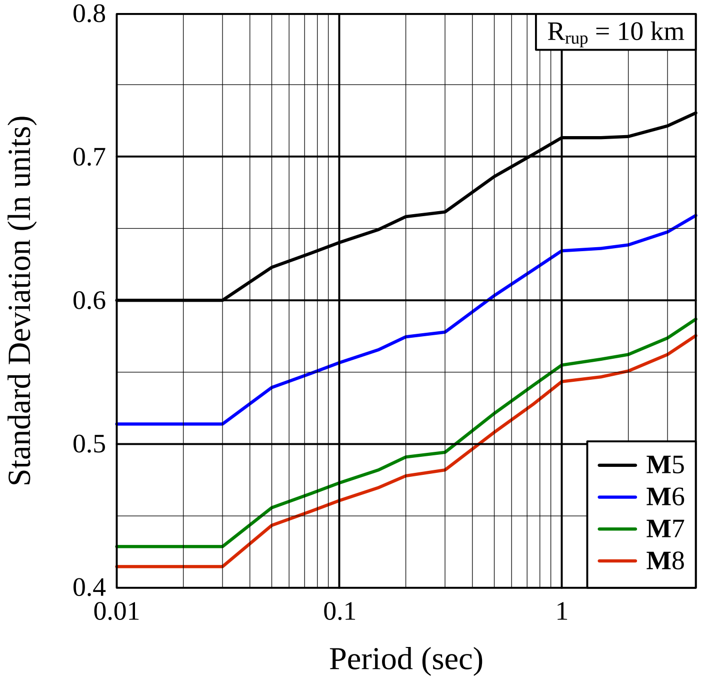


Figure 3-11. Standard deviation as a function of period for different magnitudes at 10 km.

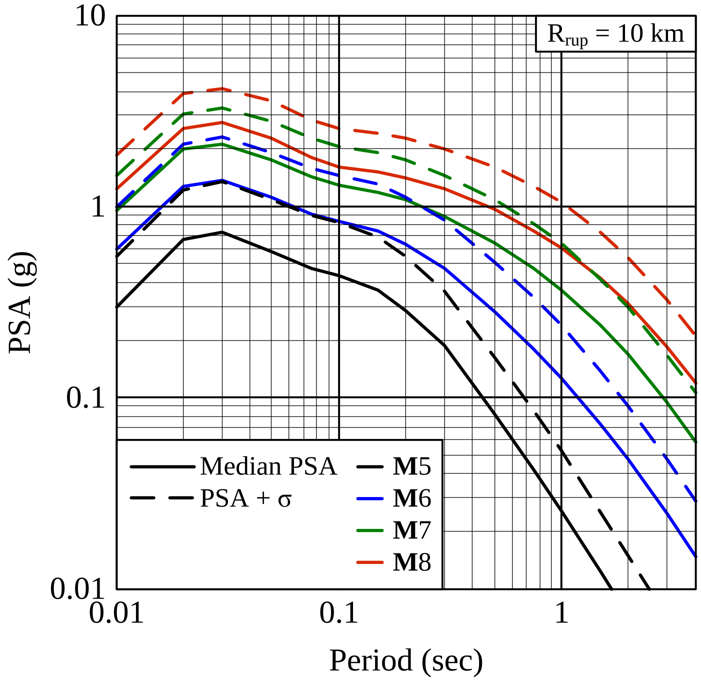


Figure 3-12. Example of application of median PSA plus one standard deviation.

3.3.5 Database

The attenuation relationship is a hybrid empirical method that uses the ratio of stochastic or theoretical ground-motion estimates to adjust empirical ground-motion relations developed for one region to use in another region. The tables below show the parameters used in Western North America (WNA) and Eastern North America (ENA) stochastic Models.

Table 3-7. Seismological parameters used in the WNA and ENA stochastic models.

Parameter	Western North America (WNA)	Eastern North America (ENA)
Source spectrum	Brune ω-square, point source	Brune ω-square, point source
Stress drop, $\Delta\sigma$ (bar)	100	105 (0.05),* 125 (0.25), 150 (0.40), 180 (0.25), 215 (0.05)
Geometric attenuation	R^{-1}; $R < 40$ km $R^{-0.5}$; $R \geq 40$ km	R^{-1}; $R < 70$ km R^{0}; 70 km $\leq R < 130$ km $R^{-0.5}$; $R \geq 130$ km
Source duration, T_s (sec)	$1/f_0$	$1/f_0$
Path duration, T_p (sec)	$0.05R$	0; $R \leq 10$ km $0.16R$; 10 km $< R \leq 70$ km $-0.03R$; 70 km $< R \leq 130$ km $0.04R$; $R > 130$ km
Path attenuation, Q	$180 f^{0.45}$	$400 f^{0.4}$ (0.3), $680 f^{0.36}$ (0.4), $100 f^{0.3}$ (0.3)
Shear Velocity, β_s (km/sec)	3.5	3.6
Density, ρ_s (g/cc)	2.8	2.8
Site attenuation, κ_o (sec)	0.04	0.003 (0.3), 0.006 (0.4), 0.012 (0.3)
Site amplification method†	Quarter-wavelength	Quarter-wavelength
Local site profile‡ (30-m velocity)	WNA generic rock (620 m/sec)	ENA hard rock (2800 m/sec)

* Where multiple values are used, weights are given in parentheses.

† Site amplification terms are given in Table 2.7.

‡ Crustal velocity models are given in Table 2.8.

Table 3-8. Parameters of the local site profiles.

Western North America (WNA)			Eastern North America (ENA)		
Depth, z (km)	Velocity, β (km/sec)*	Density, ρ (g/cc)	Depth, z (km)	Velocity, β (km/sec)*	Density, ρ (g/cc)
≤ 0.001	0.245	2.495	0	2.768	2.731
0.001-0.03	$2.206z^{0.272}$	—†	0.05	2.808	2.735
0.03-0.19	$3.542z^{0.407}$	—†	0.10	2.847	2.739
0.19-4.00	$2.505z^{0.199}$	—†	0.15	2.885	2.742
4.00-8.00	$2.927z^{0.086}$	—†	0.20	2.922	2.746
≥ 8.00	3.500	2.800	0.25	2.958	2.749
			0.30	2.993	2.752
			0.35	3.026	2.756
			0.40	3.059	2.759
			0.45	3.091	2.762
			0.50	3.122	2.765
			0.55	3.151	2.767
			0.60	3.180	2.770
			0.65	3.208	2.773
			0.70	3.234	2.775
			0.75	3.260	2.778
			0.75-2.20	$3.324z^{0.067}$	—†
			2.20-8.00	$3.447z^{0.0209}$	—†
			≥ 8.00	3.6	2.809

* Average shear-wave velocity in the upper 30 m is 620 m/sec for WNA and 2800 m/sec for ENA.

† $\rho = 2.5 + 0.09375 (\beta - 0.3)$ g/cc.

Table 3-9. Site amplification factors.

Western North America (WNA)			Eastern North America (ENA)		
Frequency, f (Hz)	Amplification, A(f)*	Site Term, G(f)†	Frequency, f (Hz)	Amplification, A(f)*	Site Term, G(f)†
0.01	1.00	1.00	0.01	1.00	1.00
0.09	1.10	1.09	0.10	1.02	1.02
0.16	1.18	1.16	0.20	1.03	1.03
0.51	1.42	1.33	0.30	1.05	1.04
0.84	1.58	1.42	0.50	1.07	1.06
1.25	1.74	1.49	0.90	1.09	1.07
2.26	2.06	1.55	1.25	1.11	1.08
3.17	2.25	1.51	1.80	1.12	1.08
6.05	2.58	1.21	3.00	1.13	1.07
16.60	3.13	0.39	5.30	1.14	1.03
61.20	4.00	0.00	8.00	1.15	0.99
			14.00	1.15	0.88
			30.00	1.15	0.65
			60.00	1.15	0.37
			100.00	1.15	0.17

* Excludes the effects of κ_0. Amplification at other frequencies are obtained by interpolation assuming a linear dependence between log frequency and log amplification.

† Includes the effets of $\kappa_0 = 0.04$ sec in WNA and $\kappa_0 = 0.006$ sec in ENA.

3.3.6 MATLAB Code

```
% by Kathryn A. Gunberg 3/31/2008
% Virginia Tech
% kgunberg@vt.edu
%
% Campbell attenuation equation, 2003
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T    = Period (sec), 0.01 or 0 for PGA
% M    = Moment magnitude
% Rrup = Closest distance to the rupture plane
% ------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = C_2003(T, M, Rrup)
% Coefficients
period   = [0.01    0.02    0.03    0.05    0.075   0.1     0.15    0.2     ...
            0.3     0.5     0.75    1       1.5     2       3       4];
c1       = [0.0305  1.3535  1.1860  0.3736  -0.0395 -0.1475 -0.1901 -0.4328 ...
            -0.6906 -0.5907 -0.5429 -0.6104 -0.9666 -1.4306 -2.2331 -2.7975];
c2       = [0.633   0.630   0.622   0.616   0.615   0.613   0.616   0.617   ...
            0.609   0.534   0.480   0.451   0.441   0.459   0.492   0.507];
c3       = [-0.0427 -0.0404 -0.0362 -0.0353 -0.0353 -0.0353 -0.0478 -0.0586 ...
            -0.0786 -0.1379 -0.1806 -0.2090 -0.2405 -0.2552 -0.2646 -0.2738];
c4       = [-1.591  -1.787  -1.691  -1.469  -1.383  -1.369  -1.368  -1.320  ...
            -1.280  -1.216  -1.184  -1.158  -1.135  -1.124  -1.121  -1.119];
c5       = [-0.00428 -0.00388 -0.00367 -0.00378 -0.00421 -0.00454 -0.00473 -0.00460...
            -0.00414 -0.00341 -0.00288 -0.00255 -0.00213 -0.00187 -0.00154 -0.00135];
c6       = [0.000483 0.000497 0.000501 0.000500 0.000486 0.000460 0.000393 0.000337...
            0.000263 0.000194 0.000160 0.000141 0.000119 0.000103 0.000084 0.000074];
c7       = [0.683   1.020   0.922   0.630   0.491   0.484   0.461   0.399   ...
            0.349   0.318   0.304   0.299   0.304   0.310   0.310   0.294];
c8       = [0.416   0.363   0.376   0.423   0.463   0.467   0.478   0.493   ...
            0.502   0.503   0.504   0.503   0.500   0.499   0.499   0.506];
c9       = [1.140   0.851   0.759   0.771   0.955   1.096   1.239   1.250   ...
            1.241   1.166   1.110   1.067   1.029   1.015   1.014   1.018];
c10      = [-0.873  -0.715  -0.922  -1.239  -1.349  -1.284  -1.079  -0.928  ...
            -0.753  -0.606  -0.526  -0.482  -0.438  -0.417  -0.393  -0.386];
c11      = [1.030   1.030   1.030   1.042   1.052   1.059   1.068   1.077   ...
            1.081   1.098   1.105   1.110   1.099   1.093   1.090   1.092];
c12      = [-0.0860 -0.0860 -0.0860 -0.0838 -0.0838 -0.0838 -0.0838 -0.0838 ...
            -0.0838 -0.0824 -0.0806 -0.0793 -0.0771 -0.0758 -0.0737 -0.0722];
% interpolate between periods if neccesary
if T == 0
    T = min(period);
end
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = C_2003(T_low, M, Rrup);
    [sa_hi,  sigma_hi]  = C_2003(T_hi,  M, Rrup);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    R = sqrt(Rrup^2 + (c7(i)*exp(c8(i)*M))^2);
    f1 = c2(i)*M + c3(i)*(8.5 - M)^2;
    f2 = c4(i)*log(R) + (c5(i) + c6(i)*M)*Rrup;
    f3 = c9(i)*max(0,(log(Rrup) - log(70))) + c10(i)*max(0,(log(Rrup) - log(130)));
    Sa = exp(c1(i) + f1 + f2 + f3);
    sigma = c11(i) + c12(i)*min(7.16,M);
end
```

3.4 Silva, Gregor and Darragh – 2003 & Silva, Gregor and Lee – 2004

3.4.1 References

Silva, W., N. Gregor, R. Darragh (2003). Development of Regional Hard Rock Attenuation Relations for Central and Eastern North America, Mid-continent and Gulf Coast Areas, report prepared by Pacific Engineering and Analysis, El Cerrito, California.

Silva, W., N. Gregor, R. Lee (2004). Development of Regional Hard Rock Attenuation Relations for South Carolina, report prepared by Pacific Engineering and Analysis, El Cerrito, California.

3.4.2 Abstract

Using generated ground motions using a variety of models and model parameters, empirical ground-motion models were developed for mid-continent and gulf coast regions in Silva et al. (2003) and for South Carolina in Silva et al. (2004). The combinations include, single corner model with variable low, medium and high stress drops, single corner model with constant low, medium and high stress drops for both saturation and no saturation, and double corner model with and without saturation. The model predicts peak ground acceleration (PGA, in g), peak ground velocity (PGV, in cm/s) and 5%-damped spectral values (in g) for periods ranging from 0.01 to 10 s. The model is applicable for hard rock conditions, earthquakes between M4.5 and M 8.5 and distances up to 400 km.

3.4.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), 0 for PGA, -1 for PGV
- **M** – Moment magnitude
- G – 1 for mid-continental region, 0 for gulf coast region, 2 for South Carolina
- R_{jb} – Joyner-Boore distance (km)
- SE – 1 to include saturation, 0 for no saturation (NOTE: irrelevant for variable stress drop)
- CM – 1 for single corner model, 2 for double corner model
- SD_{level} – 0 for low stress drop, 1 for medium, 2 for high (NOTE: irrelevant for double corner model)
- SD_{type} – 1 for constant stress drop, 0 for variable (NOTE: irrelevant for double corner model)

$$\ln(Sa) = C_1 + C_2 M + (C_6 + C_7 M)\ln\left(R_{jb} + e^{C_4}\right) + C_{10}(M-6)^2$$

Standard deviation is given in the tables.

Coefficients

Table 3-10. Mid-continent.
Regression Coefficients for Single Corner Model with Variable Medium Stress Drop as a Function of Moment Magnitude

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-19.07223	2.57205	2.1	-1.41166	0.05292	-0.31205	0.3559	1.3243
5.0	-15.15004	2.27308	2.3	-1.55609	0.06043	-0.38898	0.3660	1.1933
3.0	-11.84462	1.96000	2.4	-1.70638	0.07232	-0.39806	0.3892	1.0462
2.0	-9.00041	1.66899	2.5	-1.86794	0.08623	-0.37576	0.4160	0.9591
1.6	-7.60788	1.50586	2.5	-1.94031	0.09384	-0.35415	0.4297	0.8874
1.0	-4.51914	1.13220	2.6	-2.16445	0.11502	-0.29235	0.4518	0.8021
0.75	-2.82095	0.93101	2.6	-2.25774	0.12494	-0.24823	0.4610	0.8050
0.50	-0.84738	0.68960	2.6	-2.39187	0.13949	-0.19435	0.4714	0.7551
0.40	0.13162	0.57890	2.6	-2.45001	0.14539	-0.16638	0.4775	0.7396
0.30	1.12628	0.45746	2.6	-2.53338	0.15420	-0.13930	0.4865	0.7395
0.24	1.79388	0.38804	2.6	-2.58195	0.15895	-0.12283	0.4950	0.7274
0.20	2.27495	0.34400	2.6	-2.61448	0.16182	-0.11211	0.5040	0.7247
0.16	3.13556	0.27220	2.7	-2.72838	0.17012	-0.10222	0.5181	0.7271
0.15	3.26041	0.25961	2.7	-2.74131	0.17129	-0.09985	0.5249	0.7328
0.12	3.65946	0.22693	2.7	-2.77660	0.17414	-0.09345	0.5424	0.7503
0.10	3.92885	0.20331	2.7	-2.80630	0.17658	-0.08961	0.5602	0.7507
0.080	4.20238	0.17878	2.7	-2.84105	0.17938	-0.08624	0.5731	0.7534
0.070	4.33334	0.16542	2.7	-2.86188	0.18110	-0.08477	0.5803	0.7585
0.060	4.89845	0.12529	2.8	-2.96230	0.18763	-0.08349	0.5868	0.7656
0.055	4.96669	0.11815	2.8	-2.97508	0.18865	-0.08293	0.5907	0.7644
0.050	5.03867	0.11102	2.8	-2.98849	0.18968	-0.08242	0.5961	0.7711
0.040	5.20890	0.09698	2.8	-3.01742	0.19172	-0.08150	0.6133	0.7817
0.032	5.37895	0.08559	2.8	-3.04366	0.19337	-0.08079	0.6227	0.7858
0.025	6.02744	0.04417	2.9	-3.15877	0.20038	-0.08027	0.6222	0.7823
0.020	6.07941	0.03289	2.9	-3.18403	0.20265	-0.08044	0.6143	0.7776
0.010	4.24805	0.09552	2.7	-2.99165	0.19690	-0.08748	0.5644	0.7392
PGA	4.03930	0.10412	2.7	-2.97465	0.19631	-0.08874	0.5592	0.7353
PGV	3.22720	0.65905	2.4	-2.73277	0.20009	-0.13903	0.4408	-

Table 3-11. Gulf Coast.
Regression Coefficients for Single Corner Model with Variable Medium Stress Drop as a Function of Moment Magnitude

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-14.54986	2.30998	2.8	-2.15716	0.09152	-0.34105	0.5243	1.3791
5.0	-9.25169	1.88136	3.1	-2.51971	0.11010	-0.38752	0.5604	1.2665
3.0	-5.31480	1.49937	3.2	-2.79932	0.12984	-0.37439	0.5958	1.1393
2.0	-1.92096	1.16422	3.3	-3.08551	0.15079	-0.33869	0.6159	1.0612
1.6	0.25617	0.96349	3.4	-3.30857	0.16627	-0.31189	0.6233	0.9956
1.0	4.21778	0.55654	3.5	-3.70387	0.19724	-0.24619	0.6483	0.9271
0.75	6.01523	0.35576	3.5	-3.87179	0.21222	-0.20693	0.6622	0.9349
0.50	9.10831	0.06810	3.6	-4.24952	0.24024	-0.15976	0.6850	0.9040
0.40	10.18655	-0.04192	3.6	-4.37417	0.25066	-0.13932	0.6996	0.8991
0.30	12.43075	-0.21755	3.7	-4.69883	0.27269	-0.11900	0.7208	0.9109
0.24	13.29372	-0.29360	3.7	-4.81633	0.28167	-0.10754	0.7389	0.9111
0.20	13.93331	-0.34606	3.7	-4.90830	0.28841	-0.10055	0.7556	0.9177
0.16	15.82366	-0.46920	3.8	-5.21303	0.30744	-0.09434	0.7783	0.9306
0.15	16.02650	-0.48449	3.8	-5.24545	0.30976	-0.09294	0.7850	0.9369
0.12	16.69027	-0.53555	3.8	-5.35752	0.31804	-0.08918	0.8064	0.9587
0.10	17.18425	-0.57629	3.8	-5.44841	0.32521	-0.08711	0.8192	0.9596
0.080	17.71756	-0.62387	3.8	-5.55455	0.33408	-0.08558	0.8294	0.9628
0.070	17.99875	-0.64981	3.8	-5.61318	0.33907	-0.08507	0.8339	0.9664
0.060	18.29779	-0.67629	3.8	-5.67576	0.34425	-0.08473	0.8396	0.9730
0.055	18.46167	-0.68951	3.8	-5.70923	0.34685	-0.08461	0.8438	0.9733
0.050	18.64419	-0.70300	3.8	-5.74551	0.34952	-0.08451	0.8491	0.9799
0.040	20.50874	-0.81779	3.9	-6.06641	0.36944	-0.08430	0.8566	0.9842
0.032	20.89870	-0.84219	3.9	-6.14187	0.37424	-0.08421	0.8572	0.9821
0.025	19.78142	-0.78593	3.8	-5.97732	0.36646	-0.08469	0.8487	0.9722
0.020	19.88182	-0.80582	3.8	-6.01166	0.37073	-0.08525	0.8430	0.9685
0.010	16.81947	-0.70860	3.7	-5.55741	0.35763	-0.09091	0.7733	0.9088
PGA	15.27441	-0.61726	3.6	-5.30301	0.34239	-0.09155	0.7666	0.9031
PGV	11.09786	0.03822	3.2	-4.40038	0.33709	-0.14227	0.5888	-

Table 3-12. South Carolina

Regression Coefficients for Single Corner Model with Variable Medium Stress Drop as a Function of Moment Magnitude

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-20.34111	2.60194	1.4	-1.08558	0.04640	-0.30371	0.3573	1.3246
5.0	-16.73900	2.30757	1.5	-1.16565	0.05178	-0.37951	0.3696	1.1942
3.0	-13.57757	2.00261	1.7	-1.29760	0.06226	-0.38860	0.3852	1.0446
2.0	-10.98377	1.72186	1.8	-1.42212	0.07357	-0.36699	0.4102	0.9565
1.6	-9.47360	1.55395	1.9	-1.51379	0.08160	-0.34549	0.4239	0.8842
1.0	-6.45963	1.20847	2.0	-1.68824	0.09795	-0.28426	0.4531	0.8027
0.75	-4.85330	1.01608	2.0	-1.78223	0.10744	-0.24230	0.4684	0.8090
0.50	-2.60478	0.76905	2.1	-1.94949	0.12195	-0.18473	0.4972	0.7714
0.40	-1.40255	0.64885	2.2	-2.06185	0.13054	-0.15738	0.5207	0.7677
0.30	-0.08110	0.52001	2.3	-2.19330	0.13926	-0.12919	0.5309	0.7689
0.24	0.62132	0.44430	2.3	-2.26314	0.14359	-0.11198	0.5314	0.7524
0.20	1.42947	0.37165	2.4	-2.38047	0.15104	-0.10052	0.5373	0.7481
0.16	2.34666	0.29538	2.5	-2.52530	0.16033	-0.08963	0.5514	0.7509
0.15	2.51220	0.28131	2.5	-2.55233	0.16215	-0.08711	0.5555	0.7547
0.12	3.82298	0.19666	2.7	-2.78523	0.17649	-0.08022	0.5755	0.7742
0.10	4.74102	0.13857	2.8	-2.94210	0.18510	-0.07565	0.5996	0.7801
0.080	5.32022	0.09551	2.8	-3.04406	0.19102	-0.07192	0.6155	0.7857
0.070	6.08837	0.04583	2.9	-3.19714	0.20084	-0.07142	0.6062	0.7783
0.060	6.40243	0.01563	2.9	-3.27602	0.20733	-0.07091	0.6069	0.7804
0.055	6.58201	-0.00612	2.9	-3.31878	0.21133	-0.07040	0.6057	0.7755
0.050	6.74549	-0.01996	2.9	-3.36106	0.21467	-0.07031	0.6044	0.7772
0.040	6.56386	-0.01385	2.8	-3.35824	0.21579	-0.07078	0.6152	0.7830
0.032	6.88238	-0.04115	2.8	-3.43310	0.22124	-0.07027	0.6271	0.7892
0.025	6.62198	-0.04194	2.7	-3.40938	0.22240	-0.07041	0.6282	0.7869
0.020	6.13592	-0.02753	2.6	-3.34276	0.22097	-0.07204	0.6231	0.7845
0.010	3.80314	0.07060	2.4	-2.96769	0.20791	-0.08054	0.5625	0.7374
PGA	3.49839	0.08928	2.4	-2.91374	0.20455	-0.08156	0.5568	0.7334
PGV	1.78500	0.69725	1.9	-2.38690	0.19158	-0.12481	0.4470	-

Table 3-13. Mid-continent.

Regression Coefficients for the Single Corner Model with Variable Low Stress Drop as a Function of Moment Magnitude

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-18.82818	2.50853	2.1	-1.39437	0.05155	-0.35284	0.3623	1.3261
5.0	-14.90966	2.17243	2.3	-1.51375	0.05943	-0.40726	0.3774	1.1969
3.0	-11.55820	1.83734	2.4	-1.66484	0.07203	-0.39809	0.4056	1.0524
2.0	-8.74448	1.53854	2.5	-1.82313	0.08612	-0.36309	0.4307	0.9656
1.6	-7.14902	1.36498	2.5	-1.93736	0.09559	-0.33624	0.4415	0.8932
1.0	-4.48436	1.01787	2.6	-2.10529	0.11396	-0.26954	0.4580	0.8056
0.75	-2.60545	0.81461	2.6	-2.24962	0.12651	-0.22591	0.4650	0.8073
0.50	-0.82196	0.59874	2.6	-2.37729	0.14040	-0.17695	0.4750	0.7574
0.40	0.04301	0.50444	2.6	-2.43239	0.14596	-0.15344	0.4816	0.7423
0.30	0.91358	0.40083	2.6	-2.51171	0.15434	-0.13143	0.4910	0.7425
0.24	1.49580	0.34395	2.6	-2.55688	0.15868	-0.11864	0.4995	0.7305
0.20	1.91753	0.30871	2.6	-2.58706	0.16126	-0.11059	0.5084	0.7278
0.16	2.71047	0.24622	2.7	-2.69634	0.16908	-0.10327	0.5222	0.7300
0.15	2.81889	0.23601	2.7	-2.70814	0.17011	-0.10154	0.5289	0.7357
0.12	3.17270	0.20990	2.7	-2.74034	0.17258	-0.09693	0.5460	0.7529
0.10	3.41148	0.19064	2.7	-2.76748	0.17469	-0.09418	0.5635	0.7531
0.080	3.65547	0.17022	2.7	-2.79941	0.17715	-0.09175	0.5760	0.7556
0.070	3.77180	0.15884	2.7	-2.81861	0.17867	-0.09070	0.5830	0.7605
0.060	4.31663	0.12089	2.8	-2.91626	0.18495	-0.08978	0.5893	0.7676
0.055	4.37793	0.11466	2.8	-2.92815	0.18586	-0.08938	0.5931	0.7662
0.050	4.44314	0.10840	2.8	-2.94065	0.18679	-0.08901	0.5984	0.7729
0.040	4.60063	0.09599	2.8	-2.96783	0.18862	-0.08835	0.6153	0.7833
0.032	4.76103	0.08583	2.8	-2.99272	0.19011	-0.08783	0.6246	0.7873
0.025	5.39249	0.04598	2.9	-3.10501	0.19687	-0.08744	0.6240	0.7837
0.020	5.43661	0.03559	2.9	-3.12848	0.19893	-0.08760	0.6160	0.7790
0.010	3.62958	0.09547	2.7	-2.93410	0.19276	-0.09342	0.5661	0.7405
PGA	3.42714	0.10323	2.7	-2.91721	0.19218	-0.09443	0.5610	0.7366
PGV	2.77820	0.64929	2.4	-2.66659	0.19477	-0.15404	0.4441	-

Table 3-14. Gulf Coast.

Regression Coefficients for the Single Corner Model with Variable Low Stress Drop as a Function of Moment Magnitude

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-14.25163	2.23220	2.8	-2.13620	0.09013	-0.37542	0.5238	1.3790
5.0	-9.24105	1.78174	3.0	-2.43210	0.10715	-0.39711	0.5660	1.2690
3.0	-4.86624	1.36569	3.2	-2.78892	0.13082	-0.36709	0.6020	1.1426
2.0	-1.52175	1.02753	3.3	-3.07493	0.15219	-0.32102	0.6191	1.0631
1.6	0.60771	0.82916	3.4	-3.29808	0.16792	-0.29094	0.6251	0.9968
1.0	4.38270	0.44249	3.5	-3.68677	0.19846	-0.22467	0.6480	0.9268
0.75	6.03088	0.26122	3.5	-3.84799	0.21274	-0.18860	0.6618	0.9346
0.50	8.91163	0.00198	3.6	-4.21624	0.23987	-0.14814	0.6857	0.9045
0.40	9.88541	-0.09326	3.6	-4.33601	0.24975	-0.13159	0.7008	0.9001
0.30	11.99662	-0.25104	3.7	-4.65152	0.27084	-0.11582	0.7220	0.9119
0.24	12.77568	-0.31521	3.7	-4.76255	0.27903	-0.10726	0.7399	0.9119
0.20	13.35601	-0.35932	3.7	-4.84920	0.28512	-0.10218	0.7562	0.9182
0.16	15.16957	-0.47298	3.8	-5.14508	0.30322	-0.09778	0.7782	0.9305
0.15	15.35608	-0.48604	3.8	-5.17562	0.30531	-0.09680	0.7848	0.9367
0.12	15.96772	-0.53011	3.8	-5.28098	0.31278	-0.09419	0.8054	0.9578
0.10	16.42234	-0.56572	3.8	-5.36596	0.31923	-0.09279	0.8177	0.9583
0.080	16.90986	-0.60751	3.8	-5.46428	0.32715	-0.09179	0.8272	0.9609
0.070	17.16559	-0.63027	3.8	-5.51821	0.33158	-0.09148	0.8313	0.9642
0.060	17.43775	-0.65344	3.8	-5.57562	0.33613	-0.09130	0.8366	0.9704
0.055	18.95886	-0.74635	3.9	-5.83325	0.35180	-0.09125	0.8406	0.9705
0.050	19.13672	-0.75882	3.9	-5.86837	0.35426	-0.09122	0.8457	0.9770
0.040	19.56869	-0.78618	3.9	-5.95141	0.35968	-0.09113	0.8530	0.9811
0.032	19.93414	-0.80760	3.9	-6.02190	0.36387	-0.09109	0.8534	0.9788
0.025	18.81796	-0.75053	3.8	-5.85612	0.35579	-0.09155	0.8448	0.9688
0.020	18.89574	-0.76779	3.8	-5.88521	0.35942	-0.09203	0.8391	0.9651
0.010	15.86483	-0.67427	3.7	-5.43083	0.34620	-0.09664	0.7699	0.9060
PGA	14.35825	-0.58678	3.6	-5.18268	0.33157	-0.09714	0.7633	0.9003
PGV	10.31697	0.06538	3.2	-4.25855	0.32343	-0.15899	0.5854	-

Table 3-15. South Carolina.

Regression Coefficients for the Single Corner Model with Variable Low Stress Drop as a Function of Moment Magnitude

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-20.05231	2.53227	1.4	-1.07453	0.04458	-0.33586	0.3615	1.3257
5.0	-16.27482	2.19486	1.5	-1.16205	0.05129	-0.38905	0.3781	1.1970
3.0	-13.04615	1.86751	1.7	-1.29847	0.06256	-0.38046	0.4007	1.0503
2.0	-10.45871	1.57792	1.8	-1.42382	0.07424	-0.34646	0.4264	0.9635
1.6	-9.12302	1.41677	1.8	-1.48739	0.08097	-0.31954	0.4380	0.8914
1.0	-6.23478	1.08031	1.9	-1.65772	0.09727	-0.25183	0.4608	0.8067
0.75	-4.55982	0.89047	2.0	-1.78241	0.10846	-0.21021	0.4732	0.8119
0.50	-2.50090	0.66910	2.1	-1.94421	0.12242	-0.15772	0.5006	0.7733
0.40	-1.40924	0.56460	2.2	-2.05286	0.13061	-0.13451	0.5242	0.7704
0.30	-0.21574	0.45412	2.3	-2.17973	0.13883	-0.11152	0.5346	0.7716
0.24	0.40330	0.39049	2.3	-2.24641	0.14281	-0.09787	0.5351	0.7552
0.20	1.14750	0.32686	2.4	-2.36017	0.14988	-0.08899	0.5408	0.7502
0.16	1.99242	0.26076	2.5	-2.49951	0.15853	-0.08081	0.5542	0.7531
0.15	2.13993	0.24927	2.5	-2.52505	0.16018	-0.07896	0.5579	0.7562
0.12	3.38857	0.17291	2.7	-2.75163	0.17382	-0.07400	0.5771	0.7757
0.10	4.26612	0.12018	2.8	-2.90389	0.18190	-0.07059	0.6009	0.7808
0.080	4.80280	0.08289	2.8	-2.99953	0.18704	-0.06781	0.6163	0.7865
0.070	5.53531	0.03755	2.9	-3.14600	0.19608	-0.06765	0.6068	0.7783
0.060	5.81659	0.01153	2.9	-3.21804	0.20171	-0.06737	0.6073	0.7812
0.055	5.47728	0.02280	2.8	-3.16765	0.19979	-0.06693	0.6058	0.7755
0.050	5.61769	0.01155	2.8	-3.20499	0.20256	-0.06689	0.6043	0.7772
0.040	5.92208	-0.01071	2.8	-3.28678	0.20844	-0.06736	0.6149	0.7822
0.032	6.21793	-0.03527	2.8	-3.35589	0.21317	-0.06677	0.6266	0.7884
0.025	5.94977	-0.03501	2.7	-3.32883	0.21388	-0.06674	0.6277	0.7861
0.020	5.46547	-0.02078	2.6	-3.26088	0.21226	-0.06814	0.6227	0.7837
0.010	3.19108	0.06980	2.4	-2.89257	0.19998	-0.07545	0.5626	0.7374
PGA	2.89680	0.08717	2.4	-2.84056	0.19685	-0.07632	0.5571	0.7337
PGV	1.36709	0.68365	1.9	-2.31521	0.18396	-0.12869	0.4495	-

Table 3-16. Mid-continent.

Regression Coefficients for the Single Corner Model with Variable High Stress Drop as a Function of Moment

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-18.80138	2.59958	2.3	-1.51629	0.05717	-0.25763	0.3585	1.3250
5.0	-15.20886	2.34990	2.4	-1.62679	0.06230	-0.35359	0.3642	1.1928
3.0	-11.97362	2.06358	2.5	-1.77626	0.07329	-0.38117	0.3821	1.0436
2.0	-9.12315	1.78482	2.6	-1.94059	0.08684	-0.37239	0.4081	0.9557
1.6	-7.70148	1.62326	2.6	-2.01584	0.09460	-0.35700	0.4242	0.8847
1.0	-4.46472	1.24156	2.7	-2.25138	0.11635	-0.30377	0.4538	0.8032
0.75	-2.67167	1.03112	2.7	-2.34731	0.12639	-0.26186	0.4671	0.8085
0.50	-0.51056	0.76645	2.7	-2.48971	0.14173	-0.20549	0.4794	0.7601
0.40	0.58917	0.63923	2.7	-2.55190	0.14804	-0.17378	0.4851	0.7445
0.30	1.72806	0.49782	2.7	-2.64087	0.15740	-0.14160	0.4934	0.7441
0.24	2.49641	0.41405	2.7	-2.69325	0.16254	-0.12105	0.5013	0.7317
0.20	3.46126	0.33544	2.8	-2.80186	0.16992	-0.10713	0.5099	0.7289
0.16	4.02502	0.27487	2.8	-2.85216	0.17467	-0.09403	0.5238	0.7311
0.15	4.17095	0.25933	2.8	-2.86633	0.17597	-0.09083	0.5305	0.7369
0.12	4.63032	0.21818	2.8	-2.90541	0.17924	-0.08205	0.5480	0.7543
0.10	4.94207	0.18877	2.8	-2.93847	0.18204	-0.07672	0.5658	0.7549
0.080	5.25826	0.15855	2.8	-2.97721	0.18528	-0.07200	0.5789	0.7578
0.070	5.41104	0.14236	2.8	-3.00040	0.18726	-0.06993	0.5861	0.7629
0.060	6.03843	0.09752	2.9	-3.11001	0.19437	-0.06812	0.5929	0.7703
0.055	6.11753	0.08905	2.9	-3.12417	0.19554	-0.06731	0.5968	0.7691
0.050	6.20019	0.08062	2.9	-3.13898	0.19672	-0.06658	0.6022	0.7758
0.040	6.39121	0.06416	2.9	-3.17073	0.19905	-0.06525	0.6195	0.7866
0.032	6.57730	0.05102	2.9	-3.19920	0.20091	-0.06426	0.6289	0.7907
0.025	6.75933	0.03739	2.9	-3.23117	0.20300	-0.06354	0.6285	0.7873
0.020	7.35410	-0.00721	3.0	-3.35245	0.21111	-0.06367	0.6209	0.7829
0.010	5.41652	0.06158	2.8	-3.15000	0.20544	-0.07217	0.5713	0.7445
PGA	5.19757	0.07129	2.8	-3.13247	0.20485	-0.07375	0.5661	0.7405
PGV	4.14085	0.63457	2.5	-2.88388	0.20958	-0.11455	0.4471	-

Table 3-17. Gulf Coast.
Regression Coefficients for the Single Corner Model with Variable High Stress Drop as a Function of Moment

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-13.91863	2.33294	3.0	-2.33817	0.09908	-0.29154	0.5321	1.3821
5.0	-9.02136	1.95631	3.2	-2.64856	0.11437	-0.36070	0.5624	1.2674
3.0	-5.06249	1.59204	3.3	-2.93546	0.13367	-0.36500	0.5952	1.1390
2.0	-1.56307	1.26035	3.4	-3.23534	0.15492	-0.34181	0.6174	1.0621
1.6	0.72588	1.05610	3.5	-3.47121	0.17081	-0.32004	0.6268	0.9978
1.0	4.94057	0.63072	3.6	-3.88811	0.20282	-0.25891	0.6554	0.9321
0.75	6.90409	0.41108	3.6	-4.06719	0.21878	-0.21837	0.6699	0.9403
0.50	10.33931	0.08773	3.7	-4.47467	0.24889	-0.16562	0.6920	0.9093
0.40	11.55566	-0.03985	3.7	-4.60821	0.26010	-0.14124	0.7057	0.9039
0.30	12.94874	-0.17886	3.7	-4.77368	0.27355	-0.11589	0.7259	0.9150
0.24	15.04806	-0.33259	3.8	-5.08734	0.29385	-0.10095	0.7440	0.9152
0.20	15.77669	-0.39607	3.8	-5.18780	0.30141	-0.09155	0.7605	0.9217
0.16	16.59083	-0.46325	3.8	-5.30738	0.31025	-0.08296	0.7833	0.9348
0.15	16.81254	-0.48116	3.8	-5.34165	0.31279	-0.08098	0.7902	0.9412
0.12	18.86865	-0.61723	3.9	-5.68075	0.33451	-0.07559	0.8121	0.9635
0.10	19.43335	-0.66605	3.9	-5.78203	0.34275	-0.07256	0.8254	0.9649
0.080	20.04863	-0.72294	3.9	-5.90140	0.35305	-0.07023	0.8362	0.9687
0.070	20.37544	-0.75402	3.9	-5.96788	0.35891	-0.06938	0.8411	0.9726
0.060	20.72257	-0.78585	3.9	-6.03900	0.36501	-0.06877	0.8471	0.9795
0.055	20.91108	-0.80174	3.9	-6.07691	0.36809	-0.06854	0.8515	0.9800
0.050	21.11875	-0.81789	3.9	-6.11772	0.37124	-0.06833	0.8568	0.9866
0.040	21.61053	-0.85260	3.9	-6.21225	0.37806	-0.06793	0.8646	0.9912
0.032	22.02865	-0.88044	3.9	-6.29329	0.38353	-0.06773	0.8653	0.9892
0.025	22.40623	-0.91637	3.9	-6.37768	0.39115	-0.06821	0.8569	0.9794
0.020	22.54184	-0.94055	3.9	-6.41953	0.39634	-0.06885	0.8514	0.9758
0.010	17.92864	-0.74769	3.7	-5.71493	0.36837	-0.07577	0.7814	0.9157
PGA	17.56501	-0.73081	3.7	-5.65962	0.36566	-0.07661	0.7747	0.9100
PGV	12.88457	-0.06337	3.3	-4.71837	0.36161	-0.11586	0.5984	-

Table 3-18. South Carolina.

Regression Coefficients for the Single Corner Model with Variable High Stress Drop as a Function of Moment

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-20.56146	2.65753	1.4	-1.10167	0.04890	-0.26749	0.3524	1.3233
5.0	-17.04411	2.40199	1.6	-1.19448	0.05392	-0.36235	0.3633	1.1924
3.0	-14.08074	2.12859	1.7	-1.30133	0.06256	-0.38948	0.3726	1.0399
2.0	-11.50960	1.86114	1.8	-1.42361	0.07335	-0.38115	0.3938	0.9494
1.6	-9.98850	1.69698	1.9	-1.51498	0.08117	-0.36609	0.4078	0.8766
1.0	-6.91188	1.35161	2.0	-1.68784	0.09700	-0.31470	0.4427	0.7966
0.75	-5.02927	1.13995	2.1	-1.81934	0.10857	-0.27482	0.4618	0.8050
0.50	-2.58923	0.87023	2.2	-1.99500	0.12371	-0.21494	0.4938	0.7688
0.40	-1.50326	0.74863	2.2	-2.06874	0.13013	-0.18415	0.5176	0.7657
0.30	-0.04550	0.60048	2.3	-2.20452	0.13930	-0.15077	0.5273	0.7668
0.24	1.03708	0.49374	2.4	-2.32982	0.14711	-0.12963	0.5276	0.7495
0.20	1.63054	0.42844	2.4	-2.39747	0.15166	-0.11513	0.5338	0.7452
0.16	2.62840	0.34072	2.5	-2.54671	0.16141	-0.10088	0.5485	0.7487
0.15	2.81493	0.32360	2.5	-2.57508	0.16340	-0.09749	0.5528	0.7525
0.12	4.19608	0.22940	2.7	-2.81360	0.17833	-0.08805	0.5737	0.7727
0.10	5.16133	0.16491	2.8	-2.97485	0.18742	-0.08187	0.5981	0.7793
0.080	5.79219	0.11474	2.8	-3.08363	0.19418	-0.07674	0.6146	0.7849
0.070	6.60146	0.05996	2.9	-3.24392	0.20485	-0.07571	0.6057	0.7775
0.060	6.95517	0.02462	2.9	-3.33066	0.21231	-0.07480	0.6068	0.7804
0.055	7.15547	0.00024	2.9	-3.37781	0.21686	-0.07413	0.6058	0.7755
0.050	7.34032	-0.01632	2.9	-3.42473	0.22078	-0.07392	0.6048	0.7772
0.040	7.73231	-0.04885	2.9	-3.52618	0.22900	-0.07428	0.6159	0.7830
0.032	7.53570	-0.04513	2.8	-3.51127	0.22923	-0.07380	0.6280	0.7900
0.025	7.28719	-0.04751	2.7	-3.49198	0.23099	-0.07411	0.6292	0.7877
0.020	6.80166	-0.03323	2.6	-3.42745	0.22986	-0.07599	0.6239	0.7845
0.010	4.80627	0.04540	2.5	-3.11897	0.22107	-0.08595	0.5626	0.7374
PGA	4.48217	0.06607	2.5	-3.06158	0.21737	-0.08717	0.5568	0.7334
PGV	2.45098	0.69142	2.0	-2.50898	0.20312	-0.12192	0.4447	-

Table 3-19. Mid-continent.

Regression Coefficients for the Single Corner Model with Constant Medium Stress Drop

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-19.48096	2.63369	2.1	-1.40816	0.05251	-0.27037	0.3494	1.3226
5.0	-15.60343	2.34394	2.3	-1.55118	0.05960	-0.34570	0.3630	1.1924
3.0	-12.32672	2.03581	2.4	-1.70046	0.07122	-0.35378	0.3863	1.0451
2.0	-9.51015	1.74832	2.5	-1.86136	0.08496	-0.33001	0.4110	0.9570
1.6	-8.14308	1.58833	2.5	-1.93245	0.09238	-0.30768	0.4231	0.8842
1.0	-5.12369	1.22405	2.6	-2.15471	0.11324	-0.24573	0.4432	0.7972
0.75	-3.47330	1.02939	2.6	-2.24741	0.12308	-0.20234	0.4523	0.8000
0.50	-1.58285	0.79993	2.6	-2.37885	0.13729	-0.15090	0.4641	0.7506
0.40	-0.65379	0.69665	2.6	-2.43570	0.14303	-0.12494	0.4715	0.7357
0.30	0.28490	0.58358	2.6	-2.51730	0.15162	-0.10016	0.4819	0.7365
0.24	0.91433	0.51993	2.6	-2.56449	0.15619	-0.08536	0.4912	0.7248
0.20	1.74233	0.45792	2.7	-2.66338	0.16286	-0.07586	0.5006	0.7224
0.16	2.19706	0.41304	2.7	-2.70779	0.16694	-0.06715	0.5151	0.7249
0.15	2.31425	0.40161	2.7	-2.72023	0.16804	-0.06508	0.5220	0.7308
0.12	2.69216	0.37212	2.7	-2.75418	0.17072	-0.05952	0.5397	0.7483
0.10	2.94690	0.35069	2.7	-2.78273	0.17300	-0.05619	0.5576	0.7487
0.080	3.20588	0.32832	2.7	-2.81616	0.17563	-0.05326	0.5706	0.7515
0.070	3.75552	0.29046	2.8	-2.91238	0.18175	-0.05199	0.5777	0.7565
0.060	3.88344	0.27758	2.8	-2.93512	0.18355	-0.05087	0.5842	0.7636
0.055	3.94814	0.27096	2.8	-2.94748	0.18451	-0.05038	0.5881	0.7624
0.050	4.01659	0.26433	2.8	-2.96045	0.18549	-0.04994	0.5935	0.7691
0.040	4.18017	0.25125	2.8	-2.98855	0.18741	-0.04913	0.6107	0.7797
0.032	4.34502	0.24062	2.8	-3.01413	0.18897	-0.04850	0.6201	0.7837
0.025	4.98360	0.20066	2.9	-3.12766	0.19576	-0.04804	0.6195	0.7802
0.020	5.03110	0.19000	2.9	-3.15204	0.19790	-0.04818	0.6115	0.7754
0.010	3.65796	0.22258	2.8	-3.03868	0.19703	-0.05457	0.5613	0.7369
PGA	3.00730	0.25858	2.7	-2.94208	0.19152	-0.05571	0.5561	0.7329
PGV	2.34185	0.79105	2.4	-2.69614	0.19476	-0.10359	0.4380	-

Table 3-20. Gulf Coast.

Regression Coefficients for the Single Corner Model with Constant Medium Stress Drop

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-14.97295	2.37485	2.8	-2.14967	0.09041	-0.29863	0.5217	1.3782
5.0	-9.72740	1.95572	3.1	-2.51098	0.10865	-0.34332	0.5587	1.2658
3.0	-5.83777	1.58067	3.2	-2.78845	0.12797	-0.32881	0.5920	1.1373
2.0	-2.48893	1.25139	3.3	-3.07316	0.14866	-0.29199	0.6097	1.0576
1.6	-0.33936	1.05439	3.4	-3.29591	0.16405	-0.26496	0.6163	0.9913
1.0	3.53746	0.65933	3.5	-3.68869	0.19464	-0.20041	0.6409	0.9219
0.75	5.26938	0.46791	3.5	-3.85384	0.20926	-0.16290	0.6556	0.9302
0.50	8.26540	0.19447	3.6	-4.22696	0.23667	-0.11889	0.6802	0.9004
0.40	9.29703	0.09136	3.6	-4.34955	0.24683	-0.10023	0.6958	0.8962
0.30	11.47972	-0.07511	3.7	-4.66998	0.26828	-0.08198	0.7177	0.9085
0.24	12.30467	-0.14553	3.7	-4.78472	0.27690	-0.07185	0.7363	0.9090
0.20	12.91716	-0.19398	3.7	-4.87438	0.28333	-0.06574	0.7531	0.9156
0.16	14.76997	-0.31160	3.8	-5.17479	0.30176	-0.06037	0.7758	0.9285
0.15	14.96522	-0.32579	3.8	-5.20638	0.30397	-0.05917	0.7825	0.9348
0.12	15.60406	-0.37326	3.8	-5.31533	0.31184	-0.05594	0.8038	0.9565
0.10	16.07898	-0.41128	3.8	-5.40344	0.31863	-0.05418	0.8166	0.9574
0.080	16.58985	-0.45572	3.8	-5.50586	0.32700	-0.05288	0.8266	0.9604
0.070	16.85850	-0.47991	3.8	-5.56225	0.33169	-0.05245	0.8310	0.9639
0.060	17.14437	-0.50458	3.8	-5.62237	0.33654	-0.05218	0.8365	0.9704
0.055	18.68342	-0.59824	3.9	-5.88319	0.35235	-0.05209	0.8407	0.9706
0.050	18.86815	-0.61146	3.9	-5.91969	0.35496	-0.05201	0.8459	0.9771
0.040	19.31416	-0.64033	3.9	-6.00557	0.36070	-0.05184	0.8533	0.9814
0.032	19.69186	-0.66304	3.9	-6.07864	0.36517	-0.05176	0.8538	0.9791
0.025	18.57590	-0.60707	3.8	-5.91373	0.35737	-0.05222	0.8453	0.9692
0.020	18.66451	-0.62536	3.8	-5.94544	0.36127	-0.05272	0.8395	0.9655
0.010	15.61583	-0.53024	3.7	-5.49076	0.34812	-0.05781	0.7697	0.9057
PGA	14.09083	-0.44176	3.6	-5.23954	0.33332	-0.05839	0.7630	0.9000
PGV	10.05725	0.19114	3.2	-4.32766	0.32682	-0.10589	0.5846	-

Table 3-21. South Carolina.

Regression Coefficients for the Single Corner Model with Constant Medium Stress Drop

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-20.75572	2.66436	1.4	-1.08036	0.04575	-0.26225	0.3507	1.3227
5.0	-17.19667	2.37874	1.5	-1.15935	0.05081	-0.33621	0.3670	1.1936
3.0	-14.06689	2.07919	1.7	-1.28989	0.06096	-0.34445	0.3828	1.0435
2.0	-11.50543	1.80276	1.8	-1.41313	0.07203	-0.32162	0.4058	0.9544
1.6	-10.01702	1.63758	1.9	-1.50425	0.07995	-0.29941	0.4178	0.8813
1.0	-7.05566	1.29873	2.0	-1.67870	0.09627	-0.23741	0.4440	0.7977
0.75	-5.49548	1.11266	2.0	-1.77199	0.10566	-0.19612	0.4587	0.8033
0.50	-3.32938	0.87752	2.1	-1.93695	0.11987	-0.14101	0.4886	0.7656
0.40	-2.17689	0.76471	2.2	-2.04747	0.12821	-0.11553	0.5132	0.7630
0.30	-0.91426	0.64469	2.3	-2.17662	0.13662	-0.08967	0.5249	0.7647
0.24	-0.25005	0.57474	2.3	-2.24507	0.14078	-0.07407	0.5265	0.7488
0.20	0.52720	0.50677	2.4	-2.36056	0.14798	-0.06377	0.5331	0.7452
0.16	1.40962	0.43574	2.5	-2.50272	0.15689	-0.05410	0.5473	0.7479
0.15	1.56684	0.42291	2.5	-2.52910	0.15864	-0.05189	0.5512	0.7518
0.12	2.84539	0.34310	2.7	-2.75855	0.17249	-0.04589	0.5704	0.7705
0.10	3.74250	0.28811	2.8	-2.91299	0.18076	-0.04184	0.5949	0.7762
0.080	4.30142	0.24798	2.8	-3.01204	0.18629	-0.03854	0.6114	0.7826
0.070	5.05068	0.20098	2.9	-3.16171	0.19564	-0.03820	0.6016	0.7744
0.060	5.34872	0.17298	2.9	-3.23737	0.20169	-0.03779	0.6020	0.7773
0.055	5.51993	0.15239	2.9	-3.27833	0.20546	-0.03730	0.6010	0.7723
0.050	5.67485	0.13971	2.9	-3.31873	0.20854	-0.03723	0.5994	0.7733
0.040	5.48446	0.14693	2.8	-3.31359	0.20937	-0.03769	0.6096	0.7783
0.032	5.79121	0.12122	2.8	-3.38561	0.21443	-0.03713	0.6215	0.7844
0.025	5.52760	0.12078	2.7	-3.36044	0.21541	-0.03717	0.6227	0.7821
0.020	5.04282	0.13496	2.6	-3.29331	0.21392	-0.03869	0.6175	0.7798
0.010	2.73988	0.22873	2.4	-2.92178	0.20135	-0.04661	0.5568	0.7328
PGA	2.44059	0.24664	2.4	-2.86879	0.19811	-0.04758	0.5512	0.7292
PGV	0.89599	0.82861	1.9	-2.34455	0.18556	-0.08813	0.4429	-

Table 3-22. Mid-continent.

Regression Coefficients for the Single Corner Model with Constant Low Stress Drop

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-19.09237	2.55127	2.1	-1.41992	0.05359	-0.29994	0.3543	1.3239
5.0	-15.22296	2.22463	2.2	-1.53646	0.06087	-0.35343	0.3702	1.1946
3.0	-11.90955	1.89523	2.3	-1.68527	0.07303	-0.34299	0.3983	1.0496
2.0	-9.12644	1.60015	2.4	-1.84330	0.08701	-0.30641	0.4221	0.9618
1.6	-7.79761	1.44039	2.4	-1.91307	0.09450	-0.27892	0.4320	0.8885
1.0	-4.89906	1.08390	2.5	-2.13693	0.11627	-0.21228	0.4482	0.8000
0.75	-3.33687	0.89916	2.5	-2.23329	0.12682	-0.16950	0.4562	0.8022
0.50	-1.58102	0.68709	2.5	-2.36933	0.14193	-0.12239	0.4684	0.7532
0.40	-0.72368	0.59402	2.5	-2.43076	0.14840	-0.10021	0.4767	0.7391
0.30	0.13269	0.49251	2.5	-2.51516	0.15754	-0.07959	0.4879	0.7405
0.24	0.71018	0.43636	2.5	-2.56429	0.16246	-0.06770	0.4977	0.7292
0.20	1.13055	0.40133	2.5	-2.59747	0.16549	-0.06026	0.5075	0.7272
0.16	1.90139	0.34023	2.6	-2.70593	0.17349	-0.05345	0.5223	0.7301
0.15	2.00886	0.33012	2.6	-2.71828	0.17461	-0.05184	0.5291	0.7359
0.12	2.36108	0.30408	2.6	-2.75216	0.17736	-0.04754	0.5470	0.7536
0.10	2.59748	0.28497	2.6	-2.78005	0.17962	-0.04496	0.5648	0.7541
0.080	2.83795	0.26482	2.6	-2.81238	0.18218	-0.04266	0.5778	0.7570
0.070	2.95159	0.25367	2.6	-2.83154	0.18373	-0.04164	0.5848	0.7619
0.060	3.47181	0.21711	2.7	-2.92538	0.18980	-0.04075	0.5913	0.7691
0.055	3.53102	0.21106	2.7	-2.93706	0.19071	-0.04035	0.5952	0.7678
0.050	3.59389	0.20500	2.7	-2.94929	0.19162	-0.03999	0.6005	0.7745
0.040	3.74605	0.19303	2.7	-2.97578	0.19341	-0.03934	0.6175	0.7850
0.032	3.90146	0.18325	2.7	-2.99999	0.19487	-0.03882	0.6269	0.7891
0.025	4.50286	0.14513	2.8	-3.10735	0.20134	-0.03842	0.6263	0.7856
0.020	4.54101	0.13536	2.8	-3.12969	0.20328	-0.03854	0.6184	0.7809
0.010	2.77858	0.19423	2.6	-2.94022	0.19693	-0.04397	0.5680	0.7420
PGA	2.57877	0.20187	2.6	-2.92333	0.19630	-0.04493	0.5628	0.7380
PGV	2.01678	0.74196	2.3	-2.65712	0.19550	-0.10331	0.4439	-

Table 3-23. Gulf Coast.

Regression Coefficients for the Single Corner Model with Constant Low Stress Drop

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-14.51574	2.27743	2.8	-2.16004	0.09156	-0.32210	0.5189	1.3771
5.0	-9.56051	1.83677	3.0	-2.45407	0.10808	-0.34227	0.5606	1.2666
3.0	-5.22266	1.42630	3.2	-2.81135	0.13160	-0.31057	0.5946	1.1387
2.0	-1.89095	1.08997	3.3	-3.10319	0.15363	-0.26352	0.6106	1.0581
1.6	-0.39847	0.92377	3.3	-3.22226	0.16458	-0.23333	0.6166	0.9915
1.0	3.27417	0.54493	3.4	-3.60867	0.19579	-0.16807	0.6406	0.9217
0.75	5.67074	0.32399	3.5	-3.90708	0.21814	-0.13325	0.6561	0.9306
0.50	7.67899	0.11381	3.5	-4.13972	0.23879	-0.09489	0.6821	0.9018
0.40	8.63053	0.02055	3.5	-4.26127	0.24915	-0.07940	0.6984	0.8982
0.30	10.65378	-0.13196	3.6	-4.56857	0.27022	-0.06472	0.7206	0.9108
0.24	11.41205	-0.19463	3.6	-4.67925	0.27864	-0.05678	0.7393	0.9114
0.20	13.03902	-0.29926	3.7	-4.94340	0.29508	-0.05208	0.7561	0.9181
0.16	13.69482	-0.34602	3.7	-5.04794	0.30235	-0.04799	0.7783	0.9306
0.15	13.87411	-0.35857	3.7	-5.07762	0.30440	-0.04708	0.7849	0.9368
0.12	14.45860	-0.40049	3.7	-5.17926	0.31164	-0.04464	0.8058	0.9582
0.10	16.11475	-0.50595	3.8	-5.46456	0.32967	-0.04331	0.8180	0.9586
0.080	16.59372	-0.54655	3.8	-5.56147	0.33740	-0.04233	0.8274	0.9611
0.070	16.84332	-0.56847	3.8	-5.61422	0.34167	-0.04202	0.8314	0.9642
0.060	17.10860	-0.59071	3.8	-5.67026	0.34603	-0.04182	0.8366	0.9705
0.055	17.25532	-0.60178	3.8	-5.70035	0.34821	-0.04176	0.8406	0.9705
0.050	17.42110	-0.61316	3.8	-5.73333	0.35047	-0.04171	0.8457	0.9770
0.040	17.82567	-0.63820	3.8	-5.81156	0.35548	-0.04159	0.8529	0.9810
0.032	18.16727	-0.65766	3.8	-5.87782	0.35931	-0.04152	0.8532	0.9786
0.025	18.45810	-0.68363	3.8	-5.94442	0.36483	-0.04192	0.8446	0.9686
0.020	17.18549	-0.61880	3.7	-5.74801	0.35480	-0.04232	0.8390	0.9650
0.010	14.28559	-0.52896	3.6	-5.31196	0.34179	-0.04658	0.7693	0.9054
PGA	13.95924	-0.51587	3.6	-5.26211	0.33959	-0.04706	0.7628	0.8999
PGV	9.08776	0.19911	3.1	-4.16032	0.31577	-0.10714	0.5825	-

Table 3-24. South Carolina.

Regression Coefficients for the Single Corner Model with Constant Low Stress Drop

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-20.55815	2.60017	1.3	-1.05537	0.04356	-0.29353	0.3564	1.3243
5.0	-16.73947	2.26764	1.5	-1.15760	0.05052	-0.34549	0.3760	1.1964
3.0	-13.65946	1.95051	1.6	-1.27073	0.06054	-0.33566	0.3974	1.0491
2.0	-10.99282	1.66012	1.8	-1.41718	0.07304	-0.30030	0.4203	0.9608
1.6	-9.68073	1.50191	1.8	-1.48069	0.07973	-0.27288	0.4303	0.8875
1.0	-6.85855	1.17422	1.9	-1.65049	0.09595	-0.20544	0.4512	0.8016
0.75	-5.24001	0.99240	2.0	-1.77350	0.10692	-0.16520	0.4640	0.8067
0.50	-3.26924	0.78397	2.1	-1.93239	0.12049	-0.11585	0.4929	0.7681
0.40	-2.22508	0.68658	2.2	-2.03913	0.12843	-0.09454	0.5175	0.7657
0.30	-1.08416	0.58402	2.3	-2.16376	0.13636	-0.07370	0.5293	0.7682
0.24	-0.49842	0.52540	2.3	-2.22892	0.14015	-0.06141	0.5307	0.7516
0.20	0.21762	0.46599	2.4	-2.34043	0.14691	-0.05349	0.5368	0.7473
0.16	1.03212	0.40443	2.5	-2.47694	0.15518	-0.04627	0.5502	0.7501
0.15	1.17253	0.39399	2.5	-2.50179	0.15673	-0.04465	0.5538	0.7532
0.12	2.39286	0.32183	2.7	-2.72488	0.16988	-0.04034	0.5721	0.7720
0.10	3.25258	0.27171	2.8	-2.87481	0.17765	-0.03729	0.5963	0.7778
0.080	3.77291	0.23675	2.8	-2.96790	0.18244	-0.03480	0.6122	0.7834
0.070	4.48907	0.19370	2.9	-3.11130	0.19106	-0.03473	0.6022	0.7752
0.060	4.75723	0.16948	2.9	-3.18064	0.19633	-0.03449	0.6024	0.7773
0.055	4.41709	0.18082	2.8	-3.12981	0.19436	-0.03406	0.6011	0.7723
0.050	4.55068	0.17049	2.8	-3.16561	0.19693	-0.03402	0.5994	0.7733
0.040	4.84204	0.15000	2.8	-3.24440	0.20240	-0.03447	0.6094	0.7783
0.032	5.12821	0.12675	2.8	-3.31113	0.20681	-0.03383	0.6211	0.7844
0.025	4.85835	0.12717	2.7	-3.28306	0.20739	-0.03371	0.6223	0.7821
0.020	4.37562	0.14114	2.6	-3.21479	0.20573	-0.03501	0.6173	0.7798
0.010	2.12732	0.22793	2.4	-2.84970	0.19389	-0.04184	0.5571	0.7336
PGA	1.83761	0.24466	2.4	-2.79850	0.19087	-0.04268	0.5515	0.7294
PGV	0.46600	0.81692	1.9	-2.27508	0.17831	-0.09206	0.4459	-

Table 3-25. Mid-continent.

Regression Coefficients for the Single Corner Model with Constant High Stress Drop

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-19.70343	2.68814	2.1	-1.41959	0.05456	-0.23554	0.3441	1.3212
5.0	-16.02752	2.44418	2.3	-1.55334	0.06006	-0.32899	0.3574	1.1907
3.0	-12.85572	2.16545	2.4	-1.69535	0.07035	-0.35582	0.3756	1.0412
2.0	-10.06892	1.89280	2.5	-1.85191	0.08324	-0.34592	0.3980	0.9514
1.6	-8.68001	1.73516	2.5	-1.92392	0.09060	-0.32977	0.4113	0.8786
1.0	-5.55701	1.36536	2.6	-2.14802	0.11128	-0.27558	0.4357	0.7931
0.75	-3.81429	1.16106	2.6	-2.24164	0.12109	-0.23358	0.4473	0.7972
0.50	-1.74607	0.90876	2.6	-2.37871	0.13582	-0.17883	0.4603	0.7482
0.40	-0.70305	0.78942	2.6	-2.43840	0.14185	-0.14883	0.4676	0.7332
0.30	0.36441	0.65805	2.6	-2.52362	0.15080	-0.11897	0.4780	0.7340
0.24	1.08397	0.58122	2.6	-2.57366	0.15569	-0.10026	0.4874	0.7223
0.20	1.97802	0.50970	2.7	-2.67484	0.16259	-0.08779	0.4971	0.7200
0.16	2.50153	0.45480	2.7	-2.72265	0.16707	-0.07615	0.5121	0.7228
0.15	2.63659	0.44078	2.7	-2.73607	0.16829	-0.07333	0.5192	0.7288
0.12	3.06506	0.40391	2.7	-2.77296	0.17133	-0.06565	0.5375	0.7468
0.10	3.35414	0.37757	2.7	-2.80403	0.17391	-0.06102	0.5558	0.7474
0.080	3.64678	0.35047	2.7	-2.84039	0.17689	-0.05692	0.5693	0.7505
0.070	4.21631	0.31022	2.8	-2.93884	0.18324	-0.05514	0.5766	0.7556
0.060	4.36033	0.29517	2.8	-2.96337	0.18525	-0.05357	0.5834	0.7630
0.055	4.43278	0.28752	2.8	-2.97664	0.18632	-0.05287	0.5875	0.7619
0.050	4.50882	0.27990	2.8	-2.99056	0.18741	-0.05224	0.5930	0.7687
0.040	4.68655	0.26499	2.8	-3.02045	0.18954	-0.05109	0.6105	0.7795
0.032	4.86194	0.25301	2.8	-3.04739	0.19126	-0.05023	0.6201	0.7837
0.025	5.51533	0.21155	2.9	-3.16325	0.19826	-0.04959	0.6197	0.7803
0.020	5.57118	0.19995	2.9	-3.18948	0.20062	-0.04972	0.6119	0.7757
0.010	4.18329	0.23483	2.8	-3.08048	0.20033	-0.05744	0.5616	0.7371
PGA	3.52033	0.27213	2.7	-2.98288	0.19476	-0.05886	0.5564	0.7140
PGV	2.71517	0.80995	2.4	-2.74660	0.19917	-0.09791	0.4373	-

Table 3-26. Gulf Coast.

Regression Coefficients for the Single Corner Model with Constant High Stress Drop

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-14.92343	2.43027	2.9	-2.22382	0.09485	-0.26850	0.5246	1.3793
5.0	-10.18213	2.06757	3.1	-2.51603	0.10917	-0.33532	0.5581	1.2655
3.0	-6.35091	1.71518	3.2	-2.78676	0.12722	-0.33853	0.5890	1.1358
2.0	-2.37232	1.36543	3.4	-3.17502	0.15221	-0.31410	0.6076	1.0564
1.6	-0.80232	1.19788	3.4	-3.29152	0.16227	-0.29176	0.6151	0.9905
1.0	3.21915	0.78973	3.5	-3.68683	0.19276	-0.23069	0.6418	0.9225
0.75	5.08922	0.58119	3.5	-3.85783	0.20794	-0.19127	0.6568	0.9311
0.50	8.29484	0.28003	3.6	-4.23968	0.23616	-0.14131	0.6810	0.9010
0.40	9.43320	0.16200	3.6	-4.36652	0.24675	-0.11874	0.6963	0.8966
0.30	11.74743	-0.02246	3.7	-4.69411	0.26892	-0.09568	0.7183	0.9090
0.24	12.66006	-0.10531	3.7	-4.81457	0.27820	-0.08232	0.7373	0.9098
0.20	13.33561	-0.16266	3.7	-4.90916	0.28523	-0.07402	0.7547	0.9170
0.16	15.26405	-0.29006	3.8	-5.21720	0.30448	-0.06652	0.7780	0.9303
0.15	15.47703	-0.30669	3.8	-5.25065	0.30691	-0.06481	0.7850	0.9369
0.12	16.17236	-0.36176	3.8	-5.36632	0.31558	-0.06017	0.8071	0.9592
0.10	16.69021	-0.40538	3.8	-5.46052	0.32310	-0.05758	0.8206	0.9608
0.080	17.25027	-0.45606	3.8	-5.57097	0.33242	-0.05561	0.8315	0.9646
0.070	18.92158	-0.56453	3.9	-5.85972	0.35100	-0.05491	0.8363	0.9685
0.060	19.25288	-0.59416	3.9	-5.92801	0.35673	-0.05441	0.8422	0.9753
0.055	19.43335	-0.60894	3.9	-5.96446	0.35961	-0.05422	0.8466	0.9757
0.050	19.63311	-0.62400	3.9	-6.00383	0.36256	-0.05406	0.8520	0.9824
0.040	20.10895	-0.65650	3.9	-6.09544	0.36898	-0.05373	0.8598	0.9870
0.032	20.51285	-0.68238	3.9	-6.17374	0.37408	-0.05357	0.8604	0.9849
0.025	19.40352	-0.62778	3.8	-6.01142	0.36670	-0.05403	0.8521	0.9752
0.020	19.51657	-0.64891	3.8	-6.04880	0.37128	-0.05461	0.8464	0.9715
0.010	16.44069	-0.55019	3.7	-5.59549	0.35834	-0.06084	0.7761	0.9112
PGA	16.08302	-0.53416	3.7	-5.54089	0.35572	-0.06160	0.7693	0.9054
PGV	10.74525	0.17413	3.2	-4.45009	0.33923	-0.09819	0.5915	-

Table 3-27. South Carolina.

Regression Coefficients for the Single Corner Model with Constant High Stress Drop

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-20.96056	2.71675	1.4	-1.09530	0.04814	-0.22730	0.3442	1.3212
5.0	-17.49443	2.47125	1.6	-1.18623	0.05274	-0.31935	0.3598	1.1912
3.0	-14.56214	2.20380	1.7	-1.29165	0.06102	-0.34577	0.3703	1.0392
2.0	-12.02019	1.94074	1.8	-1.41253	0.07152	-0.33650	0.3906	0.9481
1.6	-10.51906	1.77922	1.9	-1.50306	0.07918	-0.32073	0.4034	0.8748
1.0	-7.48613	1.43919	2.0	-1.67573	0.09494	-0.26795	0.4347	0.4922
0.75	-5.64199	1.23261	2.1	-1.80682	0.10642	-0.22804	0.4524	0.7998
0.50	-3.49702	0.98628	2.1	-1.93942	0.11890	-0.16965	0.4844	0.7630
0.40	-2.23447	0.85817	2.2	-2.05340	0.12760	-0.14044	0.5092	0.7603
0.30	-0.83895	0.71930	2.3	-2.18694	0.13646	-0.10939	0.5205	0.7620
0.24	0.19834	0.61938	2.4	-2.31041	0.14402	-0.09000	0.5221	0.7460
0.20	0.75953	0.55896	2.4	-2.37683	0.14842	-0.07686	0.5290	0.7423
0.16	1.71843	0.47717	2.5	-2.52375	0.15785	-0.06412	0.5441	0.7457
0.15	2.24624	0.44033	2.6	-2.61513	0.16354	-0.06112	0.5483	0.7496
0.12	3.24012	0.37282	2.7	-2.78683	0.17423	-0.05284	0.5685	0.7690
0.10	4.18107	0.31199	2.8	-2.94569	0.18298	-0.04739	0.5934	0.7755
0.080	4.78769	0.26535	2.8	-3.05138	0.18933	-0.04289	0.6105	0.7818
0.070	5.57485	0.21375	2.9	-3.20785	0.19946	-0.04210	0.6011	0.7744
0.060	5.90954	0.18105	2.9	-3.29094	0.20644	-0.04136	0.6019	0.7766
0.055	6.09980	0.15805	2.9	-3.33603	0.21072	-0.04075	0.6010	0.7723
0.050	6.27420	0.14292	2.9	-3.38074	0.21434	-0.04059	0.5997	0.7733
0.040	6.64603	0.11313	2.9	-3.47773	0.22196	-0.04099	0.6103	0.7791
0.032	6.44287	0.11766	2.8	-3.46082	0.22193	-0.04049	0.6223	0.7852
0.025	6.18975	0.11580	2.7	-3.43970	0.22346	-0.04070	0.6236	0.7829
0.020	5.70463	0.12993	2.6	-3.37433	0.22223	-0.04245	0.6182	0.7806
0.010	3.73644	0.20458	2.5	-3.06845	0.21379	-0.05171	0.5568	0.7328
PGA	3.41869	0.22434	2.5	-3.01216	0.21025	-0.05284	0.5510	0.7290
PGV	1.56942	0.82163	2.0	-2.46320	0.19656	-0.08546	0.4401	-

Table 3-28. Mid-continent.

Regression Coefficients for the Single Corner Model with Constant Medium Stress Drop and Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-17.91423	2.37754	2.3	-1.71861	0.10433	-0.28182	0.3597	1.3253
5.0	-13.91070	2.07364	2.5	-1.88340	0.11388	-0.35716	0.3757	1.1963
3.0	-10.54155	1.75532	2.6	-2.04882	0.12727	-0.36524	0.4010	1.0506
2.0	-7.62375	1.45642	2.7	-2.22717	0.14299	-0.34147	0.4264	0.9637
1.6	-6.23481	1.29417	2.7	-2.30231	0.15083	-0.31913	0.4385	0.8917
1.0	-3.08744	0.91539	2.8	-2.54658	0.17419	-0.25719	0.4583	0.8057
0.75	-1.41000	0.71797	2.8	-2.64410	0.18452	-0.21379	0.4674	0.8087
0.50	0.51857	0.48452	2.8	-2.78232	0.19943	-0.16236	0.4790	0.7599
0.40	1.46377	0.37971	2.8	-2.84201	0.20543	-0.13639	0.4863	0.7453
0.30	2.42583	0.26430	2.8	-2.92775	0.21443	-0.11161	0.4964	0.7461
0.24	3.06862	0.19946	2.8	-2.97730	0.21920	-0.09681	0.5054	0.7345
0.20	3.53193	0.15880	2.8	-3.01048	0.22207	-0.08732	0.5147	0.7322
0.16	4.46498	0.08019	2.9	-3.13934	0.23200	-0.07861	0.5289	0.7348
0.15	4.58602	0.06845	2.9	-3.15246	0.23315	-0.07654	0.5356	0.7405
0.12	4.97456	0.03821	2.9	-3.18830	0.23596	-0.07097	0.5530	0.7580
0.10	5.23836	0.01612	2.9	-3.21848	0.23835	-0.06764	0.5706	0.7585
0.080	5.50813	-0.00703	2.9	-3.25386	0.24112	-0.06471	0.5834	0.7612
0.070	5.63835	-0.01981	2.9	-3.27511	0.24282	-0.06344	0.5906	0.7664
0.060	6.30181	-0.07040	3.0	-3.39174	0.25111	-0.06233	0.5972	0.7736
0.055	6.37083	-0.07735	3.0	-3.40488	0.25213	-0.06184	0.6011	0.7724
0.050	6.44374	-0.08429	3.0	-3.41866	0.25316	-0.06139	0.6063	0.7790
0.040	6.61705	-0.09799	3.0	-3.44851	0.25520	-0.06059	0.6231	0.7894
0.032	6.79091	-0.10914	3.0	-3.47572	0.25685	-0.05996	0.6323	0.7934
0.025	6.96175	-0.12090	3.0	-3.50625	0.25870	-0.05949	0.6320	0.7901
0.020	7.60902	-0.17372	3.1	-3.63508	0.26806	-0.05964	0.6240	0.7853
0.010	5.56137	-0.09020	2.9	-3.40512	0.25856	-0.06603	0.5741	0.7467
PGA	5.35011	-0.08193	2.9	-3.38707	0.25794	-0.06717	0.5689	0.7427
PGV	4.40490	0.47616	2.6	-3.09544	0.25711	-0.11505	0.4493	-

Table 3-29. Gulf Coast.

Regression Coefficients for the Single Corner Model with Constant Medium Stress Drop and Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-12.36761	2.03153	3.1	-2.63877	0.15707	-0.31008	0.5339	1.3828
5.0	-7.18334	1.59845	3.3	-2.98527	0.17746	-0.35477	0.5716	1.2715
3.0	-3.08593	1.20331	3.4	-3.29709	0.20010	-0.34026	0.6050	1.1441
2.0	1.25366	0.80656	3.6	-3.74757	0.23195	-0.30344	0.6221	1.0648
1.6	2.84583	0.63403	3.6	-3.87433	0.24315	-0.27642	0.6282	0.9987
1.0	7.02300	0.20984	3.7	-4.31520	0.27841	-0.21186	0.6525	0.9300
0.75	8.82898	0.01214	3.7	-4.49285	0.29408	-0.17435	0.6669	0.9382
0.50	12.13819	-0.29103	3.8	-4.91519	0.32617	-0.13035	0.6911	0.9086
0.40	13.22694	-0.39862	3.8	-5.04733	0.33707	-0.11168	0.7063	0.9044
0.30	14.47052	-0.51361	3.8	-5.20994	0.34992	-0.09344	0.7278	0.9165
0.24	16.60473	-0.66904	3.9	-5.54036	0.37238	-0.08331	0.7461	0.9169
0.20	17.26232	-0.72060	3.9	-5.63758	0.37933	-0.07720	0.7626	0.9235
0.16	18.00368	-0.77536	3.9	-5.75279	0.38735	-0.07183	0.7850	0.9362
0.15	18.20699	-0.79010	3.9	-5.78572	0.38965	-0.07062	0.7917	0.9425
0.12	20.35514	-0.93590	4.0	-6.14146	0.41343	-0.06740	0.8126	0.9639
0.10	20.87722	-0.97756	4.0	-6.23744	0.42083	-0.06563	0.8251	0.9646
0.080	21.44261	-1.02649	4.0	-6.34895	0.42994	-0.06434	0.8350	0.9676
0.070	21.74098	-1.05317	4.0	-6.41027	0.43505	-0.06391	0.8394	0.9711
0.060	22.05839	-1.08042	4.0	-6.47563	0.44033	-0.06363	0.8448	0.9775
0.055	22.23245	-1.09401	4.0	-6.51064	0.44297	-0.06354	0.8489	0.9777
0.050	22.42674	-1.10792	4.0	-6.54872	0.44569	-0.06346	0.8540	0.9841
0.040	22.89529	-1.13831	4.0	-6.63833	0.45168	-0.06330	0.8613	0.9883
0.032	23.29188	-1.16219	4.0	-6.71452	0.45635	-0.06322	0.8618	0.9861
0.025	23.64102	-1.19389	4.0	-6.79201	0.46299	-0.06368	0.8532	0.9761
0.020	23.74361	-1.21411	4.0	-6.82593	0.46721	-0.06417	0.8477	0.9726
0.010	18.80216	-0.98785	3.8	-6.06348	0.43296	-0.06926	0.7782	0.9130
PGA	18.44350	-0.97271	3.8	-6.00839	0.43044	-0.06984	0.7716	0.9073
PGV	13.42744	-0.26637	3.4	-4.94368	0.41289	-0.11734	0.5929	-

Table 3-30. South Carolina.

Regression Coefficients for the Single Corner Model with Constant Medium Stress Drop and Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-19.49851	2.44358	1.6	-1.33851	0.09176	-0.27226	0.3535	1.3235
5.0	-15.76713	2.14489	1.8	-1.44976	0.09921	-0.34622	0.3736	1.1955
3.0	-12.68162	1.84290	1.9	-1.57135	0.10979	-0.35445	0.3918	1.0469
2.0	-10.05969	1.55925	2.0	-1.70560	0.12218	-0.33162	0.4162	0.9591
1.6	-8.51490	1.38716	2.1	-1.80673	0.13133	-0.30941	0.4286	0.8866
1.0	-5.47426	1.03910	2.2	-1.99534	0.14929	-0.24741	0.4556	0.8039
0.75	-3.89260	0.85098	2.2	-2.09267	0.15905	-0.20613	0.4708	0.8102
0.50	-1.64473	0.60671	2.3	-2.27192	0.17484	-0.15102	0.5011	0.7739
0.40	-0.41821	0.48551	2.4	-2.39510	0.18462	-0.12553	0.5259	0.7711
0.30	0.92932	0.35642	2.5	-2.53880	0.19457	-0.09967	0.5377	0.7737
0.24	1.61284	0.28534	2.5	-2.61087	0.19894	-0.08407	0.5392	0.7580
0.20	2.47822	0.20789	2.6	-2.74128	0.20773	-0.07378	0.5456	0.7538
0.16	3.46248	0.12632	2.7	-2.90065	0.21841	-0.06411	0.5599	0.7568
0.15	3.62759	0.11304	2.7	-2.92848	0.22023	-0.06190	0.5639	0.7606
0.12	5.11216	0.01138	2.9	-3.19187	0.23767	-0.05589	0.5844	0.7809
0.10	6.13834	-0.05642	3.0	-3.36770	0.24805	-0.05185	0.6093	0.7878
0.080	6.73520	-0.09898	3.0	-3.47378	0.25405	-0.04855	0.6243	0.7928
0.070	7.61948	-0.15985	3.1	-3.64537	0.26565	-0.04820	0.6149	0.7846
0.060	7.94524	-0.19015	3.1	-3.72601	0.27212	-0.04780	0.6154	0.7874
0.055	7.51087	-0.16870	3.0	-3.66142	0.26868	-0.04730	0.6137	0.7817
0.050	7.67232	-0.18185	3.0	-3.70297	0.27185	-0.04724	0.6121	0.7834
0.040	8.02069	-0.20800	3.0	-3.79370	0.27856	-0.04769	0.6224	0.7886
0.032	8.35117	-0.23555	3.0	-3.86993	0.28396	-0.04714	0.6345	0.7948
0.025	7.41237	-0.18438	2.8	-3.72699	0.27609	-0.04718	0.6346	0.7917
0.020	6.86192	-0.16191	2.7	-3.64908	0.27323	-0.04870	0.6289	0.7885
0.010	4.84985	-0.08535	2.6	-3.33178	0.26390	-0.05662	0.5686	0.7420
PGA	4.53538	-0.06647	2.6	-3.27599	0.26049	-0.05758	0.5630	0.7382
PGV	2.58628	0.55455	2.1	-2.68278	0.24143	-0.09813	0.4489	-

Table 3-31. Mid-continent.

Regression Coefficients for the Single Corner Model with Constant Low Stress Drop and Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-17.52612	2.29529	2.3	-1.73008	0.10536	-0.31139	0.3654	1.3269
5.0	-13.58249	1.96072	2.4	-1.85975	0.11403	-0.36489	0.3842	1.1990
3.0	-9.90982	1.60565	2.6	-2.07280	0.13069	-0.35444	0.4138	1.0556
2.0	-7.30278	1.31553	2.6	-2.19863	0.14381	-0.31786	0.4378	0.9688
1.6	-5.63265	1.13348	2.7	-2.32961	0.15521	-0.29038	0.4474	0.8961
1.0	-2.93381	0.78321	2.7	-2.51701	0.17588	-0.22374	0.4634	0.8086
0.75	-1.34540	0.59571	2.7	-2.61803	0.18691	-0.18095	0.4712	0.8109
0.50	0.44711	0.37973	2.7	-2.76056	0.20271	-0.13385	0.4831	0.7625
0.40	1.32039	0.28510	2.7	-2.82477	0.20944	-0.11167	0.4912	0.7485
0.30	2.19908	0.18130	2.7	-2.91311	0.21897	-0.09104	0.5021	0.7499
0.24	2.78943	0.12398	2.7	-2.96449	0.22409	-0.07915	0.5117	0.7389
0.20	3.21855	0.08824	2.7	-2.99921	0.22724	-0.07171	0.5213	0.7369
0.16	3.64126	0.04811	2.7	-3.04474	0.23151	-0.06490	0.5358	0.7398
0.15	3.75047	0.03785	2.7	-3.05739	0.23266	-0.06330	0.5426	0.7456
0.12	4.56076	-0.02108	2.8	-3.17249	0.24111	-0.05900	0.5601	0.7632
0.10	4.80550	-0.04079	2.8	-3.20187	0.24348	-0.05641	0.5777	0.7638
0.080	5.05581	-0.06166	2.8	-3.23598	0.24617	-0.05411	0.5906	0.7668
0.070	5.17534	-0.07324	2.8	-3.25620	0.24779	-0.05310	0.5976	0.7718
0.060	5.29605	-0.08523	2.8	-3.27840	0.24954	-0.05220	0.6042	0.7791
0.055	5.35709	-0.09141	2.8	-3.29040	0.25047	-0.05181	0.6081	0.7779
0.050	5.92808	-0.13394	2.9	-3.39211	0.25767	-0.05145	0.6133	0.7844
0.040	6.08901	-0.14646	2.9	-3.42020	0.25956	-0.05080	0.6300	0.7949
0.032	6.25258	-0.15669	2.9	-3.44589	0.26109	-0.05027	0.6391	0.7989
0.025	6.41230	-0.16752	2.9	-3.47458	0.26279	-0.04987	0.6388	0.7956
0.020	7.01484	-0.21767	3.0	-3.59567	0.27165	-0.04999	0.6309	0.7908
0.010	5.03603	-0.13680	2.8	-3.37101	0.26174	-0.05542	0.5808	0.7518
PGA	4.83071	-0.12898	2.8	-3.35311	0.26108	-0.05639	0.5755	0.7477
PGV	3.99963	0.43627	2.5	-3.04259	0.25625	-0.11476	0.4549	-

Table 3-32. Gulf Coast.

Regression Coefficients for the Single Corner Model with Constant Low Stress Drop and Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-12.34486	1.95845	3.0	-2.57317	0.15404	-0.33355	0.5320	1.3821
5.0	-7.12762	1.49148	3.2	-2.91057	0.17493	-0.35373	0.5744	1.2728
3.0	-2.46635	1.04807	3.4	-3.32053	0.20386	-0.32203	0.6080	1.1457
2.0	1.09160	0.68925	3.5	-3.64922	0.22956	-0.27498	0.6233	1.0655
1.6	2.63452	0.51855	3.5	-3.77700	0.24128	-0.24479	0.6289	0.9992
1.0	6.58784	0.11210	3.6	-4.20864	0.27695	-0.17953	0.6525	0.9300
0.75	9.24442	-0.13451	3.7	-4.54798	0.30336	-0.14471	0.6676	0.9387
0.50	11.35480	-0.35323	3.7	-4.79775	0.32541	-0.10635	0.6930	0.9101
0.40	12.35996	-0.45077	3.7	-4.92830	0.33648	-0.09086	0.7090	0.9065
0.30	14.67303	-0.63086	3.8	-5.28067	0.36186	-0.07617	0.7309	0.9190
0.24	15.48361	-0.69729	3.8	-5.40014	0.37090	-0.06824	0.7493	0.9195
0.20	16.08791	-0.74305	3.8	-5.49275	0.37755	-0.06353	0.7658	0.9261
0.16	18.11166	-0.87999	3.9	-5.82243	0.39947	-0.05945	0.7878	0.9385
0.15	18.30605	-0.89356	3.9	-5.85465	0.40170	-0.05854	0.7942	0.9446
0.12	18.94247	-0.93912	3.9	-5.96502	0.40954	-0.05610	0.8148	0.9657
0.10	19.41416	-0.97570	3.9	-6.05319	0.41621	-0.05476	0.8269	0.9662
0.080	19.91774	-1.01826	3.9	-6.15421	0.42427	-0.05379	0.8362	0.9687
0.070	20.18058	-1.04126	3.9	-6.20917	0.42872	-0.05347	0.8403	0.9719
0.060	20.45986	-1.06460	3.9	-6.26753	0.43327	-0.05328	0.8454	0.9780
0.055	20.61413	-1.07622	3.9	-6.29889	0.43554	-0.05322	0.8493	0.9781
0.050	20.78819	-1.08818	3.9	-6.33324	0.43789	-0.05317	0.8543	0.9844
0.040	21.21243	-1.11449	3.9	-6.41476	0.44311	-0.05305	0.8614	0.9884
0.032	21.57041	-1.13489	3.9	-6.48374	0.44710	-0.05297	0.8618	0.9861
0.025	21.87723	-1.16223	3.9	-6.55296	0.45285	-0.05337	0.8530	0.9759
0.020	21.95228	-1.17915	3.9	-6.58099	0.45634	-0.05377	0.8474	0.9723
0.010	17.30516	-0.96734	3.7	-5.85881	0.42361	-0.05803	0.7783	0.9131
PGA	16.96725	-0.95374	3.7	-5.80700	0.42132	-0.05852	0.7718	0.9075
PGV	12.26101	-0.23705	3.3	-4.74443	0.39834	-0.11859	0.5911	-

Table 3-33. South Carolina.

Regression Coefficients for the Single Corner Model with Constant Low Stress Drop and Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-19.22315	2.37688	1.6	-1.32848	0.09002	-0.30354	0.3601	1.3254
5.0	-15.44147	2.04218	1.7	-1.42322	0.09738	-0.35549	0.3837	1.1986
3.0	-12.16021	1.70907	1.9	-1.57394	0.11033	-0.34567	0.4072	1.0529
2.0	-9.54716	1.41649	2.0	-1.70958	0.12320	-0.31030	0.4309	0.9653
1.6	-8.22053	1.25676	2.0	-1.77592	0.13019	-0.28289	0.4412	0.8929
1.0	-5.32394	0.92033	2.1	-1.95912	0.14797	-0.21544	0.4625	0.8078
0.75	-3.63748	0.73048	2.2	-2.09406	0.16035	-0.17521	0.4756	0.8131
0.50	-1.58622	0.51303	2.3	-2.26702	0.17549	-0.12585	0.5049	0.7759
0.40	-0.46884	0.40732	2.4	-2.38628	0.18485	-0.10455	0.5296	0.7738
0.30	0.75586	0.29579	2.5	-2.52527	0.19430	-0.08371	0.5415	0.7765
0.24	1.36003	0.23615	2.5	-2.59389	0.19828	-0.07141	0.5428	0.7602
0.20	2.16308	0.16737	2.6	-2.72013	0.20662	-0.06349	0.5488	0.7560
0.16	3.07766	0.09545	2.7	-2.87355	0.21662	-0.05627	0.5622	0.7590
0.15	3.22568	0.08459	2.7	-2.89981	0.21825	-0.05466	0.5660	0.7628
0.12	4.64940	-0.00917	2.9	-3.15639	0.23494	-0.05034	0.5857	0.7816
0.10	5.63634	-0.07192	3.0	-3.32739	0.24478	-0.04729	0.6102	0.7885
0.080	6.19239	-0.10902	3.0	-3.42712	0.24999	-0.04480	0.6248	0.7928
0.070	7.04069	-0.16563	3.1	-3.59195	0.26081	-0.04473	0.6152	0.7853
0.060	7.33406	-0.19183	3.1	-3.66580	0.26644	-0.04450	0.6155	0.7874
0.055	6.89341	-0.16928	3.0	-3.59932	0.26271	-0.04406	0.6135	0.7817
0.050	7.03853	-0.18041	3.0	-3.63716	0.26541	-0.04403	0.6118	0.7826
0.040	7.35482	-0.20260	3.0	-3.72031	0.27118	-0.04447	0.6220	0.7886
0.032	7.06323	-0.18554	2.9	-3.68550	0.26862	-0.04383	0.6339	0.7940
0.025	6.73104	-0.17676	2.8	-3.64741	0.26785	-0.04371	0.6339	0.7909
0.020	6.18299	-0.15452	2.7	-3.56843	0.26482	-0.04502	0.6284	0.7885
0.010	4.21704	-0.08408	2.6	-3.25598	0.25607	-0.05184	0.5685	0.7420
PGA	3.91273	-0.06646	2.6	-3.20209	0.25288	-0.05268	0.5631	0.7382
PGV	2.14049	0.54448	2.1	-2.61030	0.23387	-0.10207	0.4513	-

Table 3-34. Mid-continent.

Regression Coefficients for the Single Corner Model with Constant High Stress Drop and Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-17.92122	2.41939	2.4	-1.76932	0.10861	-0.24700	0.3539	1.3238
5.0	-14.33292	2.17359	2.5	-1.88598	0.11439	-0.34044	0.3691	1.1943
3.0	-11.07071	1.88506	2.6	-2.04376	0.12639	-0.36727	0.3895	1.0463
2.0	-8.18384	1.60124	2.7	-2.21757	0.14122	-0.35737	0.4130	0.9578
1.6	-6.43297	1.42055	2.8	-2.35414	0.15261	-0.34123	0.4266	0.8859
1.0	-3.52171	1.05720	2.8	-2.53979	0.17215	-0.28704	0.4510	0.8016
0.75	-1.75176	0.85016	2.8	-2.63826	0.18244	-0.24504	0.4627	0.8060
0.50	0.35595	0.59376	2.8	-2.78233	0.19789	-0.19028	0.4757	0.7578
0.40	1.41567	0.47284	2.8	-2.84495	0.20419	-0.16028	0.4829	0.7431
0.30	2.50733	0.33905	2.8	-2.93443	0.21356	-0.13042	0.4931	0.7439
0.24	3.24100	0.26094	2.8	-2.98696	0.21867	-0.11171	0.5023	0.7324
0.20	3.76921	0.21066	2.8	-3.02221	0.22178	-0.09924	0.5118	0.7302
0.16	4.77362	0.12203	2.9	-3.15491	0.23211	-0.08761	0.5265	0.7331
0.15	4.91274	0.10766	2.9	-3.16905	0.23338	-0.08479	0.5334	0.7389
0.12	5.35255	0.06996	2.9	-3.20795	0.23656	-0.07711	0.5513	0.7567
0.10	5.65135	0.04288	2.9	-3.24075	0.23928	-0.07247	0.5693	0.7575
0.080	5.95548	0.01492	2.9	-3.27916	0.24241	-0.06838	0.5826	0.7606
0.070	6.10266	-0.00018	2.9	-3.30216	0.24432	-0.06659	0.5900	0.7659
0.060	6.25069	-0.01554	2.9	-3.32741	0.24639	-0.06502	0.5969	0.7734
0.055	6.86357	-0.06114	3.0	-3.43540	0.25399	-0.06433	0.6009	0.7723
0.050	6.94435	-0.06911	3.0	-3.45017	0.25514	-0.06369	0.6063	0.7790
0.040	7.13246	-0.08472	3.0	-3.48193	0.25740	-0.06255	0.6234	0.7897
0.032	7.31723	-0.09725	3.0	-3.51057	0.25921	-0.06168	0.6328	0.7938
0.025	7.49863	-0.11031	3.0	-3.54270	0.26124	-0.06105	0.6326	0.7906
0.020	8.16024	-0.16443	3.1	-3.67439	0.27088	-0.06117	0.6248	0.7859
0.010	6.09264	-0.07836	2.9	-3.44793	0.26192	-0.06890	0.5749	0.7473
PGA	5.87466	-0.06918	2.9	-3.42987	0.26131	-0.07032	0.5697	0.7433
PGV	4.79171	0.49399	2.6	-3.14834	0.26171	-0.10937	0.4492	-

Table 3-35. Gulf Coast.

Regression Coefficients for the Single Corner Model with Constant High Stress Drop and Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-12.65135	2.09962	3.1	-2.65372	0.15931	-0.27995	0.5362	1.3837
5.0	-7.63385	1.70983	3.3	-2.99118	0.17807	-0.34677	0.5704	1.2710
3.0	-2.92833	1.29933	3.5	-3.40943	0.20580	-0.34999	0.6013	1.1422
2.0	0.76119	0.94998	3.6	-3.74466	0.23048	-0.32555	0.6196	1.0634
1.6	2.38331	0.77804	3.6	-3.87013	0.24129	-0.30322	0.6270	0.9980
1.0	6.70599	0.34088	3.7	-4.31367	0.27643	-0.24215	0.6534	0.9306
0.75	8.65230	0.12586	3.7	-4.49751	0.29269	-0.20273	0.6683	0.9392
0.50	12.17467	-0.20531	3.8	-4.92914	0.32564	-0.15276	0.6921	0.9094
0.40	13.37181	-0.32798	3.8	-5.06579	0.33699	-0.13019	0.7071	0.9050
0.30	14.74399	-0.46111	3.8	-5.23503	0.35058	-0.10713	0.7288	0.9173
0.24	16.97448	-0.62936	3.9	-5.57259	0.37377	-0.09378	0.7475	0.9181
0.20	17.69717	-0.69006	3.9	-5.67505	0.38135	-0.08547	0.7645	0.9250
0.16	18.50771	-0.75440	3.9	-5.79682	0.39016	-0.07798	0.7875	0.9383
0.15	20.19141	-0.86646	4.0	-6.07056	0.40801	-0.07627	0.7944	0.9448
0.12	20.94827	-0.92609	4.0	-6.19648	0.41744	-0.07162	0.8162	0.9669
0.10	21.51625	-0.97369	4.0	-6.29904	0.42562	-0.06904	0.8294	0.9683
0.080	22.13508	-1.02936	4.0	-6.41929	0.43578	-0.06706	0.8401	0.9721
0.070	22.46355	-1.05978	4.0	-6.48596	0.44153	-0.06636	0.8449	0.9760
0.060	22.81270	-1.09092	4.0	-6.55721	0.44750	-0.06586	0.8508	0.9827
0.055	23.00275	-1.10647	4.0	-6.59524	0.45051	-0.06568	0.8551	0.9831
0.050	23.21284	-1.12231	4.0	-6.63632	0.45359	-0.06551	0.8603	0.9896
0.040	23.71273	-1.15652	4.0	-6.73191	0.46030	-0.06519	0.8679	0.9941
0.032	24.13701	-1.18374	4.0	-6.81358	0.46562	-0.06503	0.8687	0.9922
0.025	24.51845	-1.21926	4.0	-6.89791	0.47308	-0.06549	0.8601	0.9822
0.020	24.64848	-1.24267	4.0	-6.93799	0.47804	-0.06606	0.8546	0.9786
0.010	19.65149	-1.01014	3.8	-6.17228	0.44358	-0.07230	0.7848	0.9186
PGA	19.28060	-0.99348	3.8	-6.11546	0.44085	-0.07305	0.7781	0.9129
PGV	14.16517	-0.28835	3.4	-5.07478	0.42615	-0.10965	0.6001	-

Table 3-36. South Carolina.

Regression Coefficients for the Single Corner Model with Constant High Stress Drop and Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-19.69964	2.49541	1.6	-1.35424	0.09427	-0.23731	0.3464	1.3217
5.0	-16.16105	2.24103	1.8	-1.45825	0.10047	-0.32935	0.3653	1.1930
3.0	-13.17561	1.96739	1.9	-1.57341	0.10989	-0.35578	0.3785	1.0421
2.0	-10.39119	1.68495	2.1	-1.73909	0.12390	-0.34651	0.4005	0.9523
1.6	-9.01636	1.52890	2.1	-1.80570	0.13054	-0.33074	0.4139	0.8794
1.0	-5.90447	1.17978	2.2	-1.99249	0.14792	-0.27796	0.4465	0.7988
0.75	-3.98706	0.96465	2.3	-2.13635	0.16089	-0.23804	0.4648	0.8067
0.50	-1.53095	0.69527	2.4	-2.32575	0.17750	-0.17966	0.4974	0.7714
0.40	-0.47383	0.57909	2.4	-2.40142	0.18398	-0.15044	0.5223	0.7691
0.30	1.00761	0.43107	2.5	-2.54967	0.19440	-0.11939	0.5339	0.7709
0.24	2.13449	0.32163	2.6	-2.68835	0.20357	-0.10000	0.5354	0.7552
0.20	2.71500	0.26001	2.6	-2.75836	0.20818	-0.08687	0.5421	0.7517
0.16	3.77719	0.16754	2.7	-2.92274	0.21940	-0.07412	0.5572	0.7553
0.15	4.39753	0.12042	2.8	-3.02933	0.22679	-0.07112	0.5616	0.7591
0.12	5.51538	0.04067	2.9	-3.22165	0.23948	-0.06285	0.5830	0.7801
0.10	6.58742	-0.03320	3.0	-3.40224	0.25038	-0.05740	0.6082	0.7870
0.080	7.23410	-0.08251	3.0	-3.51535	0.25724	-0.05290	0.6238	0.7920
0.070	8.15944	-0.14834	3.1	-3.69429	0.26969	-0.05210	0.6147	0.7846
0.060	8.52466	-0.18367	3.1	-3.78287	0.27715	-0.05137	0.6156	0.7874
0.055	8.73233	-0.20849	3.1	-3.83113	0.28176	-0.05076	0.6140	0.7825
0.050	8.92221	-0.22488	3.1	-3.87857	0.28560	-0.05060	0.6127	0.7834
0.040	8.66995	-0.21066	3.0	-3.86665	0.28566	-0.05100	0.6232	0.7893
0.032	9.02849	-0.24163	3.0	-3.94975	0.29191	-0.05050	0.6354	0.7956
0.025	8.68242	-0.23353	2.9	-3.91406	0.29188	-0.05071	0.6356	0.7925
0.020	7.53592	-0.16817	2.7	-3.73234	0.28177	-0.05246	0.6298	0.7893
0.010	5.47014	-0.08443	2.6	-3.40962	0.27179	-0.06172	0.5689	0.7420
PGA	5.14426	-0.06415	2.6	-3.35183	0.26815	-0.06285	0.5632	0.7383
PGV	3.01933	0.56635	2.1	-2.75593	0.24888	-0.09546	0.4467	-

Table 3-37. Mid-continent.

Regression Coefficients for the Double Corner Model

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-17.74463	2.22485	2.1	-1.40084	0.05305	-0.31641	0.3559	1.3243
5.0	-13.88893	1.89859	2.3	-1.54772	0.06068	-0.28960	0.3660	1.1933
3.0	-11.04809	1.64665	2.4	-1.70010	0.07272	-0.22943	0.3892	1.0462
2.0	-8.76880	1.45200	2.5	-1.86494	0.08722	-0.18125	0.4160	0.9591
1.6	-7.68301	1.34978	2.5	-1.94573	0.09603	-0.16127	0.4297	0.8874
1.0	-5.47019	1.12590	2.5	-2.13473	0.11710	-0.13830	0.4518	0.8021
0.75	-3.77355	0.98718	2.6	-2.28113	0.13007	-0.13323	0.4610	0.8050
0.50	-1.95968	0.80810	2.6	-2.41132	0.14449	-0.12529	0.4714	0.7551
0.40	-0.96872	0.71370	2.6	-2.46500	0.15003	-0.11749	0.4775	0.7396
0.30	0.10920	0.59537	2.6	-2.54120	0.15808	-0.10506	0.4865	0.7395
0.24	0.86777	0.52085	2.6	-2.58506	0.16235	-0.09484	0.4950	0.7274
0.20	1.42831	0.46988	2.6	-2.61380	0.16486	-0.08671	0.5040	0.7247
0.16	1.99361	0.41219	2.6	-2.65510	0.16868	-0.07801	0.5181	0.7271
0.15	2.14018	0.39715	2.6	-2.66676	0.16973	-0.07573	0.5249	0.7328
0.12	2.60454	0.35667	2.6	-2.69927	0.17238	-0.06929	0.5424	0.7503
0.10	3.30684	0.30373	2.7	-2.79751	0.17893	-0.06512	0.5602	0.7507
0.080	3.62400	0.27369	2.7	-2.83163	0.18170	-0.06128	0.5731	0.7534
0.070	3.77510	0.25773	2.7	-2.85226	0.18339	-0.05952	0.5803	0.7585
0.060	3.92454	0.24169	2.7	-2.87495	0.18521	-0.05791	0.5868	0.7656
0.055	3.99907	0.23357	2.7	-2.88734	0.18619	-0.05717	0.5907	0.7644
0.050	4.07670	0.22547	2.7	-2.90040	0.18720	-0.05647	0.5961	0.7711
0.040	4.69293	0.18262	2.8	-3.00672	0.19396	-0.05520	0.6133	0.7817
0.032	4.86717	0.17018	2.8	-3.03252	0.19560	-0.05434	0.6227	0.7858
0.025	5.03119	0.15779	2.8	-3.06134	0.19746	-0.05377	0.6222	0.7823
0.020	5.06834	0.14806	2.8	-3.08409	0.19935	-0.05361	0.6143	0.7776
0.010	3.74623	0.18152	2.7	-2.98867	0.19854	-0.05734	0.5644	0.7392
PGA	3.54103	0.18904	2.7	-2.97418	0.19819	-0.05814	0.5592	0.7353
PGV	4.06989	0.46794	2.5	-2.77481	0.19743	-0.07606	0.4408	-

Table 3-38. Gulf Coast.

Regression Coefficients for the Double Corner Model

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-16.41379	2.20767	2.5	-1.74567	0.06829	-0.33131	0.5243	1.3791
5.0	-12.20468	1.83553	2.7	-1.95111	0.07737	-0.29415	0.5604	1.2665
3.0	-8.83853	1.54958	2.9	-2.21747	0.09356	-0.23217	0.5958	1.1393
2.0	-6.28665	1.33826	3.0	-2.43987	0.10973	-0.18303	0.6159	1.0612
1.6	-5.10947	1.24004	3.0	-2.53021	0.11775	-0.16323	0.6233	0.9956
1.0	-2.15831	0.99778	3.1	-2.82918	0.14191	-0.13999	0.6483	0.9271
0.75	-0.12511	0.83880	3.2	-3.05030	0.15823	-0.13454	0.6622	0.9349
0.50	1.93674	0.64984	3.2	-3.22152	0.17312	-0.12608	0.6850	0.9040
0.40	2.99580	0.55002	3.2	-3.30621	0.17993	-0.11838	0.6996	0.8991
0.30	4.87830	0.39924	3.3	-3.51506	0.19281	-0.10565	0.7208	0.9109
0.24	5.74732	0.31977	3.3	-3.58708	0.19746	-0.09504	0.7389	0.9111
0.20	7.09082	0.22710	3.4	-3.76365	0.20689	-0.08680	0.7556	0.9177
0.16	7.79199	0.16914	3.4	-3.83080	0.21046	-0.07794	0.7783	0.9306
0.15	7.97786	0.15425	3.4	-3.85005	0.21146	-0.07567	0.7850	0.9369
0.12	9.36118	0.06628	3.5	-4.05250	0.22188	-0.06891	0.8064	0.9587
0.10	9.79610	0.03112	3.5	-4.11197	0.22526	-0.06459	0.8192	0.9596
0.080	10.26367	-0.00857	3.5	-4.18673	0.22992	-0.06062	0.8294	0.9628
0.070	10.51625	-0.03055	3.5	-4.23161	0.23289	-0.05885	0.8339	0.9664
0.060	11.69837	-0.10103	3.6	-4.43516	0.24410	-0.05724	0.8396	0.9730
0.055	11.85646	-0.11325	3.6	-4.46406	0.24596	-0.05650	0.8438	0.9733
0.050	12.02874	-0.12544	3.6	-4.49489	0.24783	-0.05578	0.8491	0.9799
0.040	12.42738	-0.15043	3.6	-4.56505	0.25176	-0.05445	0.8566	0.9842
0.032	13.81046	-0.22653	3.7	-4.80279	0.26447	-0.05370	0.8572	0.9821
0.025	14.14384	-0.25488	3.7	-4.87587	0.26995	-0.05318	0.8487	0.9722
0.020	14.33926	-0.28175	3.7	-4.93249	0.27571	-0.05331	0.8430	0.9685
0.010	11.07839	-0.18783	3.5	-4.49420	0.26735	-0.05801	0.7733	0.9088
PGA	9.90148	-0.12757	3.4	-4.30771	0.25806	-0.05882	0.7666	0.9031
PGV	8.13980	0.18271	3.0	-3.72218	0.26644	-0.08657	0.5888	-

Table 3-39. South Carolina.

Regression Coefficients for the Double Corner Model

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-18.93236	2.27993	1.4	-1.06291	0.04229	-0.31157	0.3573	1.3246
5.0	-15.32941	1.96381	1.6	-1.16602	0.04855	-0.28613	0.3696	1.1942
3.0	-12.69571	1.72502	1.7	-1.28057	0.05826	-0.22678	0.3852	1.0446
2.0	-10.65171	1.53696	1.8	-1.41349	0.07071	-0.17758	0.4102	0.9565
1.6	-9.46782	1.43351	1.9	-1.51015	0.07943	-0.15705	0.4239	0.8842
1.0	-7.11822	1.23406	2.0	-1.69182	0.09700	-0.13487	0.4531	0.8027
0.75	-5.79677	1.11610	2.0	-1.78608	0.10679	-0.12968	0.4684	0.8090
0.50	-3.73490	0.93677	2.1	-1.94936	0.12121	-0.12104	0.4972	0.7714
0.40	-2.52562	0.83241	2.2	-2.05788	0.12956	-0.11290	0.5207	0.7677
0.30	-1.13018	0.70786	2.3	-2.18295	0.13777	-0.10011	0.5309	0.7689
0.24	-0.35177	0.62905	2.3	-2.24581	0.14133	-0.08941	0.5314	0.7524
0.20	0.51391	0.55291	2.4	-2.35535	0.14773	-0.08074	0.5373	0.7481
0.16	1.49696	0.47163	2.5	-2.49086	0.15563	-0.07112	0.5514	0.7509
0.15	1.68117	0.45595	2.5	-2.51565	0.15710	-0.06869	0.5555	0.7547
0.12	3.02922	0.36865	2.7	-2.73792	0.16992	-0.06161	0.5755	0.7742
0.10	3.96807	0.30969	2.8	-2.88687	0.17721	-0.05645	0.5996	0.7801
0.080	5.06042	0.23658	2.9	-3.07011	0.18687	-0.05144	0.6155	0.7857
0.070	5.39001	0.21283	2.9	-3.14219	0.19157	-0.05016	0.6062	0.7783
0.060	5.76317	0.17770	2.9	-3.23069	0.19853	-0.04874	0.6069	0.7804
0.055	5.97780	0.15309	2.9	-3.27987	0.20285	-0.04765	0.6057	0.7755
0.050	6.72839	0.10286	3.0	-3.42641	0.21245	-0.04709	0.6044	0.7772
0.040	7.17691	0.06703	3.0	-3.53823	0.22097	-0.04667	0.6152	0.7830
0.032	7.00112	0.06791	2.9	-3.52780	0.22143	-0.04532	0.6271	0.7892
0.025	6.77623	0.06147	2.8	-3.51436	0.22369	-0.04456	0.6282	0.7869
0.020	6.29650	0.07241	2.7	-3.45328	0.22311	-0.04543	0.6231	0.7845
0.010	4.24595	0.14544	2.6	-3.14071	0.21510	-0.05128	0.5625	0.7374
PGA	3.49869	0.19289	2.5	-3.00815	0.20682	-0.05234	0.5568	0.7334
PGV	2.84051	0.54156	2.1	-2.47969	0.18992	-0.07781	0.4470	-

Table 3-40. Mid-continent.

Regression Coefficients for the Double Corner Model with Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-16.16329	1.96535	2.3	-1.71374	0.10547	-0.32832	0.3559	1.3243
5.0	-12.17910	1.62451	2.5	-1.88291	0.11564	-0.30150	0.3660	1.1933
3.0	-9.24347	1.36201	2.6	-2.05193	0.12954	-0.24133	0.3892	1.0462
2.0	-6.86049	1.15548	2.7	-2.23472	0.14610	-0.19315	0.4160	0.9591
1.6	-5.75016	1.05061	2.7	-2.32003	0.15540	-0.17317	0.4297	0.8874
1.0	-3.10841	0.79561	2.8	-2.58562	0.18195	-0.15020	0.4518	0.8021
0.75	-1.68010	0.66971	2.8	-2.68318	0.19261	-0.14513	0.4610	0.8050
0.50	0.17104	0.48663	2.8	-2.81997	0.20773	-0.13719	0.4714	0.7551
0.40	1.17695	0.39078	2.8	-2.87626	0.21352	-0.12940	0.4775	0.7396
0.30	2.27626	0.27031	2.8	-2.95623	0.22193	-0.11697	0.4865	0.7395
0.24	3.04705	0.19471	2.8	-3.00223	0.22639	-0.10675	0.4950	0.7274
0.20	3.61568	0.14311	2.8	-3.03239	0.22900	-0.09861	0.5040	0.7247
0.16	4.19281	0.08441	2.8	-3.07579	0.23300	-0.08991	0.5181	0.7271
0.15	4.34277	0.06911	2.8	-3.08805	0.23409	-0.08764	0.5249	0.7328
0.12	4.81663	0.02793	2.8	-3.12224	0.23686	-0.08119	0.5424	0.7503
0.10	5.13706	-0.00173	2.8	-3.15185	0.23929	-0.07703	0.5602	0.7507
0.080	5.94942	-0.06741	2.9	-3.27328	0.24822	-0.07318	0.5731	0.7534
0.070	6.10708	-0.08387	2.9	-3.29509	0.25000	-0.07142	0.5803	0.7585
0.060	6.26384	-0.10044	2.9	-3.31911	0.25192	-0.06982	0.5868	0.7656
0.055	6.34238	-0.10886	2.9	-3.33222	0.25295	-0.06908	0.5907	0.7644
0.050	6.42423	-0.11726	2.9	-3.34604	0.25401	-0.06838	0.5961	0.7711
0.040	6.61204	-0.13370	2.9	-3.37593	0.25613	-0.06711	0.6133	0.7817
0.032	7.33736	-0.18563	3.0	-3.49824	0.26456	-0.06625	0.6227	0.7858
0.025	7.51145	-0.19862	3.0	-3.52888	0.26652	-0.06568	0.6222	0.7823
0.020	7.55648	-0.20898	3.0	-3.55306	0.26853	-0.06551	0.6143	0.7776
0.010	6.12213	-0.16489	2.9	-3.43941	0.26601	-0.06925	0.5644	0.7392
PGA	5.91196	-0.15727	2.9	-3.42401	0.26564	-0.07004	0.5592	0.7353
PGV	5.79531	0.17529	2.6	-3.11215	0.25573	-0.08796	0.4408	-

Table 3-41. Gulf Coast.

Regression Coefficients for the Double Corner Model with Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-14.54243	1.91703	2.7	-2.10859	0.12608	-0.34322	0.5243	1.3791
5.0	-9.76826	1.50496	3.0	-2.41187	0.14194	-0.30605	0.5604	1.2665
3.0	-6.54516	1.21492	3.1	-2.65122	0.15876	-0.24408	0.5958	1.1393
2.0	-3.83140	0.98710	3.2	-2.90058	0.17769	-0.19493	0.6159	1.0612
1.6	-2.06630	0.85356	3.3	-3.09220	0.19167	-0.17514	0.6233	0.9956
1.0	0.53026	0.62351	3.3	-3.32873	0.21370	-0.15190	0.6483	0.9271
0.75	2.74561	0.44592	3.4	-3.57911	0.23302	-0.14644	0.6622	0.9349
0.50	4.87153	0.25189	3.4	-3.76122	0.24875	-0.13799	0.6850	0.9040
0.40	5.96206	0.14984	3.4	-3.85124	0.25592	-0.13028	0.6996	0.8991
0.30	8.03762	-0.01963	3.5	-4.09059	0.27175	-0.11756	0.7208	0.9109
0.24	8.93501	-0.10061	3.5	-4.16740	0.27663	-0.10695	0.7389	0.9111
0.20	9.59190	-0.15735	3.5	-4.22645	0.28002	-0.09871	0.7556	0.9177
0.16	11.20299	-0.27131	3.6	-4.44627	0.29278	-0.08984	0.7783	0.9306
0.15	11.39716	-0.28656	3.6	-4.46693	0.29383	-0.08758	0.7850	0.9369
0.12	12.01553	-0.33472	3.6	-4.53955	0.29762	-0.08082	0.8064	0.9587
0.10	13.46434	-0.43179	3.7	-4.76782	0.31108	-0.07649	0.8192	0.9596
0.080	13.96635	-0.47347	3.7	-4.84844	0.31607	-0.07252	0.8294	0.9628
0.070	14.23988	-0.49678	3.7	-4.89689	0.31927	-0.07075	0.8339	0.9664
0.060	14.53975	-0.52162	3.7	-4.95186	0.32294	-0.06914	0.8396	0.9730
0.055	15.83611	-0.60342	3.8	-5.16886	0.33606	-0.06840	0.8438	0.9733
0.050	16.02362	-0.61652	3.8	-5.20228	0.33809	-0.06769	0.8491	0.9799
0.040	16.45698	-0.64342	3.8	-5.27833	0.34234	-0.06636	0.8566	0.9842
0.032	16.84962	-0.66794	3.8	-5.35052	0.34658	-0.06561	0.8572	0.9821
0.025	17.20090	-0.69766	3.8	-5.42663	0.35229	-0.06508	0.8487	0.9722
0.020	17.40998	-0.72596	3.8	-5.48554	0.35830	-0.06521	0.8430	0.9685
0.010	13.83032	-0.59892	3.6	-4.99790	0.34481	-0.06992	0.7733	0.9088
PGA	13.52127	-0.58872	3.6	-4.95888	0.34391	-0.07073	0.7666	0.9031
PGV	10.31841	-0.16678	3.1	-4.13550	0.33428	-0.09848	0.5888	-

Table 3-42. South Carolina.

Regression Coefficients for the Double Corner Model with Saturation

T (sec)	c_1	c_2	c_4	c_6	c_7	c_{10}	$\sigma_{Parametric}$	σ_{Total}
10.0	-17.70361	2.06827	1.6	-1.31801	0.08712	-0.32461	0.3535	1.3235
5.0	-13.92420	1.72207	1.8	-1.45428	0.09906	-0.29911	0.3736	1.1955
3.0	-10.94321	1.43698	2.0	-1.63284	0.11719	-0.23803	0.3918	1.0469
2.0	-8.83343	1.24320	2.1	-1.77711	0.13055	-0.18835	0.4162	0.9591
1.6	-7.76737	1.14287	2.1	-1.85115	0.13862	-0.16740	0.4286	0.8866
1.0	-5.33824	0.93368	2.2	-2.04663	0.15785	-0.14480	0.4556	0.8039
0.75	-3.73678	0.79317	2.3	-2.19225	0.17169	-0.13937	0.4708	0.8102
0.50	-1.84742	0.62360	2.3	-2.32294	0.18424	-0.13061	0.5011	0.7739
0.40	-0.55724	0.50916	2.4	-2.44529	0.19431	-0.12238	0.5259	0.7711
0.30	0.92868	0.37406	2.5	-2.58582	0.20432	-0.10951	0.5377	0.7737
0.24	1.72573	0.29401	2.5	-2.65212	0.20809	-0.09876	0.5392	0.7580
0.20	2.68457	0.20711	2.6	-2.77743	0.21630	-0.09004	0.5456	0.7538
0.16	3.77386	0.11416	2.7	-2.93085	0.22616	-0.08037	0.5599	0.7568
0.15	3.96591	0.09800	2.7	-2.95707	0.22772	-0.07792	0.5639	0.7606
0.12	5.53031	-0.01361	2.9	-3.21501	0.24453	-0.07080	0.5844	0.7809
0.10	6.60366	-0.08665	3.0	-3.38623	0.25414	-0.06561	0.6093	0.7878
0.080	7.85421	-0.17609	3.1	-3.59574	0.26651	-0.06058	0.6243	0.7928
0.070	8.21088	-0.20169	3.1	-3.67264	0.27153	-0.05926	0.6149	0.7846
0.060	9.28186	-0.28645	3.2	-3.88204	0.28695	-0.05782	0.6154	0.7874
0.055	9.52717	-0.31412	3.2	-3.93679	0.29184	-0.05671	0.6137	0.7817
0.050	9.75655	-0.33358	3.2	-3.99128	0.29606	-0.05613	0.6121	0.7834
0.040	10.24743	-0.37291	3.2	-4.11053	0.30519	-0.05567	0.6224	0.7886
0.032	9.96722	-0.35918	3.1	-4.08417	0.30364	-0.05429	0.6345	0.7948
0.025	9.64059	-0.35408	3.0	-4.05492	0.30409	-0.05350	0.6346	0.7917
0.020	9.04691	-0.33098	2.9	-3.97551	0.30155	-0.05435	0.6289	0.7885
0.010	6.27888	-0.20223	2.7	-3.53646	0.28388	-0.06025	0.5686	0.7420
PGA	5.93818	-0.18201	2.7	-3.47772	0.28050	-0.06133	0.5630	0.7382
PGV	4.53013	0.23834	2.2	-2.81686	0.25116	-0.08693	0.4489	-

3.4.4 Calibration Plots

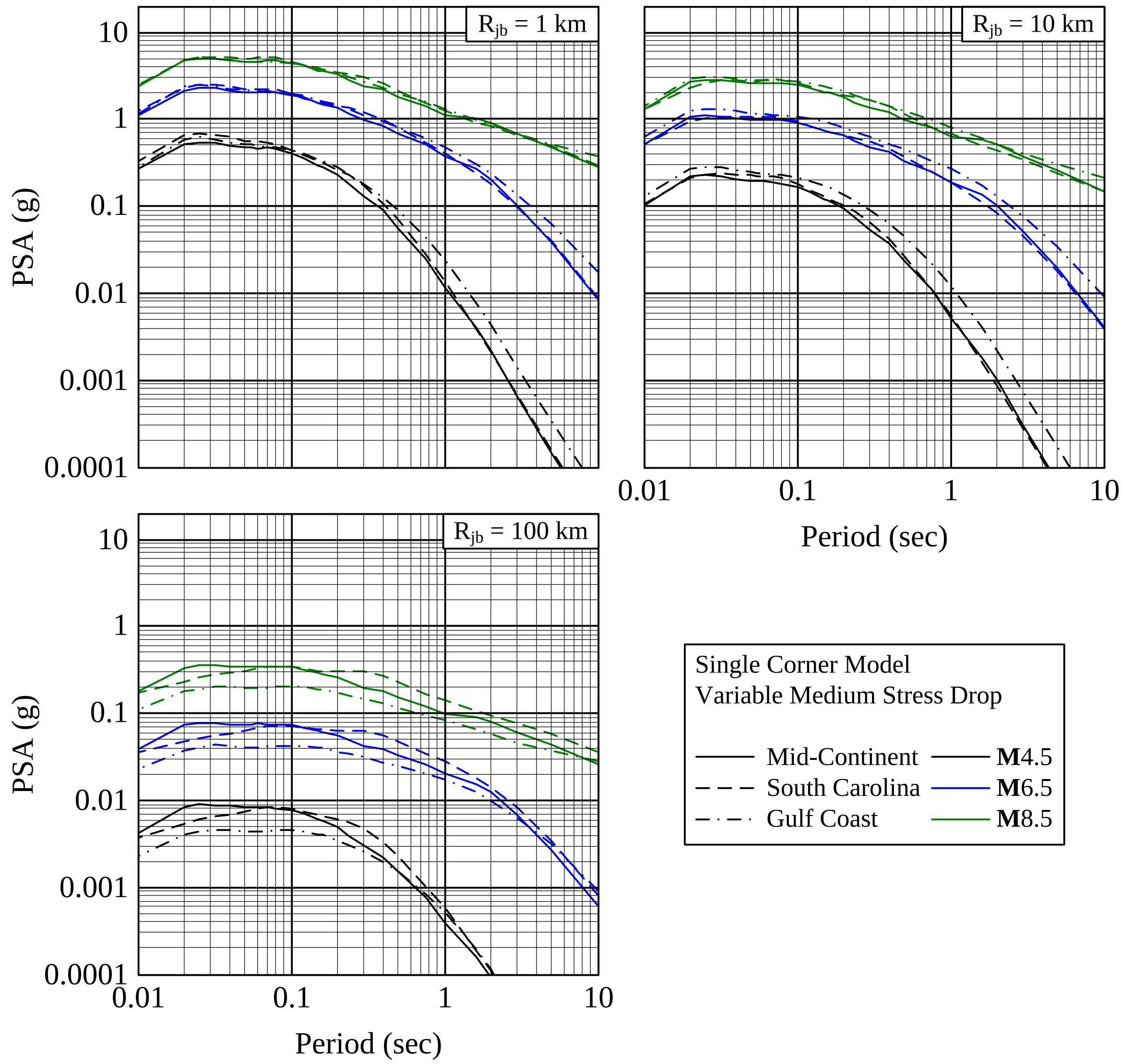
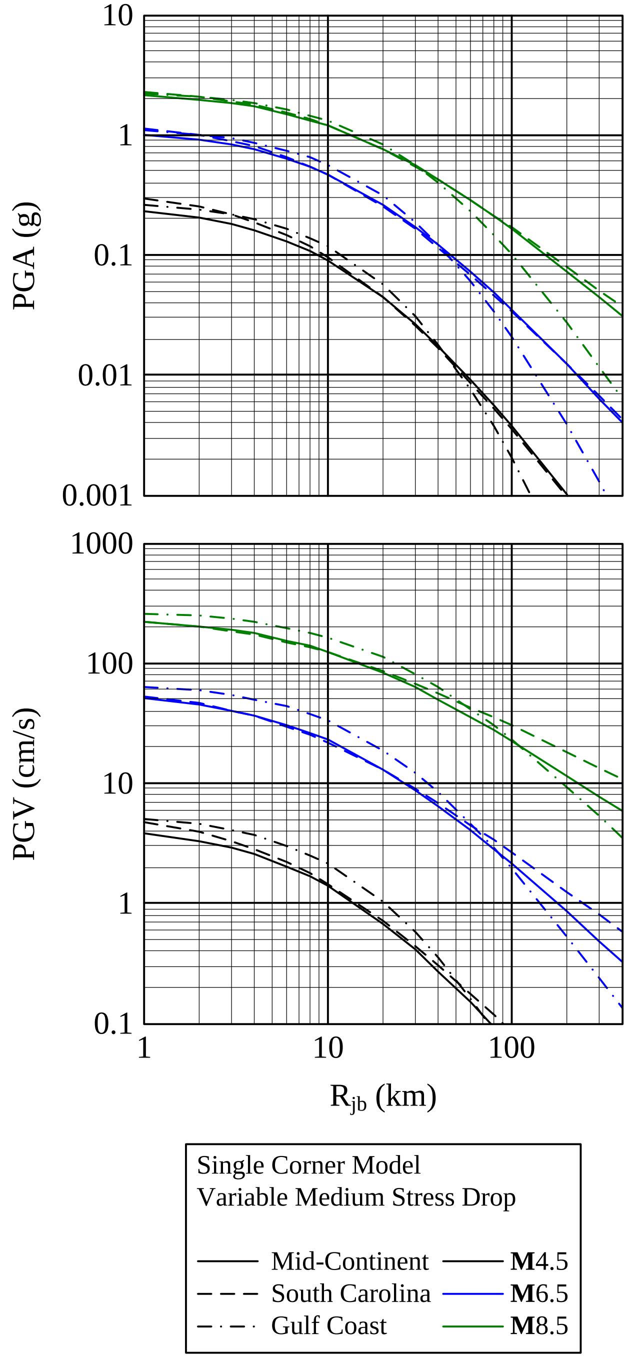
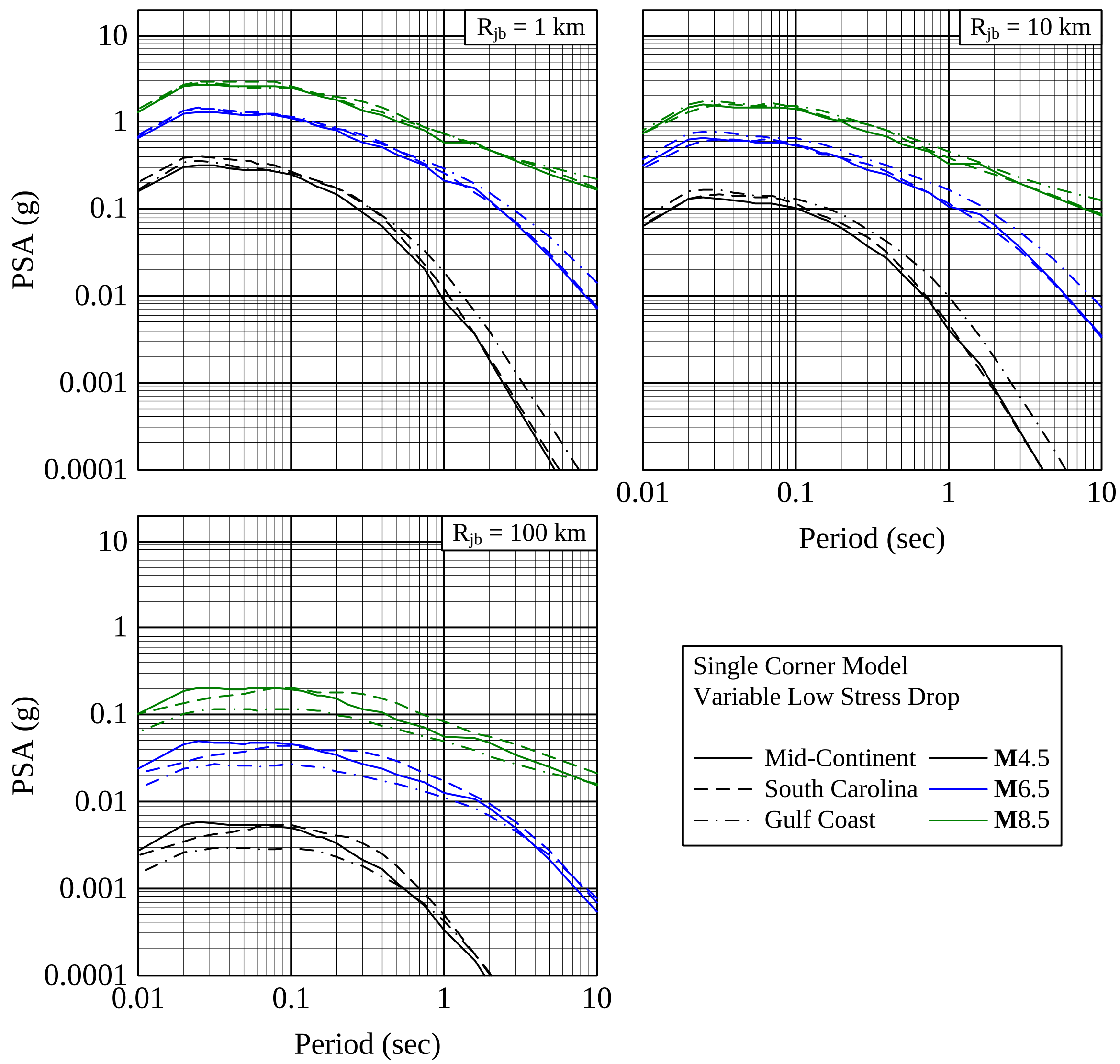


Figure 3-13.



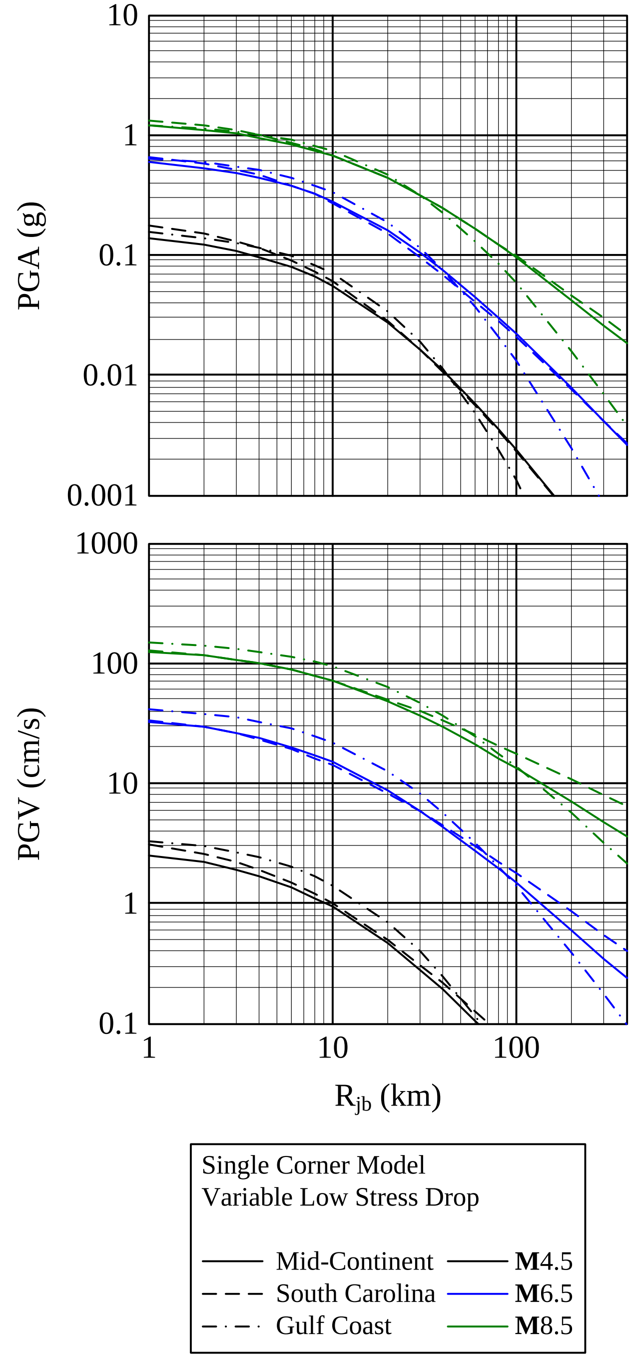
10
1
0.1
0.01
0.001
PGA (g)
1000
100
10
1
0.1
PGV (cm/s)
1
10
100
Rjb (km)
Single Corner Model
Variable Medium Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-14.



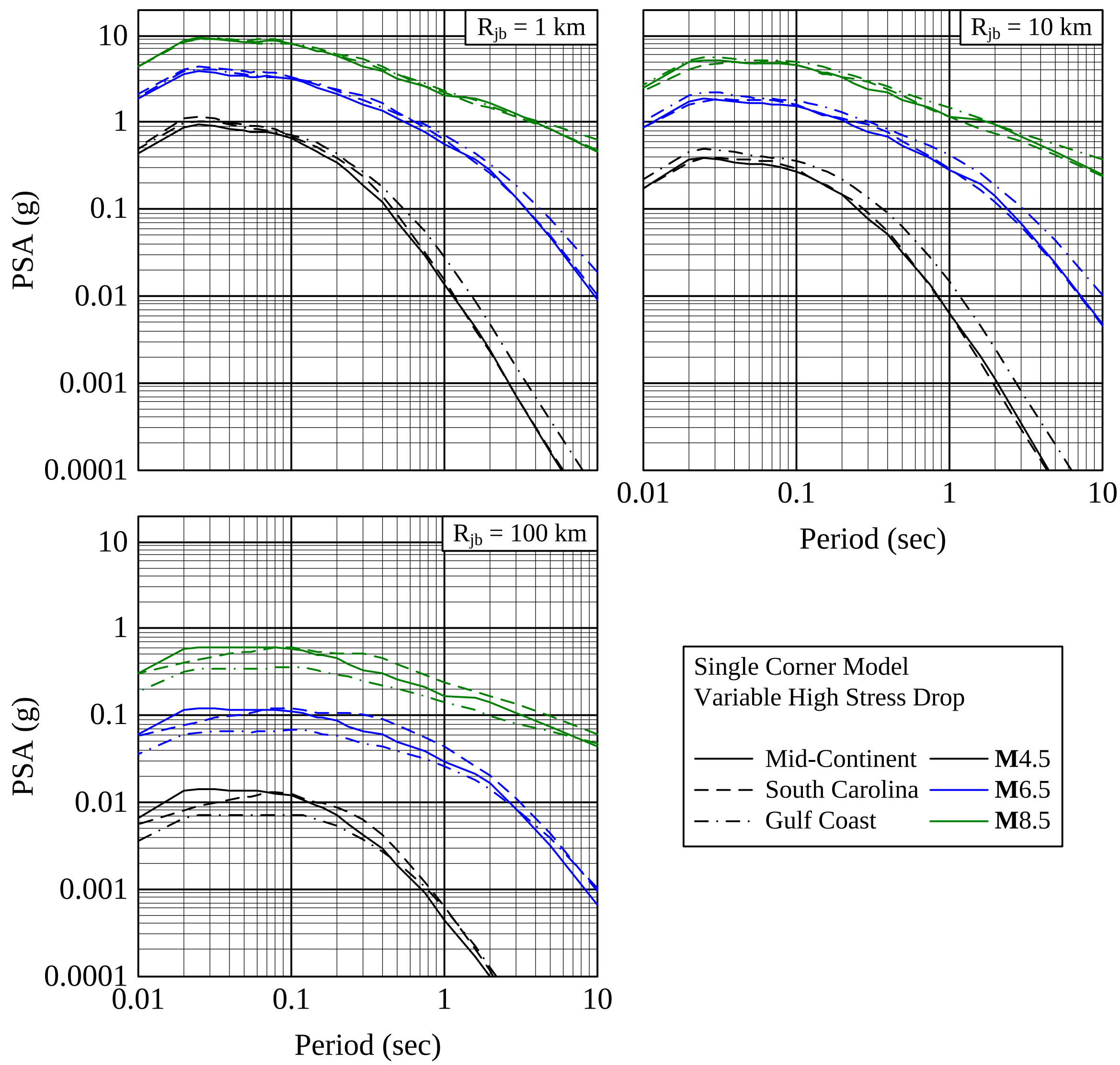
R$_{jb}$ = 1 km
R$_{jb}$ = 10 km
R$_{jb}$ = 100 km
PSA (g)
10
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
Period (sec)
Single Corner Model
Variable Low Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-15.



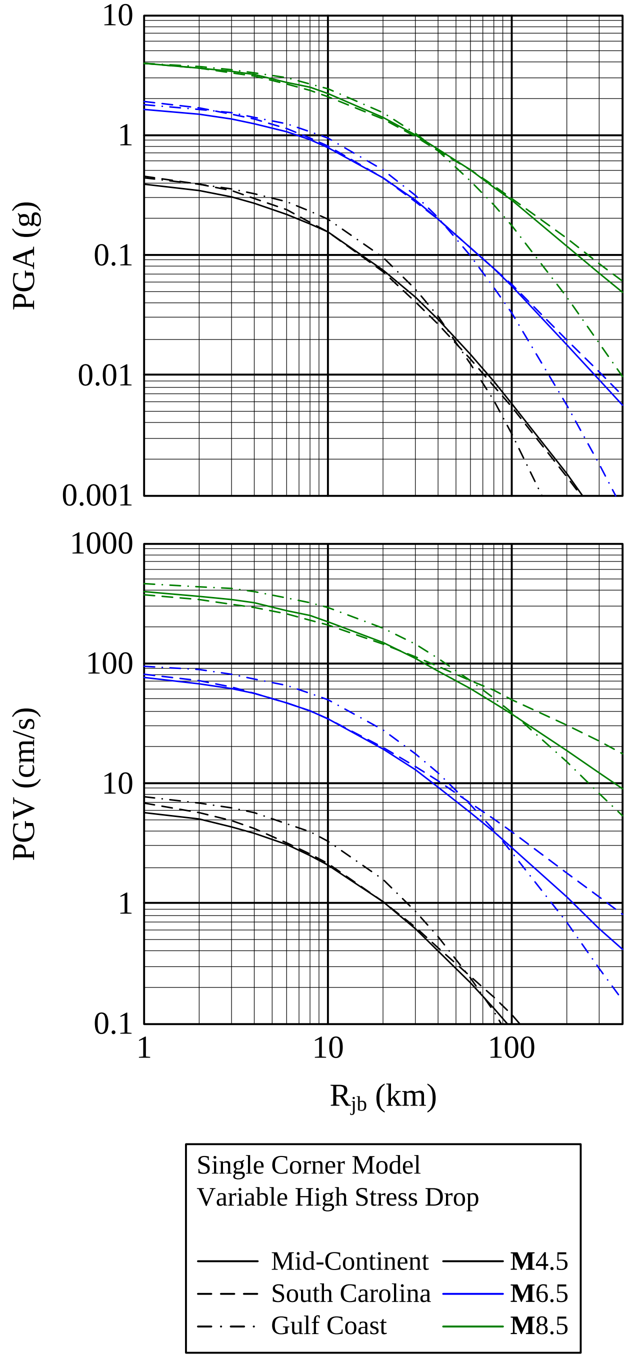
10
1
0.1
0.01
0.001
PGA (g)
1000
100
10
1
0.1
PGV (cm/s)
1
10
100
R_jb (km)
Single Corner Model
Variable Low Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-16.



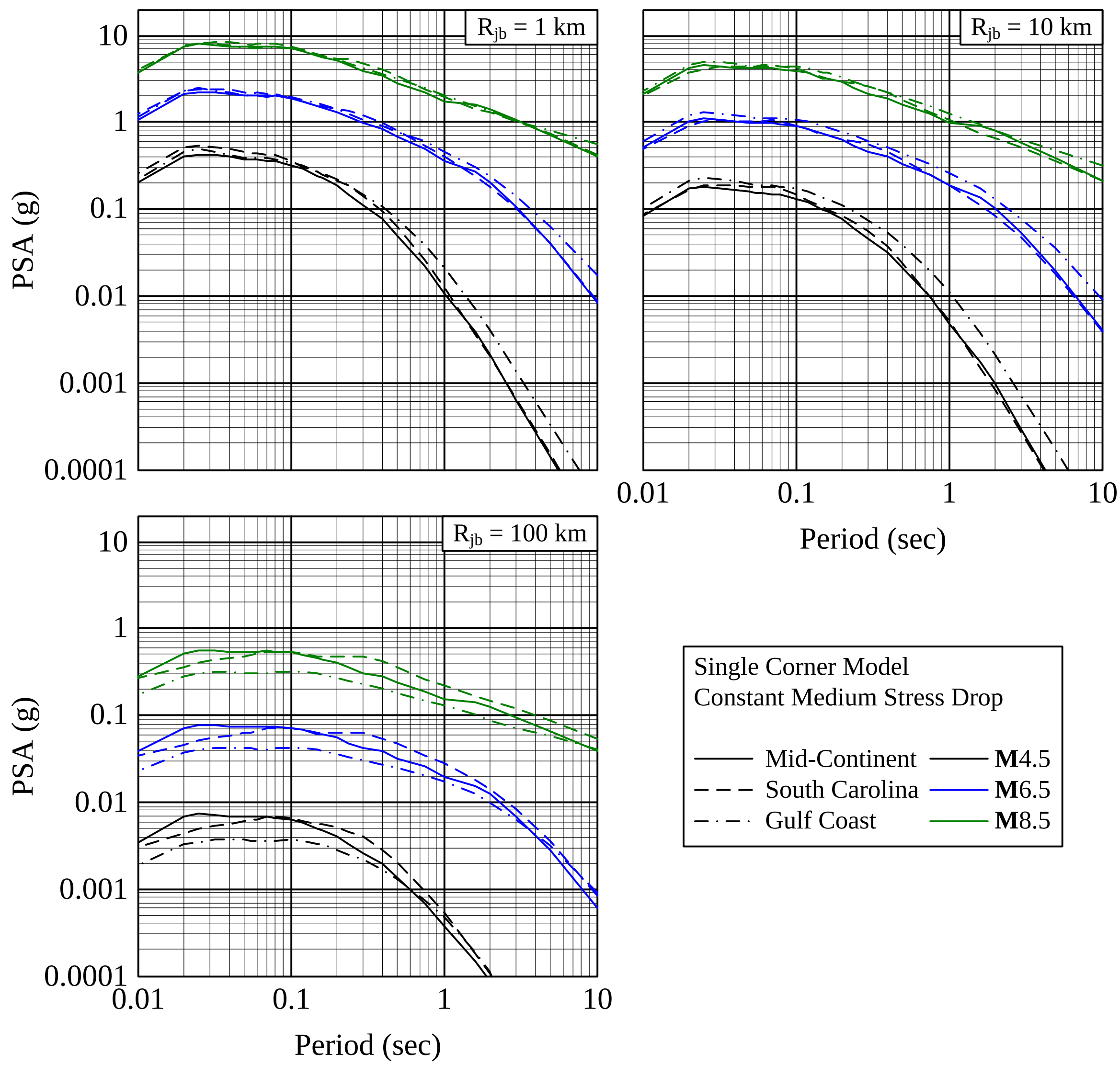
R_{jb} = 1 km
R_{jb} = 10 km
R_{jb} = 100 km
PSA (g)
PSA (g)
10
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
Period (sec)
Period (sec)
Single Corner Model
Variable High Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-17.



10
1
0.1
0.01
0.001
PGA (g)
1000
100
10
1
0.1
PGV (cm/s)
1
10
100
R_jb (km)
Single Corner Model
Variable High Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-18.



Rjb = 1 km
Rjb = 10 km
Rjb = 100 km
PSA (g)
10
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
Period (sec)
Single Corner Model
Constant Medium Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-19.

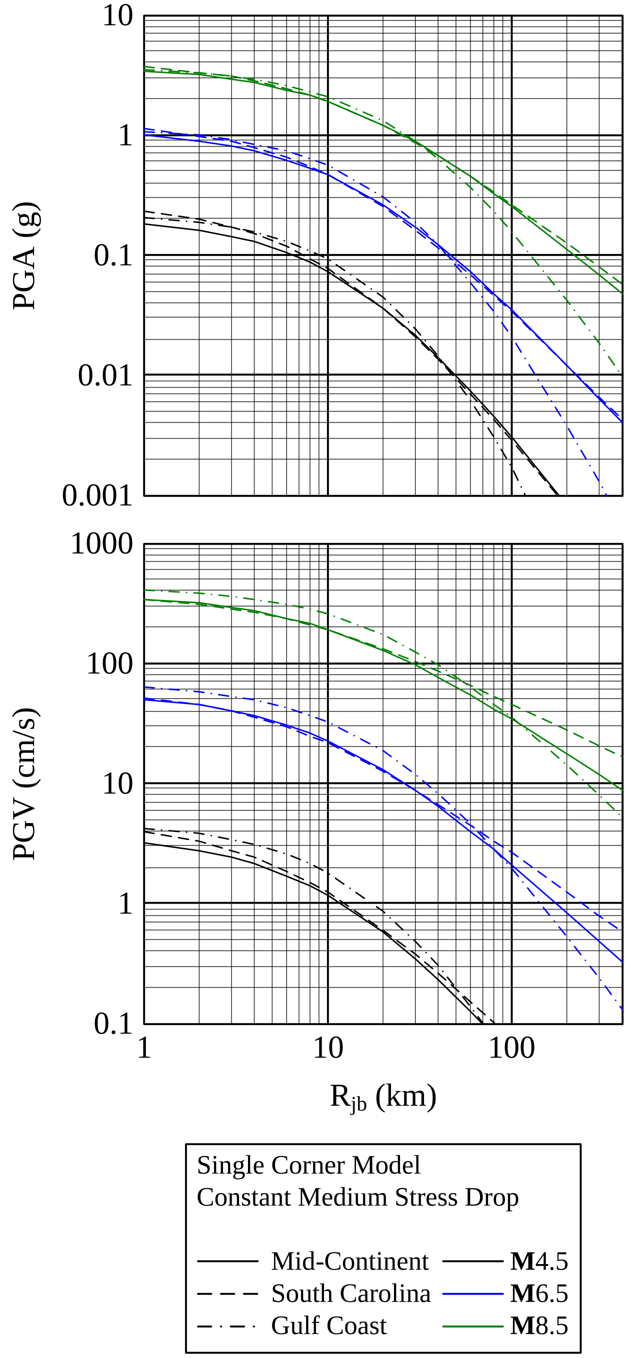
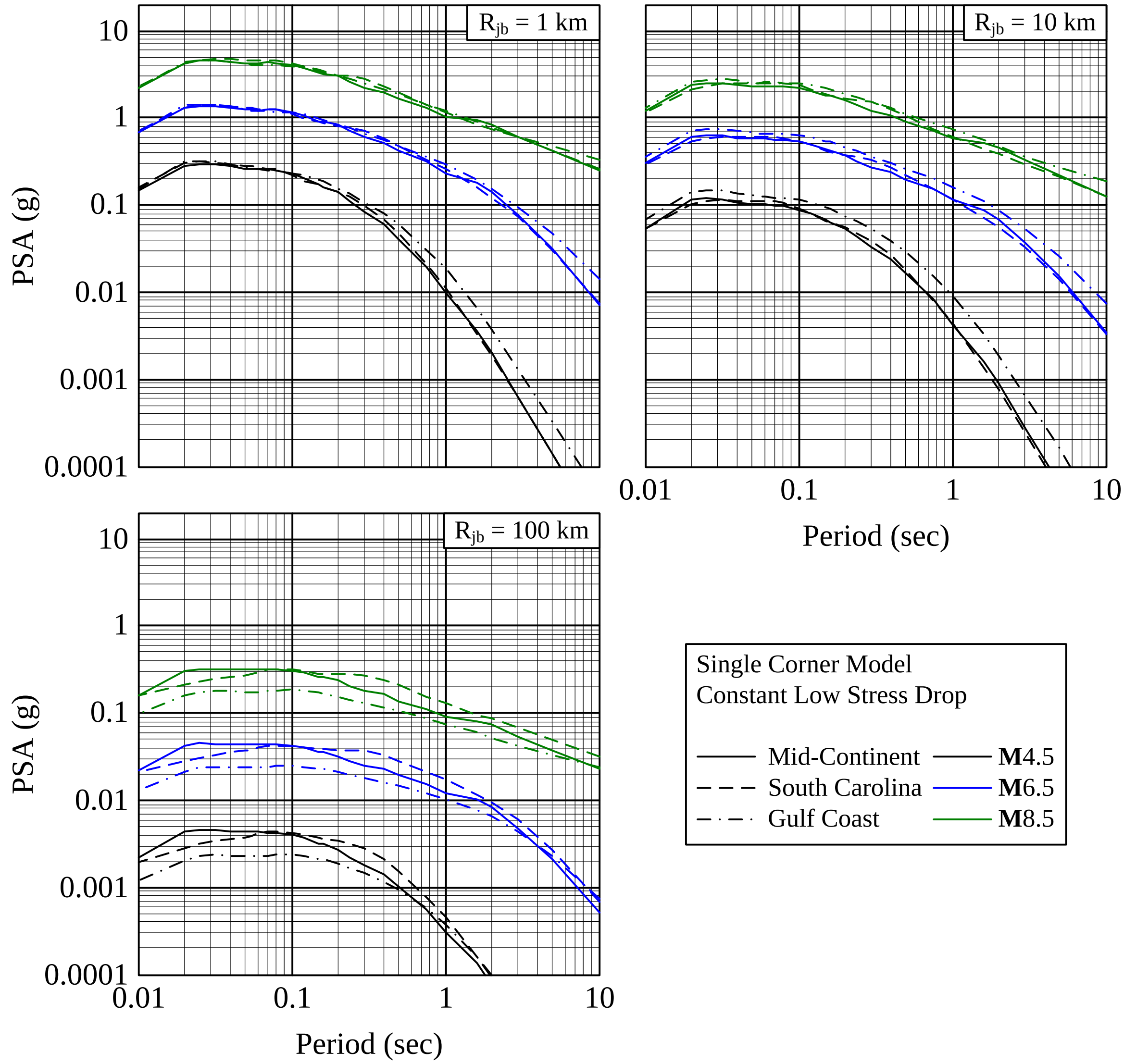
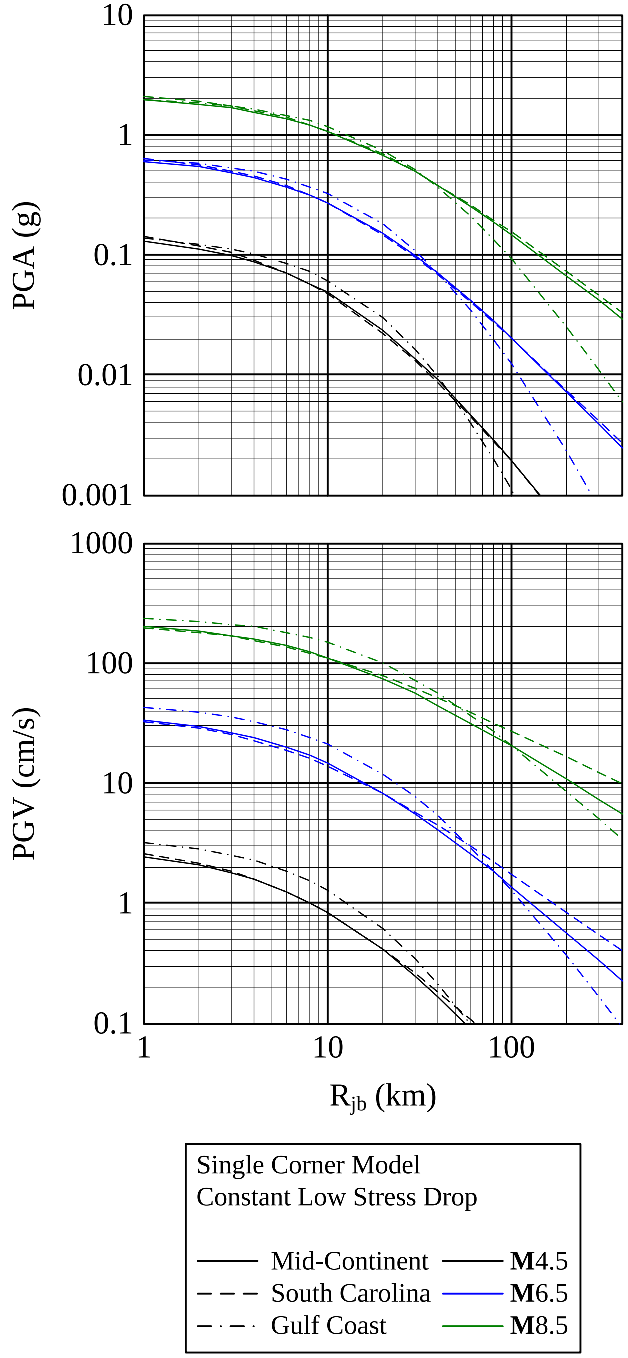

PGA (g)
10
1
0.1
0.01
0.001
PGV (cm/s)
1000
100
10
1
0.1
1
10
100
R_{jb} (km)
Single Corner Model
Constant Medium Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-20.



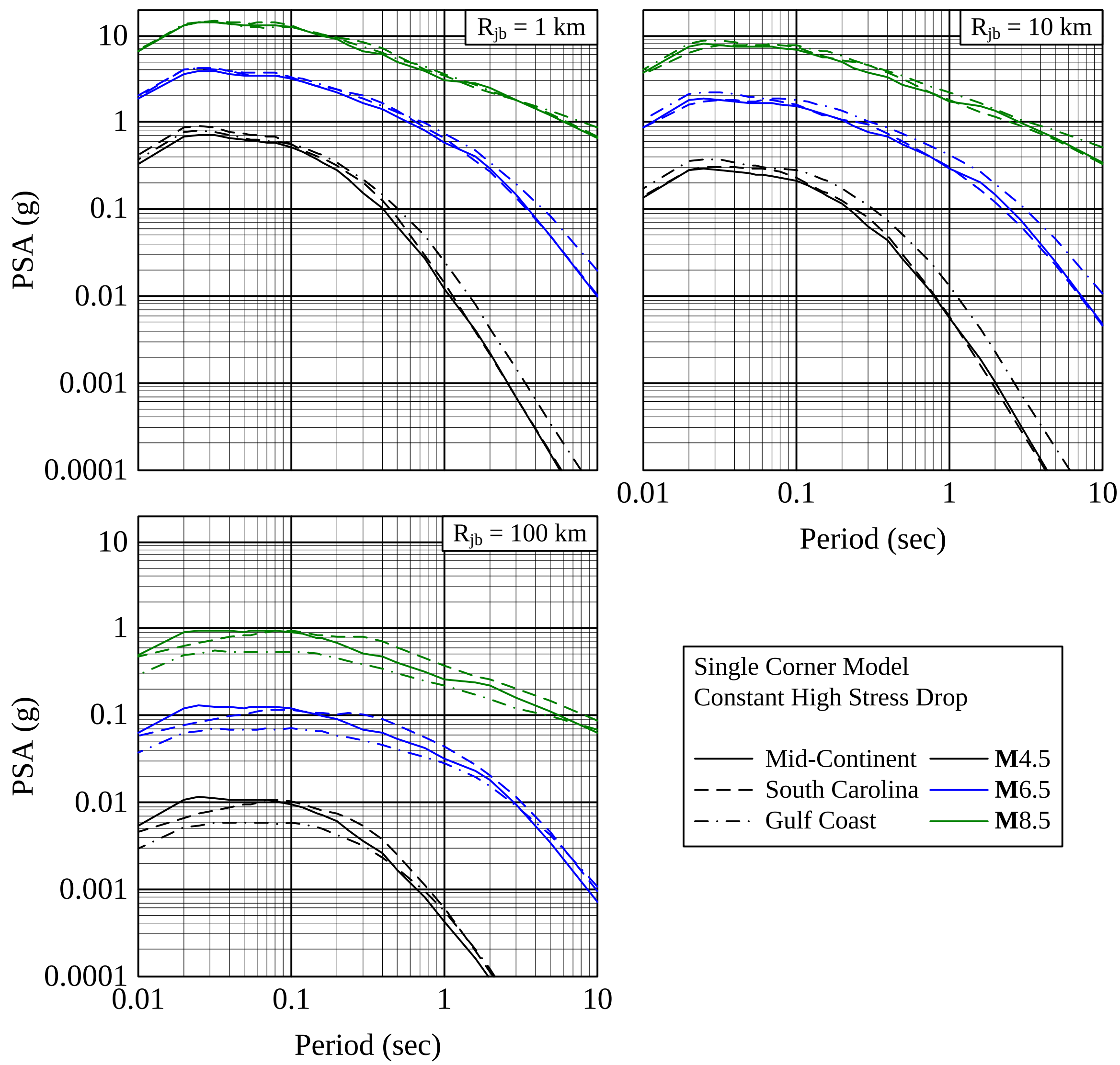
R$_{jb}$ = 1 km
R$_{jb}$ = 10 km
R$_{jb}$ = 100 km
PSA (g)
PSA (g)
10
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
Period (sec)
Period (sec)
Single Corner Model
Constant Low Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-21.



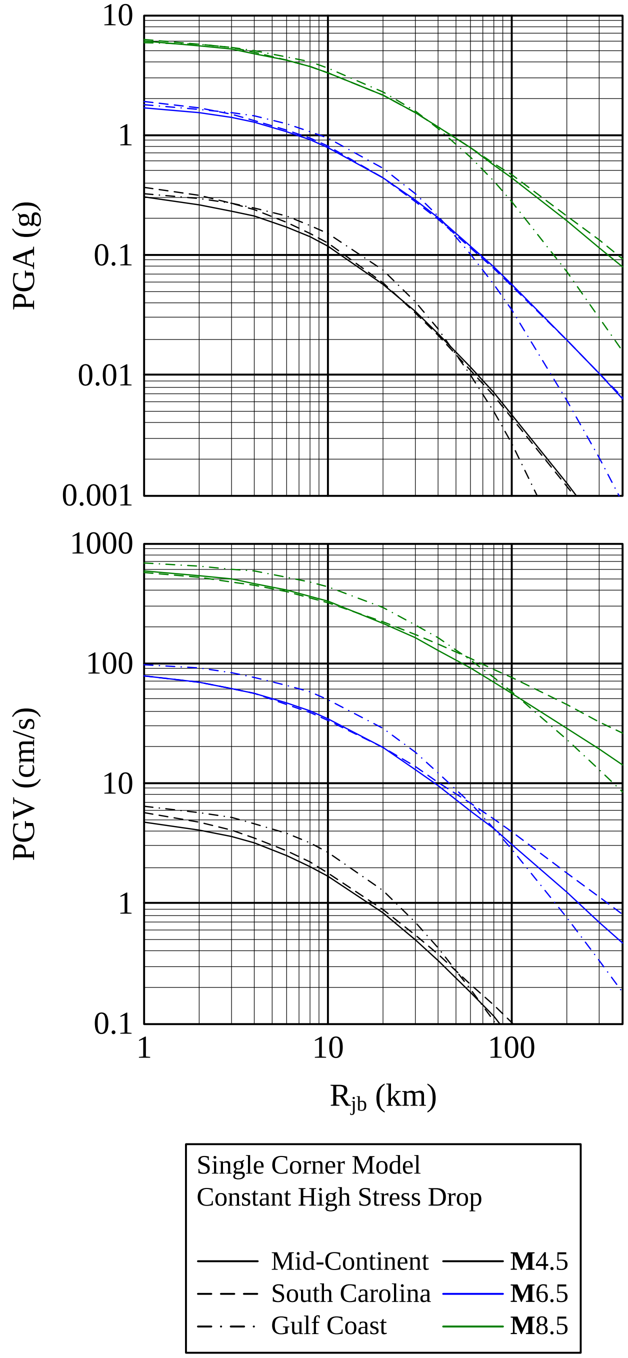
10
1
0.1
0.01
0.001
PGA (g)
1000
100
10
1
0.1
PGV (cm/s)
1
10
100
R_{jb} (km)
Single Corner Model
Constant Low Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-22.



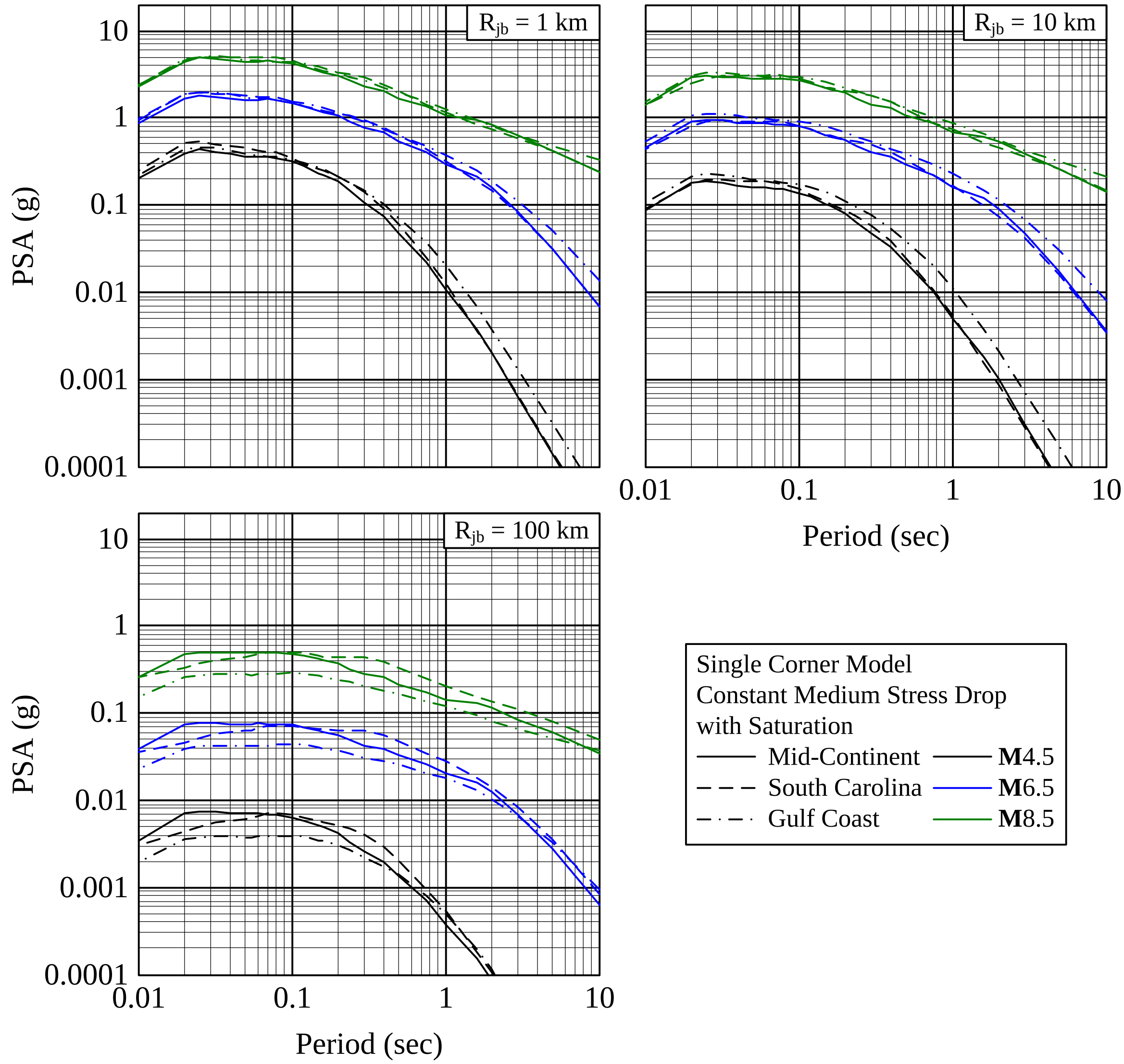
Rjb = 1 km
Rjb = 10 km
Rjb = 100 km
PSA (g)
10
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
Period (sec)
Single Corner Model
Constant High Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-23.



10
1
0.1
0.01
0.001
PGA (g)
1000
100
10
1
0.1
PGV (cm/s)
1
10
100
R$_{jb}$ (km)
Single Corner Model
Constant High Stress Drop
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-24.



R_{jb} = 1 km
R_{jb} = 10 km
R_{jb} = 100 km
10
1
0.1
0.01
0.001
0.0001
PSA (g)
0.01
0.1
1
10
Period (sec)
Single Corner Model
Constant Medium Stress Drop
with Saturation
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-25.

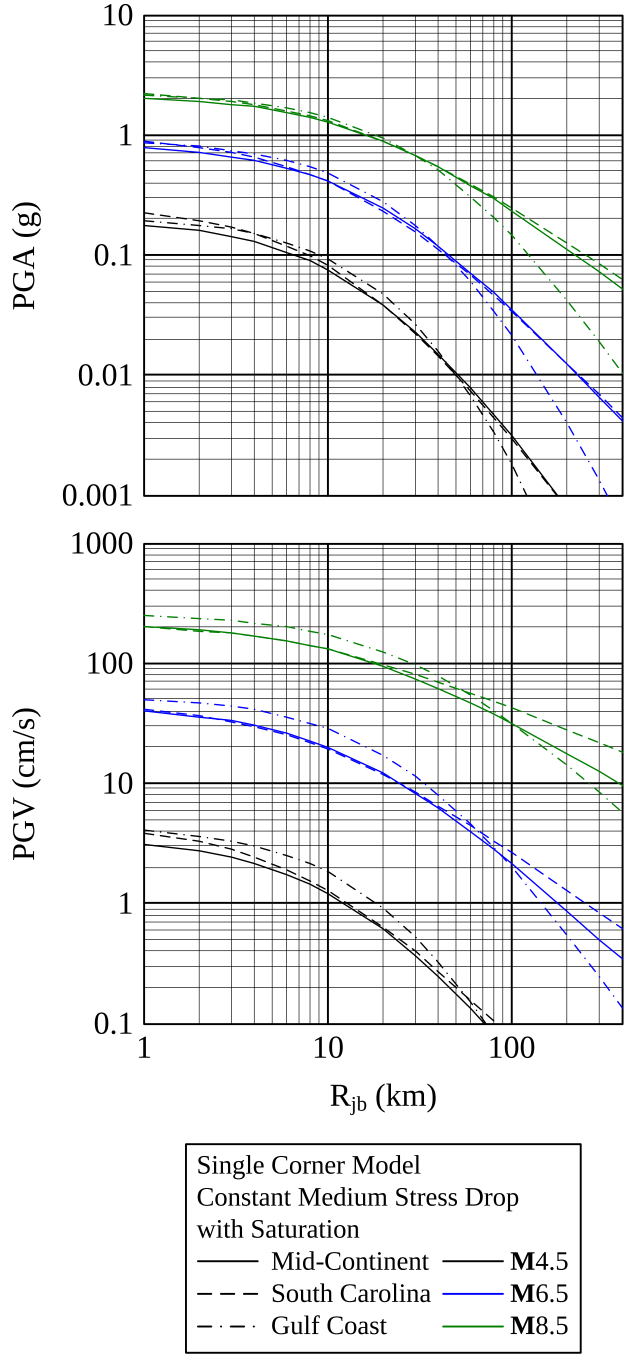
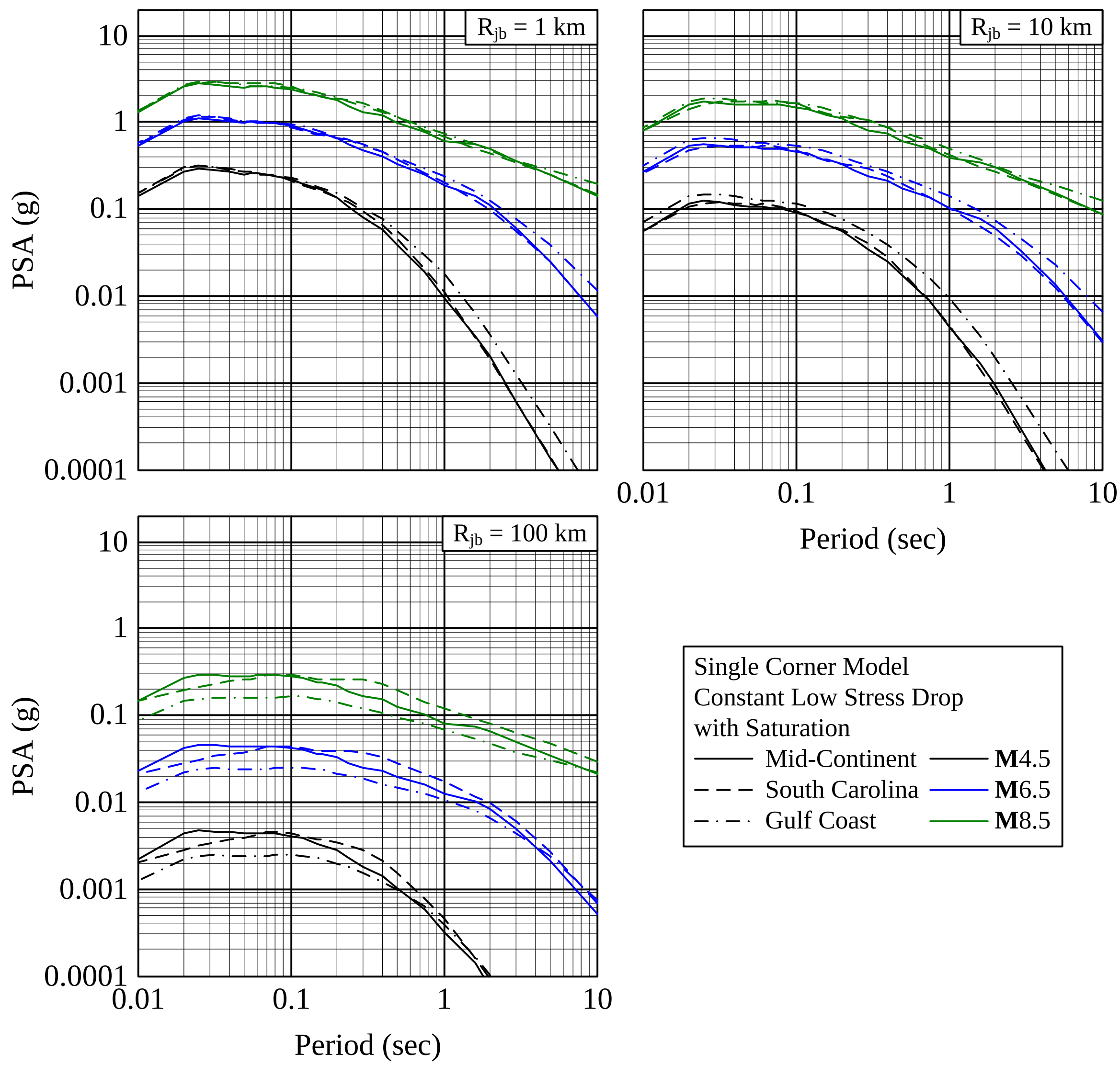
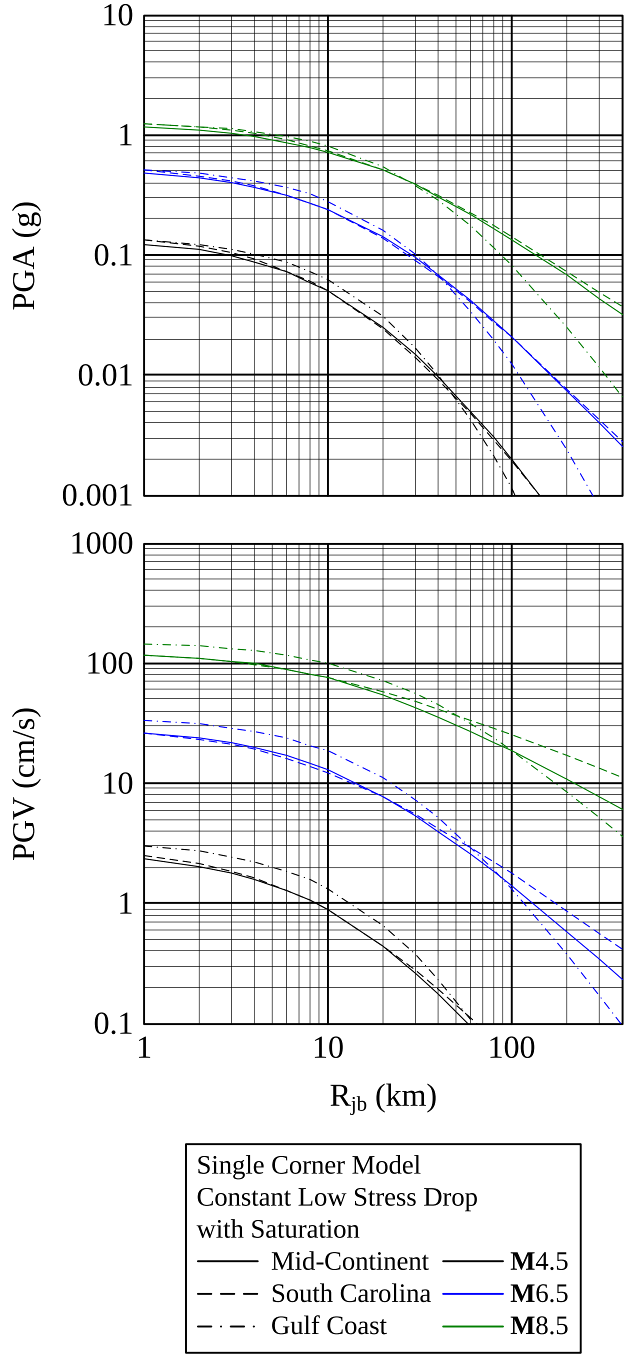

10
1
0.1
0.01
0.001
PGA (g)
1000
100
10
1
0.1
PGV (cm/s)
1
10
100
R_jb (km)
Single Corner Model
Constant Medium Stress Drop
with Saturation
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-26.



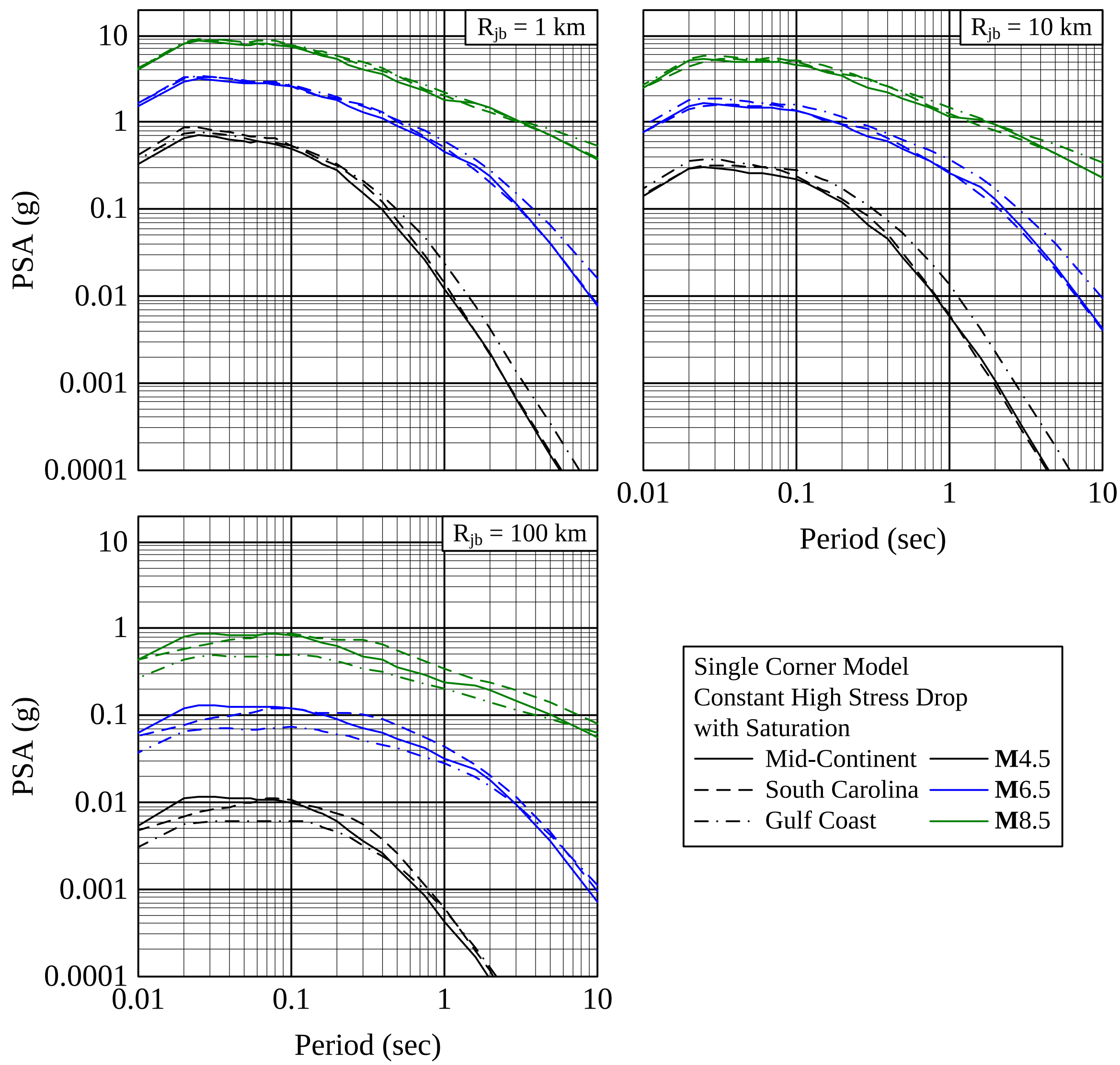
R_jb = 1 km
R_jb = 10 km
R_jb = 100 km
PSA (g)
Period (sec)
Single Corner Model
Constant Low Stress Drop
with Saturation
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-27.



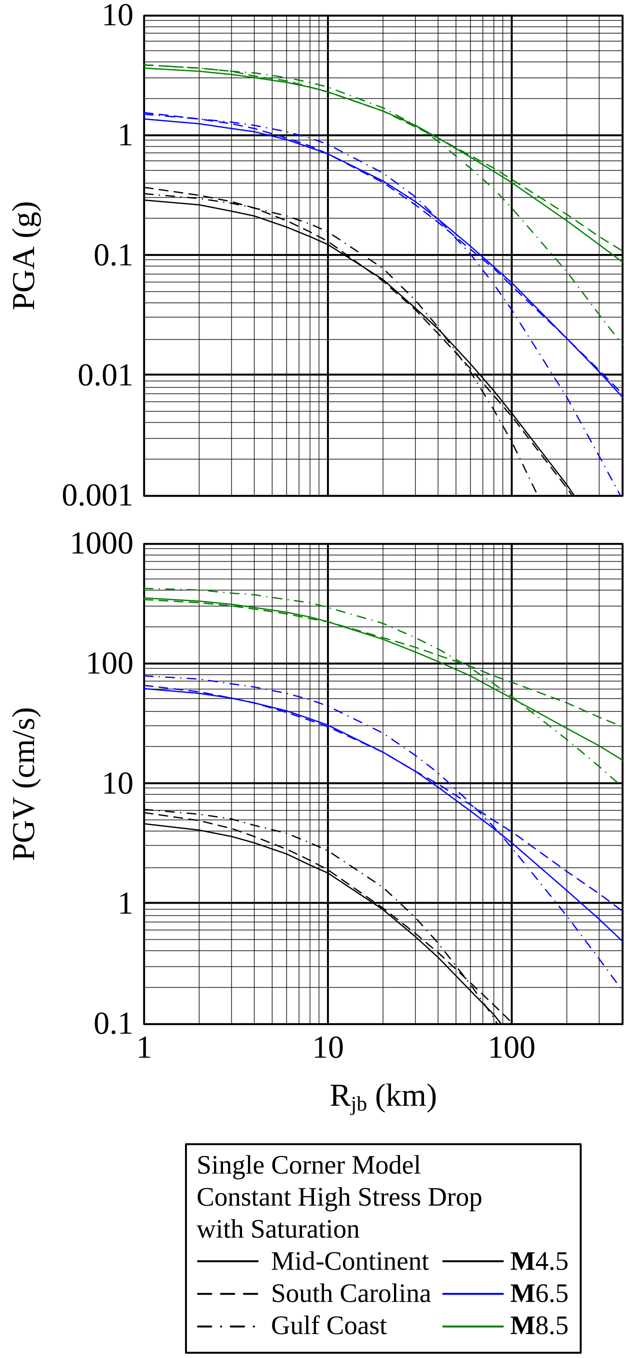
PGA (g)
10
1
0.1
0.01
0.001
PGV (cm/s)
1000
100
10
1
0.1
1
10
100
R_jb (km)
Single Corner Model
Constant Low Stress Drop
with Saturation
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-28.



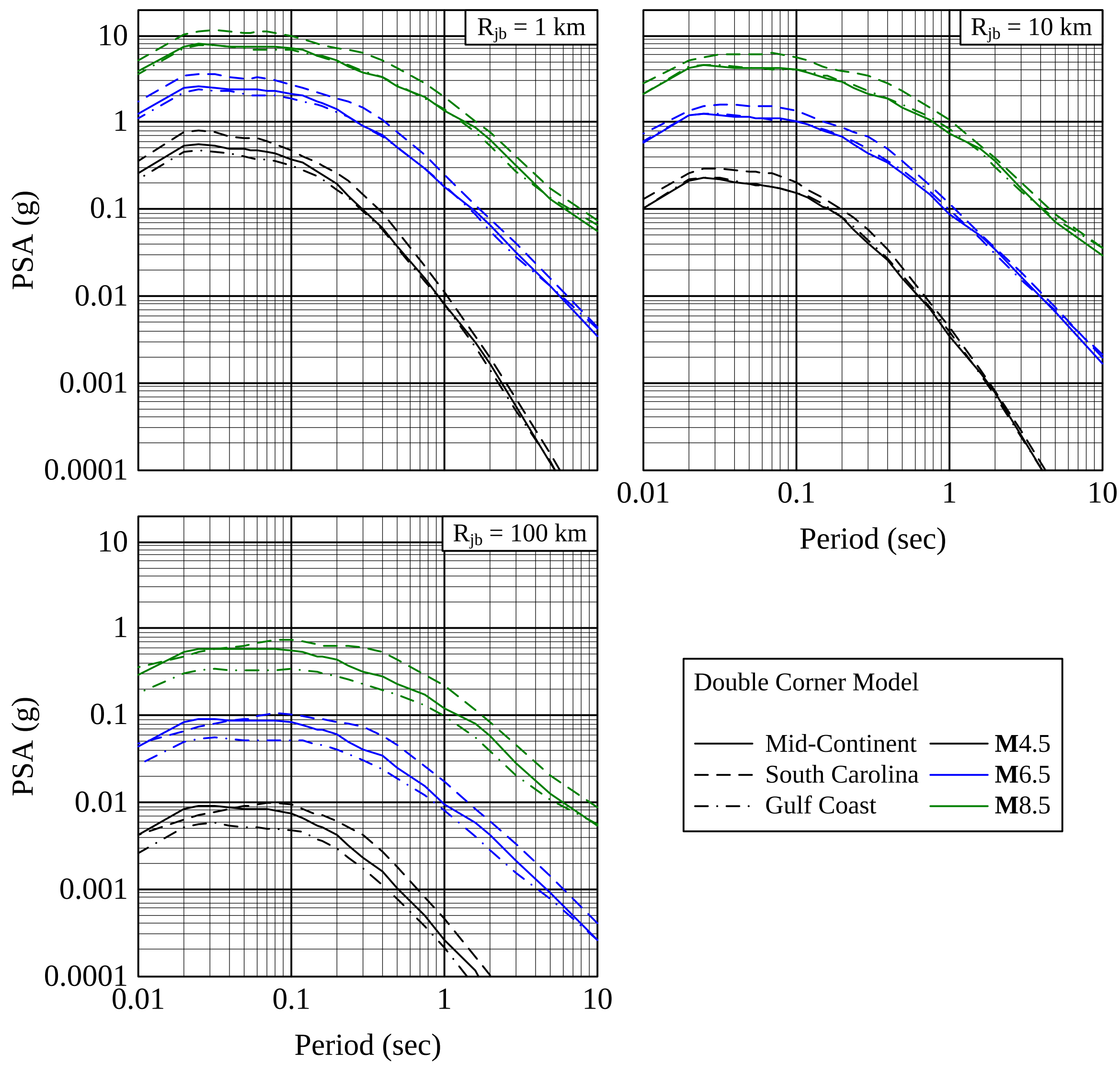
Rjb = 1 km
Rjb = 10 km
Rjb = 100 km
PSA (g)
10
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
Period (sec)
Single Corner Model
Constant High Stress Drop
with Saturation
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-29.



10
1
0.1
0.01
0.001
PGA (g)
1000
100
10
1
0.1
PGV (cm/s)
1
10
100
R_jb (km)
Single Corner Model
Constant High Stress Drop
with Saturation
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-30



R_jb = 1 km
R_jb = 10 km
R_jb = 100 km
PSA (g)
PSA (g)
10
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
Period (sec)
Period (sec)
Double Corner Model
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-31.

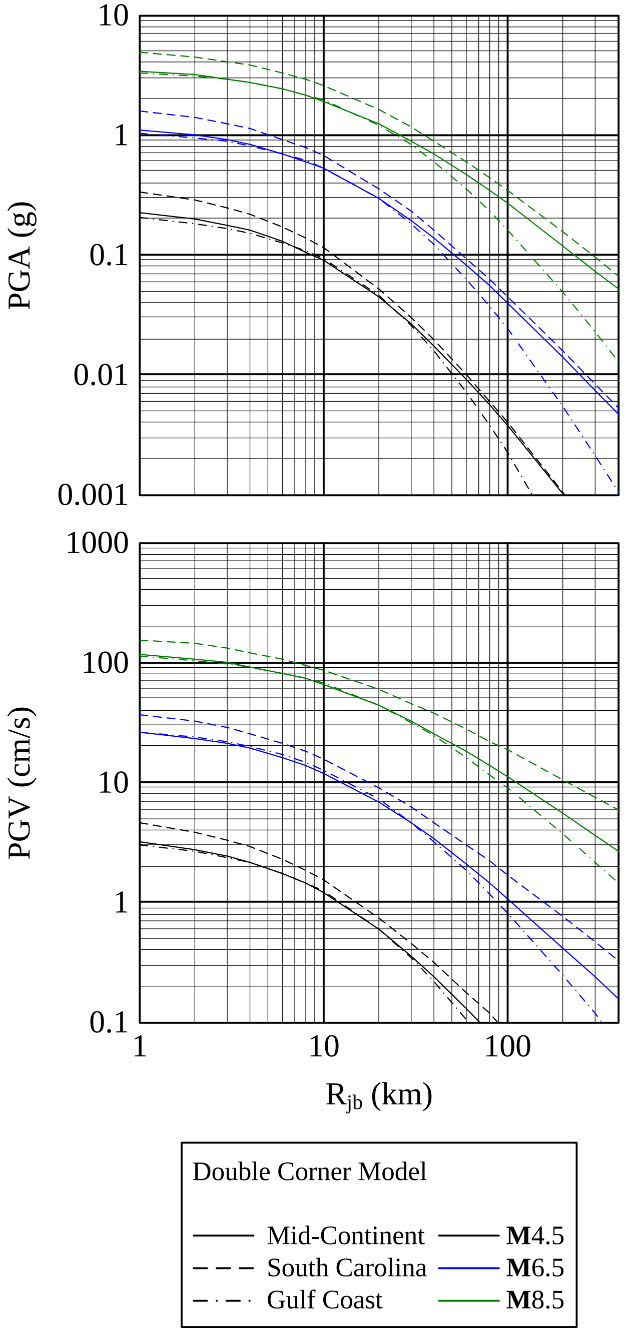
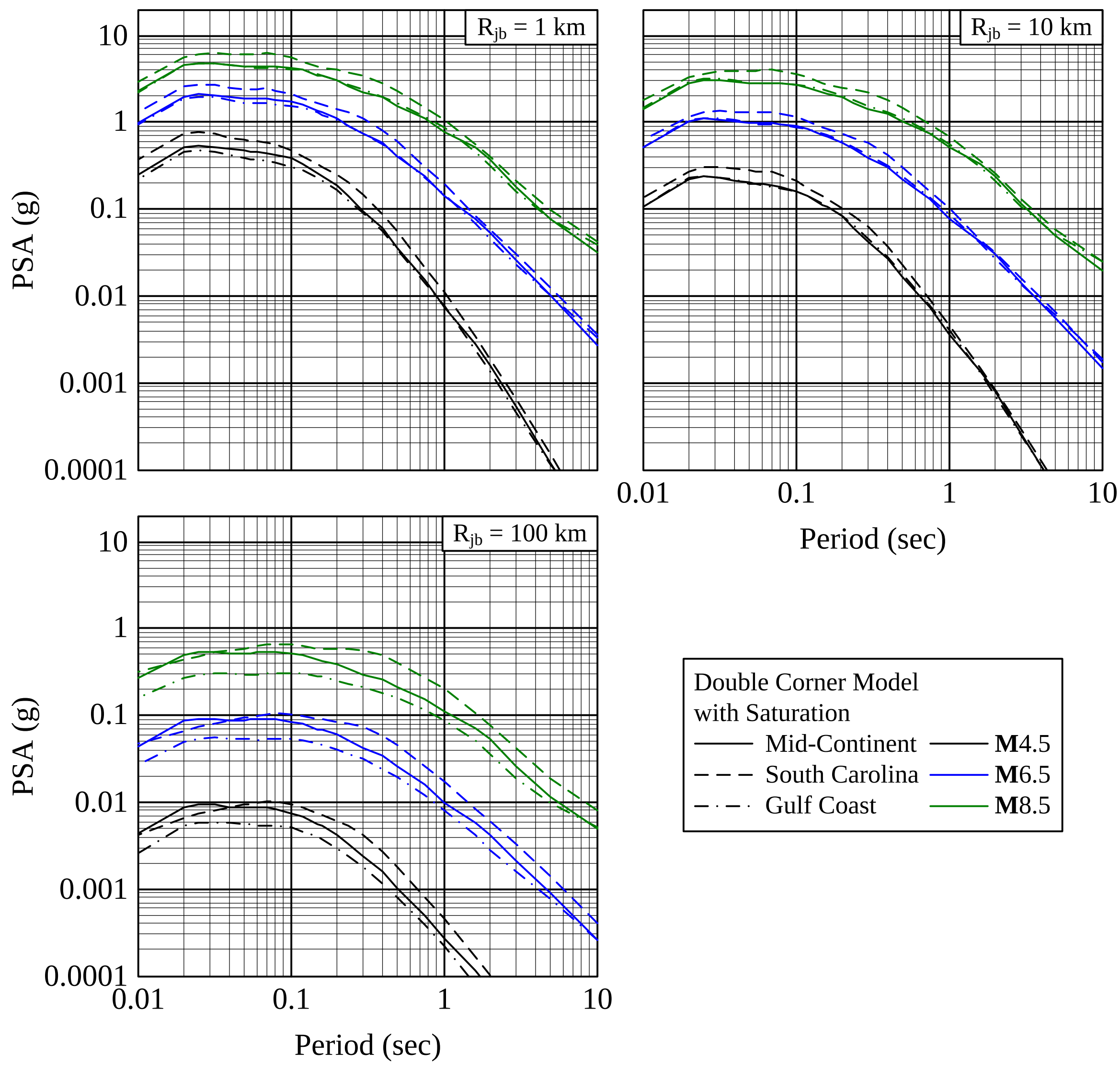
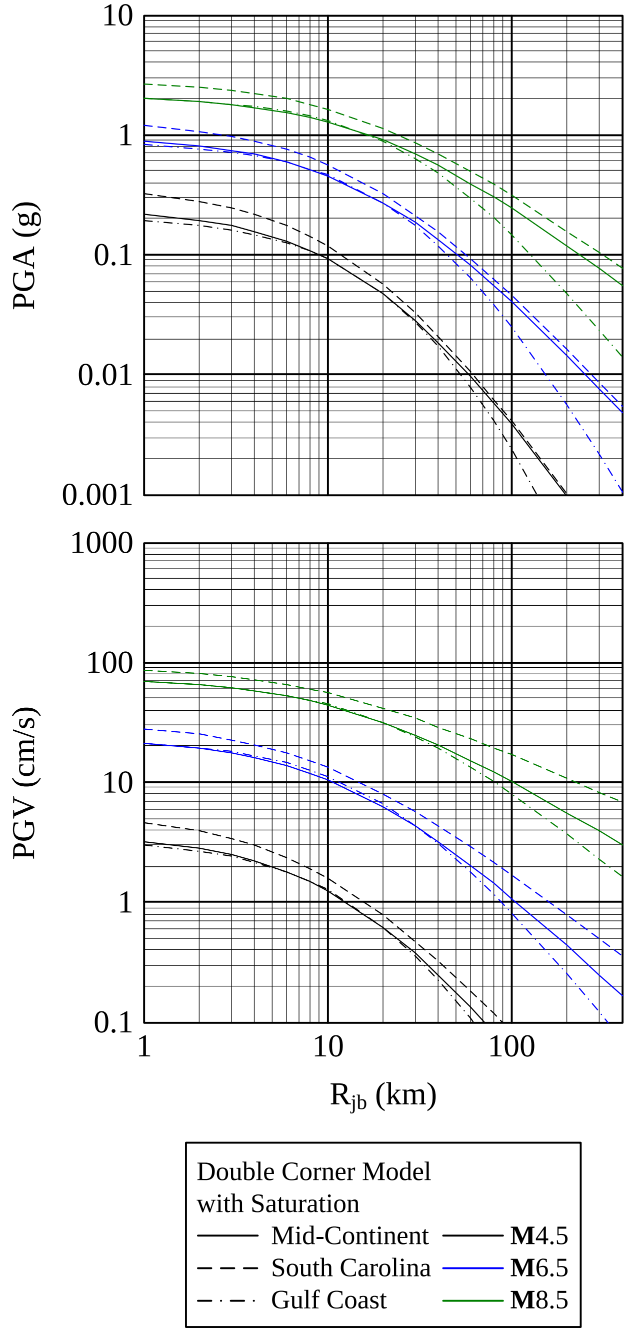

10
1
0.1
0.01
0.001
PGA (g)
1000
100
10
1
0.1
PGV (cm/s)
1
10
100
Rjb (km)
Double Corner Model
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-32.



R$_{jb}$ = 1 km
R$_{jb}$ = 10 km
R$_{jb}$ = 100 km
10
1
0.1
0.01
0.001
0.0001
PSA (g)
0.01
0.1
1
10
Period (sec)
Double Corner Model
with Saturation
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-33.



10
1
0.1
0.01
0.001
PGA (g)
1000
100
10
1
0.1
PGV (cm/s)
1
10
100
R_jb (km)
Double Corner Model
with Saturation
Mid-Continent
South Carolina
Gulf Coast
M4.5
M6.5
M8.5

Figure 3-34.

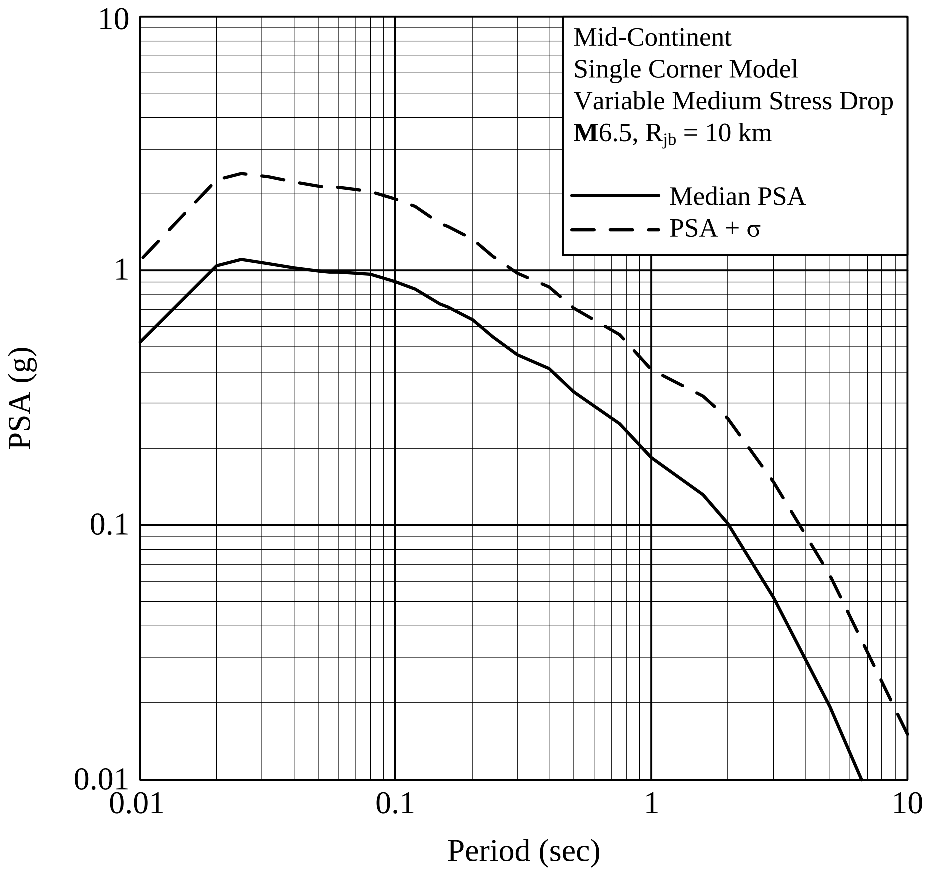


Figure 3-35. Example showing effect of adding one standard deviation.

3.4.5 Database

Table 3-43. Crustal Models

Mid-Continent		
Thickness (km)	V_S (km/s)	Density (cgs)
1.30	2.83	2.52
11.00	3.52	2.71
28.00	3.75	2.78
—	4.62	3.35
Gulf Coast		
7.00	2.31	2.37
8.00	3.05	2.58
15.00	3.76	2.78
—	4.74	3.40
South Carolina		
0.13	2.53	2.62
0.15	3.09	2.78
1.90	3.29	2.85
7.10	3.43	2.93
8.50	3.62	2.99
16.70	3.75	3.04
—	4.54	3.42

Table 3-44. Parameters for crystalline rock outcrop attenuation simulations.

M 4.5, 5.5, 6.5, 7.5, 8.5				
D (km) 1, 5, 10, 20, 50, 75, 100, 200, 400				
300 simulations for each **M**, *R* pair				
Randomly vary source depth, $\Delta\sigma$, kappa, Q_o, η, profile				
Depth. $\sigma_{lnH} = 0.6$, Intraplate Seismicity				
M	m_{blg}	Lower Bound (km)	$\bar{H}$ (km)	Upper Bound (km)
4.5	4.9	2	6	15
5.5	6.0	2	6	15
6.5	6.6	4	8	20
7.5	7.1	5	10	20
8.5	7.8	5	10	20
$\Delta\sigma$, $\sigma_{ln}\ \Delta\sigma = 0.5$				
M	m_{blg}	$\Delta\sigma$ (bars) Base Case Values	AVG. $\Delta\sigma$ (bars) = 123; Assumes **M** 5.5 = 160 bars with magnitude scaling taken from WUS; constant stress drop model has $\Delta\sigma$ (bars) = 120. High and low stress drop models are 100% higher and 100% lower than base case values.	
4.5	4.9	160, 120*		
5.5	6.0	160, 120*		
6.5	6.6	120, 120*		
7.5	7.1	90, 120*		
8.5	7.8	70, 120*		
Q(s), = 351, $\eta = 0.84$, $\sigma_{lnQo} = 0.4$ (Mid-Continent)				

Q(s), = 300, $\eta = 0.30$, $\sigma_{lnQo} = 0.4$ (Gulf Coast) Q(s), = 1,052, $\eta = 0.22$, $\sigma_{lnQo} = 0.4$ (South Carolina) Varying Q_o only sufficient, ± 1 σ covers range of CEUS inversions from 1 to 20 Hz
Kappa, $\bar{\kappa} = 0.006$ sec
Profile, Crystaline Basement, randomize top 100 ft
Geometrical attenuation $R^{-(a+b(\mathbf{M}-6.5))}$, a = 1.0296, b = -0.0422 $R^{-(a+b(\mathbf{M}-6.5))/2}$, R > 80 km, approximately twice crustal thickness (Table 3-43)

*Constant Stress Drop Model

3.4.6 MATLAB Code

```
% by Kathryn A. Gunberg 4/7/2008
% Virginia Tech
% kgunberg@vt.edu
%
% Silva, Gregor and Darragh attenuation equation, 2003 with
% Silva, Gregor and Lee attenuation equation, 2004
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T     = Period (sec), 0 for PGA, -1 for PGV
% M     = Moment magnitude
% G     = 1 for mid-continental region, 0 for gulf coast region, 2 for SC
% Rjb   = Joyner-Boore distance
% SE    = 1 for saturation model, 0 for no saturation
%       (doesn't matter for variable stres drop)
% CM    = 1 for single corner model, 2 for double corner model
% SD_l  = 0 for low stress drop, 1 for medium, 2 for high
%       (doesn't matter for double corner model)
% SD_t  = 1 for constant stress drop, 0 for variable
%       (doesn't matter for double corner model)
% ---------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = SGD_2003(T, M, G, Rjb, SE, CM, SD_l, SD_t)
% Coefficients
period   = [10.0    5.00    3.00    2.00    1.60    1.00    0.75    0.50    0.40    0.30...
            0.24    0.20    0.16    0.15    0.12    0.10    0.080   0.070   0.060   0.055...
            0.050   0.040   0.032   0.025   0.020   0.010   0       -1];
if G == 1
    if CM == 2
        if SE == 1
            % double corner with saturation
            c1   = [-16.16329   -12.17910   -9.24347    -6.86049    -5.75016    -3.10841...
                    -1.68010    0.17104     1.17695     2.27626     3.04705     3.61568...
                    4.19281     4.34277     4.81663     5.13706     5.94942     6.10708...
                    6.26384     6.34238     6.42423     6.61204     7.33736     7.51145...
                    7.55648     6.12213     5.91196     5.79531];
            c2   = [1.96535     1.62451     1.36201     1.15548     1.05061     0.79561...
                    0.66971     0.48663     0.39078     0.27031     0.19471     0.14311...
                    0.08441     0.06911     0.02793     -0.00173    -0.06741    -0.08387...
                    -0.10044    -0.10886    -0.11726    -0.13370    -0.18563    -0.19862...
                    -0.20898    -0.16489    -0.15727    0.17529];
            c4   = [2.3 2.5 2.6 2.7 2.7 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.9...
                    2.9 2.9 2.9 2.9 2.9 3.0 3.0 3.0 2.9 2.9 2.6];
            c6   = [-1.71374    -1.88291    -2.05193    -2.23472    -2.32003    -2.58562...
                    -2.68318    -2.81997    -2.87626    -2.95623    -3.00223    -3.03239...
                    -3.07579    -3.08805    -3.12224    -3.15185    -3.27328    -3.29509...
                    -3.31911    -3.33222    -3.34604    -3.37593    -3.49824    -3.52888...
                    -3.55306    -3.43941    -3.42401    -3.11215];
            c7   = [0.10547 0.11564 0.12954 0.14610 0.15540 0.18195 0.19261 0.20773 0.21352...
                    0.22193 0.22639 0.22900 0.23300 0.23409 0.23686 0.23929 0.24822 0.25000...
                    0.25192 0.25295 0.25401 0.25613 0.26456 0.26652 0.26853 0.26601 0.26564...
                    0.25573];
            c10  = [-0.32832    -0.30150    -0.24133    -0.19315    -0.17317    -0.15020...
                    -0.14513    -0.13719    -0.12940    -0.11697    -0.10675    -0.09861...
                    -0.08991    -0.08764    -0.08119    -0.07703    -0.07318    -0.07142...
                    -0.06982    -0.06908    -0.06838    -0.06711    -0.06625    -0.06568...
                    -0.06551    -0.06925    -0.07004    -0.08796];
            sigp = [0.3559  0.3660  0.3892  0.4160  0.4297  0.4518  0.4610  0.4714  0.4775...
                    0.4865  0.4950  0.5040  0.5181  0.5249  0.5424  0.5602  0.5731  0.5803...
                    0.5868  0.5907  0.5961  0.6133  0.6227  0.6222  0.6143  0.5644  0.5592...
                    0.4408];
            sigT = [1.3243  1.1933  1.0462  0.9591  0.8874  0.8021  0.8050  0.7551  0.7396...
                    0.7395  0.7274  0.7247  0.7271  0.7328  0.7503  0.7507  0.7534  0.7585...
                    0.7656  0.7644  0.7711  0.7817  0.7858  0.7823  0.7776  0.7392  0.7353...
```

```
            0.4408];
    else
        % double corner
        c1   = [-17.74463   -13.88893   -11.04809   -8.76880    -7.68301    -5.47019...
                -3.77355    -1.95968    -0.96872    0.10920     0.86777     1.42831...
                1.99361     2.14018     2.60454     3.30684     3.62400     3.77510...
                3.92454     3.99907     4.07670     4.69293     4.86717     5.03119...
                5.06834     3.74623     3.54103     4.06989];
        c2   = [2.22485 1.89859 1.64665 1.45200 1.34978 1.12590 0.98718 0.80810 0.71370...
                0.59537 0.52085 0.46988 0.41219 0.39715 0.35667 0.30373 0.27369 0.25773...
                0.24169 0.23357 0.22547 0.18262 0.17018 0.15779 0.14806 0.18152 0.18904...
                0.46794];
        c4   = [2.1 2.3 2.4 2.5 2.5 2.5 2.6 2.6 2.6 2.6 2.6 2.6 2.6 2.6 2.6 2.7 2.7 2.7...
                2.7 2.7 2.7 2.8 2.8 2.8 2.8 2.7 2.7 2.5];
        c6   = [-1.40084    -1.54772    -1.70010    -1.86494    -1.94573    -2.13473...
                -2.28113    -2.41132    -2.46500    -2.54120    -2.58506    -2.61380...
                -2.65510    -2.66676    -2.69927    -2.79751    -2.83163    -2.85226...
                -2.87495    -2.88734    -2.90040    -3.00672    -3.03252    -3.06134...
                -3.08409    -2.98867    -2.97418    -2.77481];
        c7   = [0.05305 0.06068 0.07272 0.08722 0.09603 0.11710 0.13007 0.14449 0.15003...
                0.15808 0.16235 0.16486 0.16868 0.16973 0.17238 0.17893 0.18170 0.18339...
                0.18521 0.18619 0.18720 0.19396 0.19560 0.19746 0.19935 0.19854 0.19819...
                0.19743];
        c10  = [-0.31641    -0.28960    -0.22943    -0.18125    -0.16127    -0.13830...
                -0.13323    -0.12529    -0.11749    -0.10506    -0.09484    -0.08671...
                -0.07801    -0.07573    -0.06929    -0.06512    -0.06128    -0.05952...
                -0.05791    -0.05717    -0.05647    -0.05520    -0.05434    -0.05377...
                -0.05361    -0.05734    -0.05814    -0.07606];
        sigp = [0.3559  0.3660  0.3892  0.4160  0.4297  0.4518  0.4610  0.4714  0.4775...
                0.4865  0.4950  0.5040  0.5181  0.5249  0.5424  0.5602  0.5731  0.5803...
                0.5868  0.5907  0.5961  0.6133  0.6227  0.6222  0.6143  0.5644  0.5592...
                0.4408];
        sigT = [1.3243  1.1933  1.0462  0.9591  0.8874  0.8021  0.8050  0.7551  0.7396...
                0.7395  0.7274  0.7247  0.7271  0.7328  0.7503  0.7507  0.7534  0.7585...
                0.7656  0.7644  0.7711  0.7817  0.7858  0.7823  0.7776  0.7392  0.7353...
                0.4408];
    end
else
    if SD_l == 1
        if SD_t == 0
            % single coner, variable medium stress drop
            c1   = [-19.07223   -15.15004   -11.84462   -9.00041    -7.60788    -4.51914...
                    -2.82095    -0.84738    0.13162     1.12628     1.79388     2.27495...
                    3.13556     3.26041     3.65946     3.92885     4.20238     4.33334...
                    4.89845     4.96669     5.03867     5.20890     5.37895     6.02744...
                    6.07941     4.24805     4.03930     3.22720];
            c2   = [2.57205 2.27308 1.96000 1.66899 1.50586 1.13220 0.93101 0.68960...
                    0.57890 0.45746 0.38804 0.34400 0.27220 0.25961 0.22693 0.20331...
                    0.17878 0.16542 0.12529 0.11815 0.11102 0.09698 0.08559 0.04417...
                    0.03289 0.09552 0.10412 0.65905];
            c4   = [2.1 2.3 2.4 2.5 2.5 2.6 2.6 2.6 2.6 2.6 2.6 2.6 2.7 2.7 2.7 2.7 2.7...
                    2.7 2.8 2.8 2.8 2.8 2.8 2.9 2.9 2.7 2.7 2.4];
            c6   = [-1.41166    -1.55609    -1.70638    -1.86794    -1.94031    -2.16445...
                    -2.25774    -2.39187    -2.45001    -2.53338    -2.58195    -2.61448...
                    -2.72838    -2.74131    -2.77660    -2.80630    -2.84105    -2.86188...
                    -2.96230    -2.97508    -2.98849    -3.01742    -3.04366    -3.15877...
                    -3.18403    -2.99165    -2.97465    -2.73277];
            c7   = [0.05292 0.06043 0.07232 0.08623 0.09384 0.11502 0.12494 0.13949...
                    0.14539 0.15420 0.15895 0.16182 0.17012 0.17129 0.17414 0.17658...
                    0.17938 0.18110 0.18763 0.18865 0.18968 0.19172 0.19337 0.20038...
                    0.20265 0.19690 0.19631 0.20009];
            c10  = [-0.31205    -0.38898    -0.39806    -0.37576    -0.35415    -0.29235...
                    -0.24823    -0.19435    -0.16638    -0.13930    -0.12283    -0.11211...
                    -0.10222    -0.09985    -0.09345    -0.08961    -0.08624    -0.08477...
                    -0.08349    -0.08293    -0.08242    -0.08150    -0.08079    -0.08027...
                    -0.08044    -0.08748    -0.08874    -0.13903];
            sigp = [0.3559  0.3660  0.3892  0.4160  0.4297  0.4518  0.4610  0.4714  0.4775...
                    0.4865  0.4950  0.5040  0.5181  0.5249  0.5424  0.5602  0.5731  0.5803...
                    0.5868  0.5907  0.5961  0.6133  0.6227  0.6222  0.6143  0.5644  0.5592...
                    0.4408];
            sigT = [1.3243  1.1933  1.0462  0.9591  0.8874  0.8021  0.8050  0.7551  0.7396...
```

```
            0.7395  0.7274  0.7247  0.7271  0.7328  0.7503  0.7507  0.7534  0.7585...
            0.7656  0.7644  0.7711  0.7817  0.7858  0.7823  0.7776  0.7392  0.7353...
            0.4408];
elseif SE == 0
    % single corner, constant medium stress drop
    c1   = [-19.48096   -15.60343   -12.32672   -9.51015    -8.14308    -5.12369...
            -3.47330    -1.58285    -0.65379    0.28490     0.91433     1.74233...
            2.19706     2.31425     2.69216     2.94690     3.20588     3.75552...
            3.88344     3.94814     4.01659     4.18017     4.34502     4.98360...
            5.03110     3.65796     3.00730     2.34185];
    c2   = [2.63369 2.34394 2.03581 1.74832 1.58833 1.22405 1.02939 0.79993...
            0.69665 0.58358 0.51993 0.45792 0.41304 0.40161 0.37212 0.35069...
            0.32832 0.29046 0.27758 0.27096 0.26433 0.25125 0.24062 0.20066...
            0.19000 0.22258 0.25858 0.79105];
    c4   = [2.1 2.3 2.4 2.5 2.5 2.6 2.6 2.6 2.6 2.6 2.6 2.7 2.7 2.7 2.7 2.7 2.7...
            2.8 2.8 2.8 2.8 2.8 2.8 2.9 2.9 2.8 2.7 2.4];
    c6   = [-1.40816    -1.55118    -1.70046    -1.86136    -1.93245    -2.15471...
            -2.24741    -2.37885    -2.43570    -2.51730    -2.56449    -2.66338...
            -2.70779    -2.72023    -2.75418    -2.78273    -2.81616    -2.91238...
            -2.93512    -2.94748    -2.96045    -2.98855    -3.01413    -3.12766...
            -3.15204    -3.03868    -2.94208    -2.69614];
    c7   = [0.05251 0.05960 0.07122 0.08496 0.09238 0.11324 0.12308 0.13729...
            0.14303 0.15162 0.15619 0.16286 0.16694 0.16804 0.17072 0.17300...
            0.17563 0.18175 0.18355 0.18451 0.18549 0.18741 0.18897 0.19576...
            0.19790 0.19703 0.19152 0.19476];
    c10  = [-0.27037    -0.34570    -0.35378    -0.33001    -0.30768    -0.24573...
            -0.20234    -0.15090    -0.12494    -0.10016    -0.08536    -0.07586...
            -0.06715    -0.06508    -0.05952    -0.05619    -0.05326    -0.05199...
            -0.05087    -0.05038    -0.04994    -0.04913    -0.04850    -0.04804...
            -0.04818    -0.05457    -0.05571    -0.10359];
    sigp = [0.3494  0.3630  0.3863  0.4110  0.4231  0.4432  0.4523  0.4641  0.4715...
            0.4819  0.4912  0.5006  0.5151  0.5220  0.5397  0.5576  0.5706  0.5777...
            0.5842  0.5881  0.5935  0.6107  0.6201  0.6195  0.6115  0.5613  0.5561...
            0.4380];
    sigT = [1.3226  1.1924  1.0451  0.9570  0.8842  0.7972  0.8000  0.7506  0.7357...
            0.7365  0.7248  0.7224  0.7249  0.7308  0.7483  0.7487  0.7515  0.7565...
            0.7636  0.7624  0.7691  0.7797  0.7837  0.7802  0.7754  0.7369  0.7329...
            0.4380];
else
    % single corner, constant medium stress drop with saturation
    c1   = [-17.91423   -13.91070   -10.54155   -7.62375    -6.23481    -3.08744...
            -1.41000    0.51857     1.46377     2.42583     3.06862     3.53193...
            4.46498     4.58602     4.97456     5.23836     5.50813     5.63835...
            6.30181     6.37083     6.44374     6.61705     6.79091     6.96175...
            7.60902     5.56137     5.35011     4.40490];
    c2   = [2.37754 2.07364 1.75532 1.45642 1.29417 0.91539 0.71797 0.48452...
            0.37971 0.26430 0.19946 0.15880 0.08019 0.06845 0.03821 0.01612...
            -0.00703    -0.01981    -0.07040    -0.07735    -0.08429    -0.09799...
            -0.10914    -0.12090    -0.17372    -0.09020    -0.08193    0.47616];
    c4   = [2.3 2.5 2.6 2.7 2.7 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.9 2.9 2.9 2.9 2.9...
            2.9 3.0 3.0 3.0 3.0 3.0 3.0 3.1 2.9 2.9 2.6];
    c6   = [-1.71861    -1.88340    -2.04882    -2.22717    -2.30231    -2.54658...
            -2.64410    -2.78232    -2.84201    -2.92775    -2.97730    -3.01048...
            -3.13934    -3.15246    -3.18830    -3.21848    -3.25386    -3.27511...
            -3.39174    -3.40488    -3.41866    -3.44851    -3.47572    -3.50625...
            -3.63508    -3.40512    -3.38707    -3.09544];
    c7   = [0.10433 0.11388 0.12727 0.14299 0.15083 0.17419 0.18452 0.19943...
            0.20543 0.21443 0.21920 0.22207 0.23200 0.23315 0.23596 0.23835...
            0.24112 0.24282 0.25111 0.25213 0.25316 0.25520 0.25685 0.25870...
            0.26806 0.25856 0.25794 0.25711];
    c10  = [-0.28182    -0.35716    -0.36524    -0.34147    -0.31913    -0.25719...
            -0.21379    -0.16236    -0.13639    -0.11161    -0.09681    -0.08732...
            -0.07861    -0.07654    -0.07097    -0.06764    -0.06471    -0.06344...
            -0.06233    -0.06184    -0.06139    -0.06059    -0.05996    -0.05949...
            -0.05964    -0.06603    -0.06717    -0.11505];
    sigp = [0.3597  0.3757  0.4010  0.4264  0.4385  0.4583  0.4674  0.4790  0.4863...
            0.4964  0.5054  0.5147  0.5289  0.5356  0.5530  0.5706  0.5834  0.5906...
            0.5972  0.6011  0.6063  0.6231  0.6323  0.6320  0.6240  0.5741  0.5689...
            0.4493];
    sigT = [1.3253  1.1963  1.0506  0.9637  0.8917  0.8057  0.8087  0.7599  0.7453...
            0.7461  0.7345  0.7322  0.7348  0.7405  0.7580  0.7585  0.7612  0.7664...
```

```
            0.7736  0.7724  0.7790  0.7894  0.7934  0.7901  0.7853  0.7467  0.7427...
            0.4493];
    end
elseif SD_l == 0
    if SD_t == 0
        % single coner, variable low stress drop
        c1   = [-18.82818   -14.90966   -11.55820   -8.74448    -7.14902    -4.48436...
            -2.60545    -0.82196    0.04301     0.91358     1.49580     1.91753...
            2.71047     2.81889     3.17270     3.41148     3.65547     3.77180...
            4.31663     4.37793     4.44314     4.60063     4.76103     5.39249...
            5.43661     3.62958     3.42714     2.77820];
        c2   = [2.50853 2.17243 1.83734 1.53854 1.36498 1.01787 0.81461 0.59874...
            0.50444 0.40083 0.34395 0.30871 0.24622 0.23601 0.20990 0.19064...
            0.17022 0.15884 0.12089 0.11466 0.10840 0.09599 0.08583 0.04598...
            0.03559 0.09547 0.10323 0.64929];
        c4   = [2.1 2.3 2.4 2.5 2.5 2.6 2.6 2.6 2.6 2.6 2.6 2.6 2.7 2.7 2.7 2.7 2.7...
            2.7 2.8 2.8 2.8 2.8 2.8 2.9 2.9 2.7 2.7 2.4];
        c6   = [-1.39437    -1.51375    -1.66484    -1.82313    -1.93736    -2.10529...
            -2.24962    -2.37729    -2.43239    -2.51171    -2.55688    -2.58706...
            -2.69634    -2.70814    -2.74034    -2.76748    -2.79941    -2.81861...
            -2.91626    -2.92815    -2.94065    -2.96783    -2.99272    -3.10501...
            -3.12848    -2.93410    -2.91721    -2.66659];
        c7   = [0.05155 0.05943 0.07203 0.08612 0.09559 0.11396 0.12651 0.14040...
            0.14596 0.15434 0.15868 0.16126 0.16908 0.17011 0.17258 0.17469...
            0.17715 0.17867 0.18495 0.18586 0.18679 0.18862 0.19011 0.19687...
            0.19893 0.19276 0.19218 0.19477];
        c10  = [-0.35284    -0.40726    -0.39809    -0.36309    -0.33624    -0.26954...
            -0.22591    -0.17695    -0.15344    -0.13143    -0.11864    -0.11059...
            -0.10327    -0.10154    -0.09693    -0.09418    -0.09175    -0.09070...
            -0.08978    -0.08938    -0.08901    -0.08835    -0.08783    -0.08744...
            -0.08760    -0.09342    -0.09443    -0.15404];
        sigp = [0.3623  0.3774  0.4056  0.4307  0.4415  0.4580  0.4650  0.4750  0.4816...
            0.4910  0.4995  0.5084  0.5222  0.5289  0.5460  0.5635  0.5760  0.5830...
            0.5893  0.5931  0.5984  0.6153  0.6246  0.6240  0.6160  0.5661  0.5610...
            0.4441];
        sigT = [1.3261  1.1969  1.0524  0.9656  0.8932  0.8056  0.8073  0.7574  0.7423...
            0.7425  0.7305  0.7278  0.7300  0.7357  0.7529  0.7531  0.7556  0.7605...
            0.7676  0.7662  0.7729  0.7833  0.7873  0.7837  0.7790  0.7405  0.7366...
            0.4441];
    elseif SE == 0
        % single corner, constant low stress drop
        c1   = [-19.09237   -15.22296   -11.90955   -9.12644    -7.79761    -4.89906...
            -3.33687    -1.58102    -0.72368    0.13269     0.71018     1.13055...
            1.90139     2.00886     2.36108     2.59748     2.83795     2.95159...
            3.47181     3.53102     3.59389     3.74605     3.90146     4.50286...
            4.54101     2.77858     2.57877     2.01678];
        c2   = [2.55127 2.22463 1.89523 1.60015 1.44039 1.08390 0.89916 0.68709...
            0.59402 0.49251 0.43636 0.40133 0.34023 0.33012 0.30408 0.28497...
            0.26482 0.25367 0.21711 0.21106 0.20500 0.19303 0.18325 0.14513...
            0.13536 0.19423 0.20187 0.74196];
        c4   = [2.1 2.2 2.3 2.4 2.4 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.6 2.6 2.6 2.6 2.6...
            2.6 2.7 2.7 2.7 2.7 2.7 2.8 2.8 2.6 2.6 2.3];
        c6   = [-1.41992    -1.53646    -1.68527    -1.84330    -1.91307    -2.13693...
            -2.23329    -2.36933    -2.43076    -2.51516    -2.56429    -2.59747...
            -2.70593    -2.71828    -2.75216    -2.78005    -2.81238    -2.83154...
            -2.92538    -2.93706    -2.94929    -2.97578    -2.99999    -3.10735...
            -3.12969    -2.94022    -2.92333    -2.65712];
        c7   = [0.05359 0.06087 0.07303 0.08701 0.09450 0.11627 0.12682 0.14193...
            0.14840 0.15754 0.16246 0.16549 0.17349 0.17461 0.17736 0.17962...
            0.18218 0.18373 0.18980 0.19071 0.19162 0.19341 0.19487 0.20134...
            0.20328 0.19693 0.19630 0.19550];
        c10  = [-0.29994    -0.35343    -0.34299    -0.30641    -0.27892    -0.21228...
            -0.16950    -0.12239    -0.10021    -0.07959    -0.06770    -0.06026...
            -0.05345    -0.05184    -0.04754    -0.04496    -0.04266    -0.04164...
            -0.04075    -0.04035    -0.03999    -0.03934    -0.03882    -0.03842...
            -0.03854    -0.04397    -0.04493    -0.10331];
        sigp = [0.3543  0.3702  0.3983  0.4221  0.4320  0.4482  0.4562  0.4684  0.4767...
            0.4879  0.4977  0.5075  0.5223  0.5291  0.5470  0.5648  0.5778  0.5848...
            0.5913  0.5952  0.6005  0.6175  0.6269  0.6263  0.6184  0.5680  0.5628...
            0.4439];
        sigT = [1.3239  1.1946  1.0496  0.9618  0.8885  0.8000  0.8022  0.7532  0.7391...
```

```
            0.7405  0.7292  0.7272  0.7301  0.7359  0.7536  0.7541  0.7570  0.7619...
            0.7691  0.7678  0.7745  0.7850  0.7891  0.7856  0.7809  0.7420  0.7380...
            0.4439];
    else
        % single corner, constant low stress drop with saturation
        c1   = [-17.52612   -13.58249   -9.90982    -7.30278    -5.63265    -2.93381...
            -1.34540    0.44711     1.32039     2.19908     2.78943     3.21855...
            3.64126     3.75047     4.56076     4.80550     5.05581     5.17534...
            5.29605     5.35709     5.92808     6.08901     6.25258     6.41230...
            7.01484     5.03603     4.83071     3.99963];
        c2   = [2.29529 1.96072 1.60565 1.31553 1.13348 0.78321 0.59571 0.37973...
            0.28510 0.18130 0.12398 0.08824 0.04811 0.03785 -0.02108    -0.04079...
            -0.06166    -0.07324    -0.08523    -0.09141    -0.13394    -0.14646...
            -0.15669    -0.16752    -0.21767    -0.13680    -0.12898    0.43627];
        c4   = [2.3 2.4 2.6 2.6 2.7 2.7 2.7 2.7 2.7 2.7 2.7 2.7 2.7 2.7 2.8 2.8 2.8...
            2.8 2.8 2.8 2.9 2.9 2.9 2.9 3.0 2.8 2.8 2.5];
        c6   = [-1.73008    -1.85975    -2.07280    -2.19863    -2.32961    -2.51701...
            -2.61803    -2.76056    -2.82477    -2.91311    -2.96449    -2.99921...
            -3.04474    -3.05739    -3.17249    -3.20187    -3.23598    -3.25620...
            -3.27840    -3.29040    -3.39211    -3.42020    -3.44589    -3.47458...
            -3.59567    -3.37101    -3.35311    -3.04259];
        c7   = [0.10536 0.11403 0.13069 0.14381 0.15521 0.17588 0.18691 0.20271...
            0.20944 0.21897 0.22409 0.22724 0.23151 0.23266 0.24111 0.24348...
            0.24617 0.24779 0.24954 0.25047 0.25767 0.25956 0.26109 0.26279...
            0.27165 0.26174 0.26108 0.25625];
        c10  = [-0.31139    -0.36489    -0.35444    -0.31786    -0.29038    -0.22374...
            -0.18095    -0.13385    -0.11167    -0.09104    -0.07915    -0.07171...
            -0.06490    -0.06330    -0.05900    -0.05641    -0.05411    -0.05310...
            -0.05220    -0.05181    -0.05145    -0.05080    -0.05027    -0.04987...
            -0.04999    -0.05542    -0.05639    -0.11476];
        sigp = [0.3654  0.3842  0.4138  0.4378  0.4474  0.4634  0.4712  0.4831  0.4912...
            0.5021  0.5117  0.5213  0.5358  0.5426  0.5601  0.5777  0.5906  0.5976...
            0.6042  0.6081  0.6133  0.6300  0.6391  0.6388  0.6309  0.5808  0.5755...
            0.4549];
        sigT = [1.3269  1.1990  1.0556  0.9688  0.8961  0.8086  0.8109  0.7625  0.7485...
            0.7499  0.7389  0.7369  0.7398  0.7456  0.7632  0.7638  0.7668  0.7718...
            0.7791  0.7779  0.7844  0.7949  0.7989  0.7956  0.7908  0.7518  0.7477...
            0.4549];
    end
else
    if SD_t == 0
        % single coner, variable high stress drop
        c1   = [-18.80138   -15.20886   -11.97362   -9.12315    -7.70148    -4.46472...
            -2.67167    -0.51056    0.58917     1.72806     2.49641     3.46126...
            4.02502     4.17095     4.63032     4.94207     5.25826     5.41104...
            6.03843     6.11753     6.20019     6.39121     6.57730     6.75933...
            7.35410     5.41652     5.19757     4.14085];
        c2   = [2.59958 2.34990 2.06358 1.78482 1.62326 1.24156 1.03112 0.76645...
            0.63923 0.49782 0.41405 0.33544 0.27487 0.25933 0.21818 0.18877...
            0.15855 0.14236 0.09752 0.08905 0.08062 0.06416 0.05102 0.03739...
            -0.00721    0.06158 0.07129 0.63457];
        c4   = [2.3 2.4 2.5 2.6 2.6 2.7 2.7 2.7 2.7 2.7 2.7 2.8 2.8 2.8 2.8 2.8 2.8...
            2.8 2.9 2.9 2.9 2.9 2.9 2.9 3.0 2.8 2.8 2.5];
        c6   = [-1.51629    -1.62679    -1.77626    -1.94059    -2.01584    -2.25138...
            -2.34731    -2.48971    -2.55190    -2.64087    -2.69325    -2.80186...
            -2.85216    -2.86633    -2.90541    -2.93847    -2.97721    -3.00040...
            -3.11001    -3.12417    -3.13898    -3.17073    -3.19920    -3.23117...
            -3.35245    -3.15000    -3.13247    -2.88388];
        c7   = [0.05717 0.06230 0.07329 0.08684 0.09460 0.11635 0.12639 0.14173...
            0.14804 0.15740 0.16254 0.16992 0.17467 0.17597 0.17924 0.18204...
            0.18528 0.18726 0.19437 0.19554 0.19672 0.19905 0.20091 0.20300...
            0.21111 0.20544 0.20485 0.20958];
        c10  = [-0.25763    -0.35359    -0.38117    -0.37239    -0.35700    -0.30377...
            -0.26186    -0.20549    -0.17378    -0.14160    -0.12105    -0.10713...
            -0.09403    -0.09083    -0.08205    -0.07672    -0.07200    -0.06993...
            -0.06812    -0.06731    -0.06658    -0.06525    -0.06426    -0.06354...
            -0.06367    -0.07217    -0.07375    -0.11455];
        sigp = [0.3585  0.3642  0.3821  0.4081  0.4242  0.4538  0.4671  0.4794  0.4851...
            0.4934  0.5013  0.5099  0.5238  0.5305  0.5480  0.5658  0.5789  0.5861...
            0.5929  0.5968  0.6022  0.6195  0.6289  0.6285  0.6209  0.5713  0.5661...
            0.4471];
```

```
    sigT = [1.3250  1.1928  1.0436  0.9557  0.8847  0.8032  0.8085  0.7601  0.7445...
            0.7441  0.7317  0.7289  0.7311  0.7369  0.7543  0.7549  0.7578  0.7629...
            0.7703  0.7691  0.7758  0.7866  0.7907  0.7873  0.7829  0.7445  0.7405...
            0.4471];
elseif SE == 0
    % single corner, constant high stress drop
    c1   = [-19.70343   -16.02752   -12.85572   -10.06892   -8.68001    -5.55701...
            -3.81429    -1.74607    -0.70305    0.36441     1.08397     1.97802...
            2.50153     2.63659     3.06506     3.35414     3.64678     4.21631...
            4.36033     4.43278     4.50882     4.68655     4.86194     5.51533...
            5.57118     4.18329     3.52033     2.71517];
    c2   = [2.68814 2.44418 2.16545 1.89280 1.73516 1.36536 1.16106 0.90876...
            0.78942 0.65805 0.58122 0.50970 0.45480 0.44078 0.40391 0.37757...
            0.35047 0.31022 0.29517 0.28752 0.27990 0.26499 0.25301 0.21155...
            0.19995 0.23483 0.27213 0.80995];
    c4   = [2.1 2.3 2.4 2.5 2.5 2.6 2.6 2.6 2.6 2.6 2.6 2.7 2.7 2.7 2.7 2.7 2.7...
            2.8 2.8 2.8 2.8 2.8 2.8 2.9 2.9 2.8 2.7 2.4];
    c6   = [-1.41959    -1.55334    -1.69535    -1.85191    -1.92392    -2.14802...
            -2.24164    -2.37871    -2.43840    -2.52362    -2.57366    -2.67484...
            -2.72265    -2.73607    -2.77296    -2.80403    -2.84039    -2.93884...
            -2.96337    -2.97664    -2.99056    -3.02045    -3.04739    -3.16325...
            -3.18948    -3.08048    -2.98288    -2.74660];
    c7   = [0.05456 0.06006 0.07035 0.08324 0.09060 0.11128 0.12109 0.13582...
            0.14185 0.15080 0.15569 0.16259 0.16707 0.16829 0.17133 0.17391...
            0.17689 0.18324 0.18525 0.18632 0.18741 0.18954 0.19126 0.19826...
            0.20062 0.20033 0.19476 0.19917];
    c10  = [-0.23554    -0.32899    -0.35582    -0.34592    -0.32977    -0.27558...
            -0.23358    -0.17883    -0.14883    -0.11897    -0.10026    -0.08779...
            -0.07615    -0.07333    -0.06565    -0.06102    -0.05692    -0.05514...
            -0.05357    -0.05287    -0.05224    -0.05109    -0.05023    -0.04959...
            -0.04972    -0.05744    -0.05886    -0.09791];
    sigp = [0.3441  0.3574  0.3756  0.3980  0.4113  0.4357  0.4473  0.4603  0.4676...
            0.4780  0.4874  0.4971  0.5121  0.5192  0.5375  0.5558  0.5693  0.5766...
            0.5834  0.5875  0.5930  0.6105  0.6201  0.6197  0.6119  0.5616  0.5564...
            0.4373];
    sigT = [1.3212  1.1907  1.0412  0.9514  0.8786  0.7931  0.7972  0.7482  0.7332...
            0.7340  0.7223  0.7200  0.7228  0.7288  0.7468  0.7474  0.7505  0.7556...
            0.7630  0.7619  0.7687  0.7795  0.7837  0.7803  0.7757  0.7371  0.7140...
            0.4373];
else
    % single corner, constant high stress drop with saturation
    c1   = [-17.92122   -14.33292   -11.07071   -8.18384    -6.43297    -3.52171...
            -1.75176    0.35595     1.41567     2.50733     3.24100     3.76921...
            4.77362 4.91274 5.35255 5.65135 5.95548 6.10266 6.25069 6.86357...
            6.94435 7.13246 7.31723 7.49863 8.16024 6.09264 5.87466 4.79171];
    c2   = [2.41939 2.17359 1.88506 1.60124 1.42055 1.05720 0.85016 0.59376...
            0.47284 0.33905 0.26094 0.21066 0.12203 0.10766 0.06996 0.04288...
            0.01492 -0.00018    -0.01554    -0.06114    -0.06911    -0.08472...
            -0.09725    -0.11031    -0.16443    -0.07836    -0.06918    0.49399];
    c4   = [2.4 2.5 2.6 2.7 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.9 2.9 2.9 2.9 2.9...
            2.9 2.9 3.0 3.0 3.0 3.0 3.0 3.1 2.9 2.9 2.6];
    c6   = [-1.76932    -1.88598    -2.04376    -2.21757    -2.35414    -2.53979...
            -2.63826    -2.78233    -2.84495    -2.93443    -2.98696    -3.02221...
            -3.15491    -3.16905    -3.20795    -3.24075    -3.27916    -3.30216...
            -3.32741    -3.43540    -3.45017    -3.48193    -3.51057    -3.54270...
            -3.67439    -3.44793    -3.42987    -3.14834];
    c7   = [0.10861 0.11439 0.12639 0.14122 0.15261 0.17215 0.18244 0.19789...
            0.20419 0.21356 0.21867 0.22178 0.23211 0.23338 0.23656 0.23928...
            0.24241 0.24432 0.24639 0.25399 0.25514 0.25740 0.25921 0.26124...
            0.27088 0.26192 0.26131 0.26171];
    c10  = [-0.24700    -0.34044    -0.36727    -0.35737    -0.34123    -0.28704...
            -0.24504    -0.19028    -0.16028    -0.13042    -0.11171    -0.09924...
            -0.08761    -0.08479    -0.07711    -0.07247    -0.06838    -0.06659...
            -0.06502    -0.06433    -0.06369    -0.06255    -0.06168    -0.06105...
            -0.06117    -0.06890    -0.07032    -0.10937];
    sigp = [0.3539  0.3691  0.3895  0.4130  0.4266  0.4510  0.4627  0.4757  0.4829...
            0.4931  0.5023  0.5118  0.5265  0.5334  0.5513  0.5693  0.5826  0.5900...
            0.5969  0.6009  0.6063  0.6234  0.6328  0.6326  0.6248  0.5749  0.5697...
            0.4492];
    sigT = [1.3238  1.1943  1.0463  0.9578  0.8859  0.8016  0.8060  0.7578  0.7431...
            0.7439  0.7324  0.7302  0.7331  0.7389  0.7567  0.7575  0.7606  0.7659...
```

```
                  0.7734  0.7723  0.7790  0.7897  0.7938  0.7906  0.7859  0.7473  0.7433...
                  0.4492];
            end
        end
    end
elseif G == 0
    if CM == 2
        if SE == 1
            % double corner with saturation
            c1   = [-14.54243   -9.76826    -6.54516    -3.83140    -2.06630    0.53026...
                    2.74561     4.87153     5.96206     8.03762     8.93501     9.59190...
                    11.20299    11.39716    12.01553    13.46434    13.96635    14.23988...
                    14.53975    15.83611    16.02362    16.45698    16.84962    17.20090...
                    17.40998    13.83032    13.52127    10.31841];
            c2   = [1.91703 1.50496 1.21492 0.98710 0.85356 0.62351 0.44592 0.25189 0.14984...
                    -0.01963    -0.10061    -0.15735    -0.27131    -0.28656    -0.33472...
                    -0.43179    -0.47347    -0.49678    -0.52162    -0.60342    -0.61652...
                    -0.64342    -0.66794    -0.69766    -0.72596    -0.59892    -0.58872...
                    -0.16678];
            c4   = [2.7 3.0 3.1 3.2 3.3 3.3 3.4 3.4 3.4 3.5 3.5 3.5 3.6 3.6 3.6 3.7 3.7 3.7...
                    3.7 3.8 3.8 3.8 3.8 3.8 3.8 3.6 3.6 3.1];
            c6   = [-2.10859    -2.41187    -2.65122    -2.90058    -3.09220    -3.32873...
                    -3.57911    -3.76122    -3.85124    -4.09059    -4.16740    -4.22645...
                    -4.44627    -4.46693    -4.53955    -4.76782    -4.84844    -4.89689...
                    -4.95186    -5.16886    -5.20228    -5.27833    -5.35052    -5.42663...
                    -5.48554    -4.99790    -4.95888    -4.13550];
            c7   = [0.12608 0.14194 0.15876 0.17769 0.19167 0.21370 0.23302 0.24875 0.25592...
                    0.27175 0.27663 0.28002 0.29278 0.29383 0.29762 0.31108 0.31607 0.31927...
                    0.32294 0.33606 0.33809 0.34234 0.34658 0.35229 0.35830 0.34481 0.34391...
                    0.33428];
            c10  = [-0.34322    -0.30605    -0.24408    -0.19493    -0.17514    -0.15190...
                    -0.14644    -0.13799    -0.13028    -0.11756    -0.10695    -0.09871...
                    -0.08984    -0.08758    -0.08082    -0.07649    -0.07252    -0.07075...
                    -0.06914    -0.06840    -0.06769    -0.06636    -0.06561    -0.06508...
                    -0.06521    -0.06992    -0.07073    -0.09848];
            sigp = [0.5243  0.5604  0.5958  0.6159  0.6233  0.6483  0.6622  0.6850  0.6996...
                    0.7208  0.7389  0.7556  0.7783  0.7850  0.8064  0.8192  0.8294  0.8339...
                    0.8396  0.8438  0.8491  0.8566  0.8572  0.8487  0.8430  0.7733  0.7666...
                    0.5888];
            sigT = [1.3791  1.2665  1.1393  1.0612  0.9956  0.9271  0.9349  0.9040  0.8991...
                    0.9109  0.9111  0.9177  0.9306  0.9369  0.9587  0.9596  0.9628  0.9664...
                    0.9730  0.9733  0.9799  0.9842  0.9821  0.9722  0.9685  0.9088  0.9031...
                    0.5888];
        else
            % double corner
            c1   = [-16.41379   -12.20468   -8.83853    -6.28665    -5.10947    -2.15831...
                    -0.12511    1.93674     2.99580     4.87830     5.74732     7.09082...
                    7.79199     7.97786     9.36118     9.79610     10.26367    10.51625...
                    11.69837    11.85646    12.02874    12.42738    13.81046    14.14384...
                    14.33926    11.07839    9.90148 8.13980];
            c2   = [2.20767 1.83553 1.54958 1.33826 1.24004 0.99778 0.83880 0.64984 0.55002...
                    0.39924 0.31977 0.22710 0.16914 0.15425 0.06628 0.03112 -0.00857...
                    -0.03055    -0.10103    -0.11325    -0.12544    -0.15043    -0.22653...
                    -0.25488    -0.28175    -0.18783    -0.12757    0.18271];
            c4   = [2.5 2.7 2.9 3.0 3.0 3.1 3.2 3.2 3.2 3.3 3.3 3.4 3.4 3.4 3.5 3.5 3.5 3.5...
                    3.6 3.6 3.6 3.6 3.7 3.7 3.7 3.5 3.4 3.0];
            c6   = [-1.74567    -1.95111    -2.21747    -2.43987    -2.53021    -2.82918...
                    -3.05030    -3.22152    -3.30621    -3.51506    -3.58708    -3.76365...
                    -3.83080    -3.85005    -4.05250    -4.11197    -4.18673    -4.23161...
                    -4.43516    -4.46406    -4.49489    -4.56505    -4.80279    -4.87587...
                    -4.93249    -4.49420    -4.30771    -3.72218];
            c7   = [0.06829 0.07737 0.09356 0.10973 0.11775 0.14191 0.15823 0.17312 0.17993...
                    0.19281 0.19746 0.20689 0.21046 0.21146 0.22188 0.22526 0.22992 0.23289...
                    0.24410 0.24596 0.24783 0.25176 0.26447 0.26995 0.27571 0.26735 0.25806...
                    0.26644];
            c10  = [-0.33131    -0.29415    -0.23217    -0.18303    -0.16323    -0.13999...
                    -0.13454    -0.12608    -0.11838    -0.10565    -0.09504    -0.08680...
                    -0.07794    -0.07567    -0.06891    -0.06459    -0.06062    -0.05885...
                    -0.05724    -0.05650    -0.05578    -0.05445    -0.05370    -0.05318...
                    -0.05331    -0.05801    -0.05882    -0.08657];
            sigp = [0.5243  0.5604  0.5958  0.6159  0.6233  0.6483  0.6622  0.6850  0.6996...
```

```
              0.7208  0.7389  0.7556  0.7783  0.7850  0.8064  0.8192  0.8294  0.8339...
              0.8396  0.8438  0.8491  0.8566  0.8572  0.8487  0.8430  0.7733  0.7666...
              0.5888];
        sigT = [1.3791  1.2665  1.1393  1.0612  0.9956  0.9271  0.9349  0.9040  0.8991...
              0.9109  0.9111  0.9177  0.9306  0.9369  0.9587  0.9596  0.9628  0.9664...
              0.9730  0.9733  0.9799  0.9842  0.9821  0.9722  0.9685  0.9088  0.9031...
              0.5888];
    end
else
    if SD_l == 1
        if SD_t == 0
            % single coner, variable medium stress dop
            c1   = [-14.54986   -9.25169    -5.31480    -1.92096    0.25617     4.21778...
                    6.01523     9.10831     10.18655    12.43075    13.29372    13.93331...
                    15.82366    16.02650    16.69027    17.18425    17.71756    17.99875...
                    18.29779    18.46167    18.64419    20.50874    20.89870    19.78142...
                    19.88182    16.81947    15.27441    11.09786];
            c2   = [2.30998 1.88136 1.49937 1.16422 0.96349 0.55654 0.35576 0.06810...
                    -0.04192    -0.21755    -0.29360    -0.34606    -0.46920    -0.48449...
                    -0.53555    -0.57629    -0.62387    -0.64981    -0.67629    -0.68951...
                    -0.70300    -0.81779    -0.84219    -0.78593    -0.80582    -0.70860...
                    -0.61726    0.03822];
            c4   = [2.8 3.1 3.2 3.3 3.4 3.5 3.5 3.6 3.6 3.7 3.7 3.7 3.8 3.8 3.8 3.8 3.8...
                    3.8 3.8 3.8 3.8 3.9 3.9 3.8 3.8 3.7 3.6 3.2];
            c6   = [-2.15716    -2.51971    -2.79932    -3.08551    -3.30857    -3.70387...
                    -3.87179    -4.24952    -4.37417    -4.69883    -4.81633    -4.90830...
                    -5.21303    -5.24545    -5.35752    -5.44841    -5.55455    -5.61318...
                    -5.67576    -5.70923    -5.74551    -6.06641    -6.14187    -5.97732...
                    -6.01166    -5.55741    -5.30301    -4.40038];
            c7   = [0.09152 0.11010 0.12984 0.15079 0.16627 0.19724 0.21222 0.24024...
                    0.25066 0.27269 0.28167 0.28841 0.30744 0.30976 0.31804 0.32521...
                    0.33408 0.33907 0.34425 0.34685 0.34952 0.36944 0.37424 0.36646...
                    0.37073 0.35763 0.34239 0.33709];
            c10  = [-0.34105    -0.38752    -0.37439    -0.33869    -0.31189    -0.24619...
                    -0.20693    -0.15976    -0.13932    -0.11900    -0.10754    -0.10055...
                    -0.09434    -0.09294    -0.08918    -0.08711    -0.08558    -0.08507...
                    -0.08473    -0.08461    -0.08451    -0.08430    -0.08421    -0.08469...
                    -0.08525    -0.09091    -0.09155    -0.14227];
            sigp = [0.5243  0.5604  0.5958  0.6159  0.6233  0.6483  0.6622  0.6850  0.6996...
                    0.7208  0.7389  0.7556  0.7783  0.7850  0.8064  0.8192  0.8294  0.8339...
                    0.8396  0.8438  0.8491  0.8566  0.8572  0.8487  0.8430  0.7733  0.7666...
                    0.5888];
            sigT = [1.3791  1.2665  1.1393  1.0612  0.9956  0.9271  0.9349  0.9040  0.8991...
                    0.9109  0.9111  0.9177  0.9306  0.9369  0.9587  0.9596  0.9628  0.9664...
                    0.9730  0.9733  0.9799  0.9842  0.9821  0.9722  0.9685  0.9088  0.9031...
                    0.5888];
        elseif SE == 0
            % single corner, constant medium stress drop
            c1   = [-14.97295   -9.72740    -5.83777    -2.48893    -0.33936    3.53746...
                    5.26938     8.26540     9.29703     11.47972    12.30467    12.91716...
                    14.76997    14.96522    15.60406    16.07898    16.58985    16.85850...
                    17.14437    18.68342    18.86815    19.31416    19.69186    18.57590...
                    18.66451    15.61583    14.09083    10.05725];
            c2   = [2.37485     1.95572     1.58067     1.25139     1.05439     0.65933...
                    0.46791     0.19447     0.09136     -0.07511    -0.14553    -0.19398...
                    -0.31160    -0.32579    -0.37326    -0.41128    -0.45572    -0.47991...
                    -0.50458    -0.59824    -0.61146    -0.64033    -0.66304    -0.60707...
                    -0.62536    -0.53024    -0.44176    0.19114];
            c4   = [2.8 3.1 3.2 3.3 3.4 3.5 3.5 3.6 3.6 3.7 3.7 3.7 3.8 3.8 3.8 3.8 3.8...
                    3.8 3.8 3.9 3.9 3.9 3.9 3.8 3.8 3.7 3.6 3.2];
            c6   = [-2.14967    -2.51098    -2.78845    -3.07316    -3.29591    -3.68869...
                    -3.85384    -4.22696    -4.34955    -4.66998    -4.78472    -4.87438...
                    -5.17479    -5.20638    -5.31533    -5.40344    -5.50586    -5.56225...
                    -5.62237    -5.88319    -5.91969    -6.00557    -6.07864    -5.91373...
                    -5.94544    -5.49076    -5.23954    -4.32766];
            c7   = [0.09041 0.10865 0.12797 0.14866 0.16405 0.19464 0.20926 0.23667...
                    0.24683 0.26828 0.27690 0.28333 0.30176 0.30397 0.31184 0.31863...
                    0.32700 0.33169 0.33654 0.35235 0.35496 0.36070 0.36517 0.35737...
                    0.36127 0.34812 0.33332 0.32682];
            c10  = [-0.29863    -0.34332    -0.32881    -0.29199    -0.26496    -0.20041...
                    -0.16290    -0.11889    -0.10023    -0.08198    -0.07185    -0.06574...
```

```
            -0.06037    -0.05917    -0.05594    -0.05418    -0.05288    -0.05245...
            -0.05218    -0.05209    -0.05201    -0.05184    -0.05176    -0.05222...
            -0.05272    -0.05781    -0.05839    -0.10589];
        sigp = [0.5217  0.5587  0.5920  0.6097  0.6163  0.6409  0.6556  0.6802  0.6958...
            0.7177  0.7363  0.7531  0.7758  0.7825  0.8038  0.8166  0.8266  0.8310...
            0.8365  0.8407  0.8459  0.8533  0.8538  0.8453  0.8395  0.7697  0.7630...
            0.5846];
        sigT = [1.3782  1.2658  1.1373  1.0576  0.9913  0.9219  0.9302  0.9004  0.8962...
            0.9085  0.9090  0.9156  0.9285  0.9348  0.9565  0.9574  0.9604  0.9639...
            0.9704  0.9706  0.9771  0.9814  0.9791  0.9692  0.9655  0.9057  0.9000...
            0.5846];
    else
        % single corner, constant medium stress drop with saturation
        c1   = [-12.36761   -7.18334    -3.08593    1.25366     2.84583     7.02300...
            8.82898     12.13819    13.22694    14.47052    16.60473    17.26232...
            18.00368    18.20699    20.35514    20.87722    21.44261    21.74098...
            22.05839    22.23245    22.42674    22.89529    23.29188    23.64102...
            23.74361    18.80216    18.44350    13.42744];
        c2   = [2.03153 1.59845 1.20331 0.80656 0.63403 0.20984 0.01214 -0.29103...
            -0.39862    -0.51361    -0.66904    -0.72060    -0.77536    -0.79010...
            -0.93590    -0.97756    -1.02649    -1.05317    -1.08042    -1.09401...
            -1.10792    -1.13831    -1.16219    -1.19389    -1.21411    -0.98785...
            -0.97271    -0.26637];
        c4   = [3.1 3.3 3.4 3.6 3.6 3.7 3.7 3.8 3.8 3.8 3.9 3.9 3.9 3.9 4.0 4.0 4.0...
            4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 3.8 3.8 3.4];
        c6   = [-2.63877    -2.98527    -3.29709    -3.74757    -3.87433    -4.31520...
            -4.49285    -4.91519    -5.04733    -5.20994    -5.54036    -5.63758...
            -5.75279    -5.78572    -6.14146    -6.23744    -6.34895    -6.41027...
            -6.47563    -6.51064    -6.54872    -6.63833    -6.71452    -6.79201...
            -6.82593    -6.06348    -6.00839    -4.94368];
        c7   = [0.15707 0.17746 0.20010 0.23195 0.24315 0.27841 0.29408 0.32617...
            0.33707 0.34992 0.37238 0.37933 0.38735 0.38965 0.41343 0.42083...
            0.42994 0.43505 0.44033 0.44297 0.44569 0.45168 0.45635 0.46299...
            0.46721 0.43296 0.43044 0.41289];
        c10  = [-0.31008    -0.35477    -0.34026    -0.30344    -0.27642    -0.21186...
            -0.17435    -0.13035    -0.11168    -0.09344    -0.08331    -0.07720...
            -0.07183    -0.07062    -0.06740    -0.06563    -0.06434    -0.06391...
            -0.06363    -0.06354    -0.06346    -0.06330    -0.06322    -0.06368...
            -0.06417    -0.06926    -0.06984    -0.11734];
        sigp = [0.5339  0.5716  0.6050  0.6221  0.6282  0.6525  0.6669  0.6911  0.7063...
            0.7278  0.7461  0.7626  0.7850  0.7917  0.8126  0.8251  0.8350  0.8394...
            0.8448  0.8489  0.8540  0.8613  0.8618  0.8532  0.8477  0.7782  0.7716...
            0.5929];
        sigT = [1.3828  1.2715  1.1441  1.0648  0.9987  0.9300  0.9382  0.9086  0.9044...
            0.9165  0.9169  0.9235  0.9362  0.9425  0.9639  0.9646  0.9676  0.9711...
            0.9775  0.9777  0.9841  0.9883  0.9861  0.9761  0.9726  0.9130  0.9073...
            0.5929];
    end
elseif SD_l == 0
    if SD_t == 0
        % single coner, variable low stress drop
        c1   = [-14.25163   -9.24105    -4.86624    -1.52175    0.60771     4.38270...
            6.03088     8.91163     9.88541     11.99662    12.77568    13.35601...
            15.16957    15.35608    15.96772    16.42234    16.90986    17.16559...
            17.43775    18.95886    19.13672    19.56869    19.93414    18.81796...
            18.89574    15.86483    14.35825    10.31697];
        c2   = [2.23220 1.78174 1.36569 1.02753 0.82916 0.44249 0.26122 0.00198...
            -0.09326    -0.25104    -0.31521    -0.35932    -0.47298    -0.48604...
            -0.53011    -0.56572    -0.60751    -0.63027    -0.65344    -0.74635...
            -0.75882    -0.78618    -0.80760    -0.75053    -0.76779    -0.67427...
            -0.58678    0.06538];
        c4   = [2.8 3.0 3.2 3.3 3.4 3.5 3.5 3.6 3.6 3.7 3.7 3.7 3.8 3.8 3.8 3.8 3.8...
            3.8 3.8 3.9 3.9 3.9 3.9 3.8 3.8 3.7 3.6 3.2];
        c6   = [-2.13620    -2.43210    -2.78892    -3.07493    -3.29808    -3.68677...
            -3.84799    -4.21624    -4.33601    -4.65152    -4.76255    -4.84920...
            -5.14508    -5.17562    -5.28098    -5.36596    -5.46428    -5.51821...
            -5.57562    -5.83325    -5.86837    -5.95141    -6.02190    -5.85612...
            -5.88521    -5.43083    -5.18268    -4.25855];
        c7   = [0.09013 0.10715 0.13082 0.15219 0.16792 0.19846 0.21274 0.23987...
            0.24975 0.27084 0.27903 0.28512 0.30322 0.30531 0.31278 0.31923...
            0.32715 0.33158 0.33613 0.35180 0.35426 0.35968 0.36387 0.35579...
```

```
            0.35942 0.34620 0.33157 0.32343];
        c10  = [-0.37542    -0.39711    -0.36709    -0.32102    -0.29094    -0.22467...
            -0.18860    -0.14814    -0.13159    -0.11582    -0.10726    -0.10218...
            -0.09778    -0.09680    -0.09419    -0.09279    -0.09179    -0.09148...
            -0.09130    -0.09125    -0.09122    -0.09113    -0.09109    -0.09155...
            -0.09203    -0.09664    -0.09714    -0.15899];
        sigp = [0.5238  0.5660  0.6020  0.6191  0.6251  0.6480  0.6618  0.6857  0.7008...
            0.7220  0.7399  0.7562  0.7782  0.7848  0.8054  0.8177  0.8272  0.8313...
            0.8366  0.8406  0.8457  0.8530  0.8534  0.8448  0.8391  0.7699  0.7633...
            0.5854];
        sigT = [1.3790  1.2690  1.1426  1.0631  0.9968  0.9268  0.9346  0.9045  0.9001...
            0.9119  0.9119  0.9182  0.9305  0.9367  0.9578  0.9583  0.9609  0.9642...
            0.9704  0.9705  0.9770  0.9811  0.9788  0.9688  0.9651  0.9060  0.9003...
            0.5854];
    elseif SE == 0
        % single corner, constant low stress drop
        c1   = [-14.51574   -9.56051    -5.22266    -1.89095    -0.39847    3.27417...
            5.67074     7.67899     8.63053     10.65378    11.41205    13.03902...
            13.69482    13.87411    14.45860    16.11475    16.59372    16.84332...
            17.10860    17.25532    17.42110    17.82567    18.16727    18.45810...
            17.18549    14.28559    13.95924    9.08776];
        c2   = [2.27743 1.83677 1.42630 1.08997 0.92377 0.54493 0.32399 0.11381...
            0.02055 -0.13196    -0.19463    -0.29926    -0.34602    -0.35857...
            -0.40049    -0.50595    -0.54655    -0.56847    -0.59071    -0.60178...
            -0.61316    -0.63820    -0.65766    -0.68363    -0.61880    -0.52896...
            -0.51587    0.19911];
        c4   = [2.8 3.0 3.2 3.3 3.3 3.4 3.5 3.5 3.5 3.6 3.6 3.7 3.7 3.7 3.7 3.8 3.8...
            3.8 3.8 3.8 3.8 3.8 3.8 3.8 3.7 3.6 3.6 3.1];
        c6   = [-2.16004    -2.45407    -2.81135    -3.10319    -3.22226    -3.60867...
            -3.90708    -4.13972    -4.26127    -4.56857    -4.67925    -4.94340...
            -5.04794    -5.07762    -5.17926    -5.46456    -5.56147    -5.61422...
            -5.67026    -5.70035    -5.73333    -5.81156    -5.87782    -5.94442...
            -5.74801    -5.31196    -5.26211    -4.16032];
        c7   = [0.09156 0.10808 0.13160 0.15363 0.16458 0.19579 0.21814 0.23879...
            0.24915 0.27022 0.27864 0.29508 0.30235 0.30440 0.31164 0.32967...
            0.33740 0.34167 0.34603 0.34821 0.35047 0.35548 0.35931 0.36483...
            0.35480 0.34179 0.33959 0.31577];
        c10  = [-0.32210    -0.34227    -0.31057    -0.26352    -0.23333    -0.16807...
            -0.13325    -0.09489    -0.07940    -0.06472    -0.05678    -0.05208...
            -0.04799    -0.04708    -0.04464    -0.04331    -0.04233    -0.04202...
            -0.04182    -0.04176    -0.04171    -0.04159    -0.04152    -0.04192...
            -0.04232    -0.04658    -0.04706    -0.10714];
        sigp = [0.5189  0.5606  0.5946  0.6106  0.6166  0.6406  0.6561  0.6821  0.6984...
            0.7206  0.7393  0.7561  0.7783  0.7849  0.8058  0.8180  0.8274  0.8314...
            0.8366  0.8406  0.8457  0.8529  0.8532  0.8446  0.8390  0.7693  0.7628...
            0.5825];
        sigT = [1.3771  1.2666  1.1387  1.0581  0.9915  0.9217  0.9306  0.9018  0.8982...
            0.9108  0.9114  0.9181  0.9306  0.9368  0.9582  0.9586  0.9611  0.9642...
            0.9705  0.9705  0.9770  0.9810  0.9786  0.9686  0.9650  0.9054  0.8999...
            0.5825];
    else
        % single corner, constant low stress drop with saturation
        c1   = [-12.34486   -7.12762    -2.46635    1.09160     2.63452     6.58784...
            9.24442     11.35480    12.35996    14.67303    15.48361    16.08791...
            18.11166    18.30605    18.94247    19.41416    19.91774    20.18058...
            20.45986    20.61413    20.78819    21.21243    21.57041    21.87723...
            21.95228    17.30516    16.96725    12.26101];
        c2   = [1.95845 1.49148 1.04807 0.68925 0.51855 0.11210 -0.13451    -0.35323...
            -0.45077    -0.63086    -0.69729    -0.74305    -0.87999    -0.89356...
            -0.93912    -0.97570    -1.01826    -1.04126    -1.06460    -1.07622...
            -1.08818    -1.11449    -1.13489    -1.16223    -1.17915    -0.96734...
            -0.95374    -0.23705];
        c4   = [3.0 3.2 3.4 3.5 3.5 3.6 3.7 3.7 3.7 3.8 3.8 3.8 3.9 3.9 3.9 3.9 3.9...
            3.9 3.9 3.9 3.9 3.9 3.9 3.9 3.9 3.7 3.7 3.3];
        c6   = [-2.57317    -2.91057    -3.32053    -3.64922    -3.77700    -4.20864...
            -4.54798    -4.79775    -4.92830    -5.28067    -5.40014    -5.49275...
            -5.82243    -5.85465    -5.96502    -6.05319    -6.15421    -6.20917...
            -6.26753    -6.29889    -6.33324    -6.41476    -6.48374    -6.55296...
            -6.58099    -5.85881    -5.80700    -4.74443];
        c7   = [0.15404 0.17493 0.20386 0.22956 0.24128 0.27695 0.30336 0.32541...
            0.33648 0.36186 0.37090 0.37755 0.39947 0.40170 0.40954 0.41621...
```

```
            0.42427 0.42872 0.43327 0.43554 0.43789 0.44311 0.44710 0.45285...
            0.45634 0.42361 0.42132 0.39834];
        c10  = [-0.33355    -0.35373    -0.32203    -0.27498    -0.24479    -0.17953...
            -0.14471    -0.10635    -0.09086    -0.07617    -0.06824    -0.06353...
            -0.05945    -0.05854    -0.05610    -0.05476    -0.05379    -0.05347...
            -0.05328    -0.05322    -0.05317    -0.05305    -0.05297    -0.05337...
            -0.05377    -0.05803    -0.05852    -0.11859];
        sigp = [0.5320  0.5744  0.6080  0.6233  0.6289  0.6525  0.6676  0.6930  0.7090...
            0.7309  0.7493  0.7658  0.7878  0.7942  0.8148  0.8269  0.8362  0.8403...
            0.8454  0.8493  0.8543  0.8614  0.8618  0.8530  0.8474  0.7783  0.7718...
            0.5911];
        sigT = [1.3821  1.2728  1.1457  1.0655  0.9992  0.9300  0.9387  0.9101  0.9065...
            0.9190  0.9195  0.9261  0.9385  0.9446  0.9657  0.9662  0.9687  0.9719...
            0.9780  0.9781  0.9844  0.9884  0.9861  0.9759  0.9723  0.9131  0.9075...
            0.5911];
    end
else
    if SD_t == 0
        % single coner, variable high stress drop
        c1   = [-13.91863   -9.02136    -5.06249    -1.56307    0.72588     4.94057...
            6.90409     10.33931    11.55566    12.94874    15.04806    15.77669...
            16.59083    16.81254    18.86865    19.43335    20.04863    20.37544...
            20.72257    20.91108    21.11875    21.61053    22.02865    22.40623...
            22.54184    17.92864    17.56501    12.88457];
        c2   = [2.33294 1.95631 1.59204 1.26035 1.05610 0.63072 0.41108 0.08773...
            -0.03985    -0.17886    -0.33259    -0.39607    -0.46325    -0.48116...
            -0.61723    -0.66605    -0.72294    -0.75402    -0.78585    -0.80174...
            -0.81789    -0.85260    -0.88044    -0.91637    -0.94055    -0.74769...
            -0.73081    -0.06337];
        c4   = [3.0 3.2 3.3 3.4 3.5 3.6 3.6 3.7 3.7 3.7 3.8 3.8 3.8 3.8 3.9 3.9 3.9...
            3.9 3.9 3.9 3.9 3.9 3.9 3.9 3.9 3.7 3.7 3.3];
        c6   = [-2.33817    -2.64856    -2.93546    -3.23534    -3.47121    -3.88811...
            -4.06719    -4.47467    -4.60821    -4.77368    -5.08734    -5.18780...
            -5.30738    -5.34165    -5.68075    -5.78203    -5.90140    -5.96788...
            -6.03900    -6.07691    -6.11772    -6.21225    -6.29329    -6.37768...
            -6.41953    -5.71493    -5.65962    -4.71837];
        c7   = [0.09908 0.11437 0.13367 0.15492 0.17081 0.20282 0.21878 0.24889...
            0.26010 0.27355 0.29385 0.30141 0.31025 0.31279 0.33451 0.34275...
            0.35305 0.35891 0.36501 0.36809 0.37124 0.37806 0.38353 0.39115...
            0.39634 0.36837 0.36566 0.36161];
        c10  = [-0.29154    -0.36070    -0.36500    -0.34181    -0.32004    -0.25891...
            -0.21837    -0.16562    -0.14124    -0.11589    -0.10095    -0.09155...
            -0.08296    -0.08098    -0.07559    -0.07256    -0.07023    -0.06938...
            -0.06877    -0.06854    -0.06833    -0.06793    -0.06773    -0.06821...
            -0.06885    -0.07577    -0.07661    -0.11586];
        sigp = [0.5321  0.5624  0.5952  0.6174  0.6268  0.6554  0.6699  0.6920  0.7057...
            0.7259  0.7440  0.7605  0.7833  0.7902  0.8121  0.8254  0.8362  0.8411...
            0.8471  0.8515  0.8568  0.8646  0.8653  0.8569  0.8514  0.7814  0.7747...
            0.5984];
        sigT = [1.3821  1.2674  1.1390  1.0621  0.9978  0.9321  0.9403  0.9093  0.9039...
            0.9150  0.9152  0.9217  0.9348  0.9412  0.9635  0.9649  0.9687  0.9726...
            0.9795  0.9800  0.9866  0.9912  0.9892  0.9794  0.9758  0.9157  0.9100...
            0.5984];
    elseif SE == 0
        % single corner, constant high stress drop
        c1   = [-14.92343   -10.18213   -6.35091    -2.37232    -0.80232    3.21915...
            5.08922     8.29484     9.43320     11.74743    12.66006    13.33561...
            15.26405    15.47703    16.17236    16.69021    17.25027    18.92158...
            19.25288    19.43335    19.63311    20.10895    20.51285    19.40352...
            19.51657    16.44069    16.08302    10.74525];
        c2   = [2.43027 2.06757 1.71518 1.36543 1.19788 0.78973 0.58119 0.28003...
            0.16200 -0.02246    -0.10531    -0.16266    -0.29006    -0.30669...
            -0.36176    -0.40538    -0.45606    -0.56453    -0.59416    -0.60894...
            -0.62400    -0.65650    -0.68238    -0.62778    -0.64891    -0.55019...
            -0.53416    0.17413];
        c4   = [2.9 3.1 3.2 3.4 3.4 3.5 3.5 3.6 3.6 3.7 3.7 3.7 3.8 3.8 3.8 3.8 3.8...
            3.9 3.9 3.9 3.9 3.9 3.9 3.8 3.8 3.7 3.7 3.2];
        c6   = [-2.22382    -2.51603    -2.78676    -3.17502    -3.29152    -3.68683...
            -3.85783    -4.23968    -4.36652    -4.69411    -4.81457    -4.90916...
            -5.21720    -5.25065    -5.36632    -5.46052    -5.57097    -5.85972...
            -5.92801    -5.96446    -6.00383    -6.09544    -6.17374    -6.01142...
```

```
                -6.04880    -5.59549    -5.54089    -4.45009];
            c7   = [0.09485 0.10917 0.12722 0.15221 0.16227 0.19276 0.20794 0.23616...
                0.24675 0.26892 0.27820 0.28523 0.30448 0.30691 0.31558 0.32310...
                0.33242 0.35100 0.35673 0.35961 0.36256 0.36898 0.37408 0.36670...
                0.37128 0.35834 0.35572 0.33923];
            c10  = [-0.26850    -0.33532    -0.33853    -0.31410    -0.29176    -0.23069...
                -0.19127    -0.14131    -0.11874    -0.09568    -0.08232    -0.07402...
                -0.06652    -0.06481    -0.06017    -0.05758    -0.05561    -0.05491...
                -0.05441    -0.05422    -0.05406    -0.05373    -0.05357    -0.05403...
                -0.05461    -0.06084    -0.06160    -0.09819];
            sigp = [0.5246  0.5581  0.5890  0.6076  0.6151  0.6418  0.6568  0.6810  0.6963...
                0.7183  0.7373  0.7547  0.7780  0.7850  0.8071  0.8206  0.8315  0.8363...
                0.8422  0.8466  0.8520  0.8598  0.8604  0.8521  0.8464  0.7761  0.7693...
                0.5915];
            sigT = [1.3793  1.2655  1.1358  1.0564  0.9905  0.9225  0.9311  0.9010  0.8966...
                0.9090  0.9098  0.9170  0.9303  0.9369  0.9592  0.9608  0.9646  0.9685...
                0.9753  0.9757  0.9824  0.9870  0.9849  0.9752  0.9715  0.9112  0.9054...
                0.5915];
        else
            % single corner, constant high stress drop with saturation
            c1   = [-12.65135   -7.63385    -2.92833    0.76119     2.38331     6.70599...
                8.65230     12.17467    13.37181    14.74399    16.97448    17.69717...
                18.50771    20.19141    20.94827    21.51625    22.13508    22.46355...
                22.81270    23.00275    23.21284    23.71273    24.13701    24.51845...
                24.64848    19.65149    19.28060    14.16517];
            c2   = [2.09962 1.70983 1.29933 0.94998 0.77804 0.34088 0.12586 -0.20531...
                -0.32798    -0.46111    -0.62936    -0.69006    -0.75440    -0.86646...
                -0.92609    -0.97369    -1.02936    -1.05978    -1.09092    -1.10647...
                -1.12231    -1.15652    -1.18374    -1.21926    -1.24267    -1.01014...
                -0.99348    -0.28835];
            c4   = [3.1 3.3 3.5 3.6 3.6 3.7 3.7 3.8 3.8 3.8 3.9 3.9 3.9 4.0 4.0 4.0 4.0...
                4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 3.8 3.8 3.4];
            c6   = [-2.65372    -2.99118    -3.40943    -3.74466    -3.87013    -4.31367...
                -4.49751    -4.92914    -5.06579    -5.23503    -5.57259    -5.67505...
                -5.79682    -6.07056    -6.19648    -6.29904    -6.41929    -6.48596...
                -6.55721    -6.59524    -6.63632    -6.73191    -6.81358    -6.89791...
                -6.93799    -6.17228    -6.11546    -5.07478];
            c7   = [0.15931 0.17807 0.20580 0.23048 0.24129 0.27643 0.29269 0.32564...
                0.33699 0.35058 0.37377 0.38135 0.39016 0.40801 0.41744 0.42562...
                0.43578 0.44153 0.44750 0.45051 0.45359 0.46030 0.46562 0.47308...
                0.47804 0.44358 0.44085 0.42615];
            c10  = [-0.27995    -0.34677    -0.34999    -0.32555    -0.30322    -0.24215...
                -0.20273    -0.15276    -0.13019    -0.10713    -0.09378    -0.08547...
                -0.07798    -0.07627    -0.07162    -0.06904    -0.06706    -0.06636...
                -0.06586    -0.06568    -0.06551    -0.06519    -0.06503    -0.06549...
                -0.06606    -0.07230    -0.07305    -0.10965];
            sigp = [0.5362  0.5704  0.6013  0.6196  0.6270  0.6534  0.6683  0.6921  0.7071...
                0.7288  0.7475  0.7645  0.7875  0.7944  0.8162  0.8294  0.8401  0.8449...
                0.8508  0.8551  0.8603  0.8679  0.8687  0.8601  0.8546  0.7848  0.7781...
                0.6001];
            sigT = [1.3837  1.2710  1.1422  1.0634  0.9980  0.9306  0.9392  0.9094  0.9050...
                0.9173  0.9181  0.9250  0.9383  0.9448  0.9669  0.9683  0.9721  0.9760...
                0.9827  0.9831  0.9896  0.9941  0.9922  0.9822  0.9786  0.9186  0.9129...
                0.6001];
        end
    end
end
else
    if CM == 2
        if SE == 1
            % double corner with saturation
            c1   = [-17.70361   -13.92420   -10.94321   -8.83343    -7.76737    -5.33824...
                -3.73678    -1.84742    -0.55724    0.92868     1.72573     2.68457...
                3.77386     3.96591     5.53031     6.60366     7.85421     8.21088...
                9.28186     9.52717     9.75655     10.24743    9.96722     9.64059...
                9.04691     6.27888     5.93818     4.53013];
            c2   = [2.06827 1.72207 1.43698 1.24320 1.14287 0.93368 0.79317 0.62360 0.50916...
                0.37406 0.29401 0.20711 0.11416 0.09800 -0.01361    -0.08665    -0.17609...
                -0.20169    -0.28645    -0.31412    -0.33358    -0.37291    -0.35918...
                -0.35408    -0.33098    -0.20223    -0.18201    0.23834];
            c4   = [1.6 1.8 2.0 2.1 2.1 2.2 2.3 2.3 2.4 2.5 2.5 2.6 2.7 2.7 2.9 3.0 3.1 3.1...
```

```
            3.2 3.2 3.2 3.2 3.1 3.0 2.9 2.7 2.7 2.2];
    c6   = [-1.31801    -1.45428    -1.63284    -1.77711    -1.85115    -2.04663...
            -2.19225    -2.32294    -2.44529    -2.58582    -2.65212    -2.77743...
            -2.93085    -2.95707    -3.21501    -3.38623    -3.59574    -3.67264...
            -3.88204    -3.93679    -3.99128    -4.11053    -4.08417    -4.05492...
            -3.97551    -3.53646    -3.47772    -2.81686];
    c7   = [0.08712 0.09906 0.11719 0.13055 0.13862 0.15785 0.17169 0.18424 0.19431...
            0.20432 0.20809 0.21630 0.22616 0.22772 0.24453 0.25414 0.26651 0.27153...
            0.28695 0.29184 0.29606 0.30519 0.30364 0.30409 0.30155 0.28388 0.28050...
            0.25116];
    c10  = [-0.32461    -0.29911    -0.23803    -0.18835    -0.16740    -0.14480...
            -0.13937    -0.13061    -0.12238    -0.10951    -0.09876    -0.09004...
            -0.08037    -0.07792    -0.07080    -0.06561    -0.06058    -0.05926...
            -0.05782    -0.05671    -0.05613    -0.05567    -0.05429    -0.05350...
            -0.05435    -0.06025    -0.06133    -0.08693];
    sigp = [0.3535  0.3736  0.3918  0.4162  0.4286  0.4556  0.4708  0.5011  0.5259...
            0.5377  0.5392  0.5456  0.5599  0.5639  0.5844  0.6093  0.6243  0.6149...
            0.6154  0.6137  0.6121  0.6224  0.6345  0.6346  0.6289  0.5686  0.5630...
            0.4489];
    sigT = [1.3235  1.1955  1.0469  0.9591  0.8866  0.8039  0.8102  0.7739  0.7711...
            0.7737  0.7580  0.7538  0.7568  0.7606  0.7809  0.7878  0.7928  0.7846...
            0.7874  0.7817  0.7834  0.7886  0.7948  0.7917  0.7885  0.7420  0.7382...
            0.4489];
else
    % double corner
    c1   = [-18.93236   -15.32941   -12.69571   -10.65171   -9.46782    -7.11822...
            -5.79677    -3.73490    -2.52562    -1.13018    -0.35177    0.51391...
            1.49696 1.68117 3.02922 3.96807 5.06042 5.39001 5.76317 5.97780 6.72839...
            7.17691 7.00112 6.77623 6.29650 4.24595 3.49869 2.84051];
    c2   = [2.27993 1.96381 1.72502 1.53696 1.43351 1.23406 1.11610 0.93677 0.83241...
            0.70786 0.62905 0.55291 0.47163 0.45595 0.36865 0.30969 0.23658 0.21283...
            0.17770 0.15309 0.10286 0.06703 0.06791 0.06147 0.07241 0.14544 0.19289...
            0.54156];
    c4   = [1.4 1.6 1.7 1.8 1.9 2.0 2.0 2.1 2.2 2.3 2.3 2.4 2.5 2.5 2.7 2.8 2.9 2.9...
            2.9 2.9 3.0 3.0 2.9 2.8 2.7 2.6 2.5 2.1];
    c6   = [-1.06291    -1.16602    -1.28057    -1.41349    -1.51015    -1.69182...
            -1.78608    -1.94936    -2.05788    -2.18295    -2.24581    -2.35535...
            -2.49086    -2.51565    -2.73792    -2.88687    -3.07011    -3.14219...
            -3.23069    -3.27987    -3.42641    -3.53823    -3.52780    -3.51436...
            -3.45328    -3.14071    -3.00815    -2.47969];
    c7   = [0.04229 0.04855 0.05826 0.07071 0.07943 0.09700 0.10679 0.12121 0.12956...
            0.13777 0.14133 0.14773 0.15563 0.15710 0.16992 0.17721 0.18687 0.19157...
            0.19853 0.20285 0.21245 0.22097 0.22143 0.22369 0.22311 0.21510 0.20682...
            0.18992];
    c10  = [-0.31157    -0.28613    -0.22678    -0.17758    -0.15705    -0.13487...
            -0.12968    -0.12104    -0.11290    -0.10011    -0.08941    -0.08074...
            -0.07112    -0.06869    -0.06161    -0.05645    -0.05144    -0.05016...
            -0.04874    -0.04765    -0.04709    -0.04667    -0.04532    -0.04456...
            -0.04543    -0.05128    -0.05234    -0.07781];
    sigp = [0.3573  0.3696  0.3852  0.4102  0.4239  0.4531  0.4684  0.4972  0.5207...
            0.5309  0.5314  0.5373  0.5514  0.5555  0.5755  0.5996  0.6155  0.6062...
            0.6069  0.6057  0.6044  0.6152  0.6271  0.6282  0.6231  0.5625  0.5568...
            0.4470];
    sigT = [1.3246  1.1942  1.0446  0.9565  0.8842  0.8027  0.8090  0.7714  0.7677...
            0.7689  0.7524  0.7481  0.7509  0.7547  0.7742  0.7801  0.7857  0.7783...
            0.7804  0.7755  0.7772  0.7830  0.7892  0.7869  0.7845  0.7374  0.7334...
            0.4470];
end
else
if SD_l == 1
    if SD_t == 0
        % single coner, variable medium stress drop
        c1   = [-20.34111   -16.73900   -13.57757   -10.98377   -9.47360    -6.45963...
                -4.85330    -2.60478    -1.40255    -0.08110    0.62132     1.42947...
                2.34666 2.51220 3.82298 4.74102 5.32022 6.08837 6.40243 6.58201...
                6.74549 6.56386 6.88238 6.62198 6.13592 3.80314 3.49839 1.78500];
        c2   = [2.60194 2.30757 2.00261 1.72186 1.55395 1.20847 1.01608 0.76905...
                0.64885 0.52001 0.44430 0.37165 0.29538 0.28131 0.19666 0.13857...
                0.09551 0.04583 0.01563 -0.00612    -0.01996    -0.01385    -0.04115...
                -0.04194    -0.02753    0.07060 0.08928 0.69725];
        c4   = [1.4 1.5 1.7 1.8 1.9 2.0 2.0 2.1 2.2 2.3 2.3 2.4 2.5 2.5 2.7 2.8 2.8...
```

```
            2.9 2.9 2.9 2.9 2.8 2.8 2.7 2.6 2.4 2.4 1.9];
    c6   = [-1.08558    -1.16565    -1.29760    -1.42212    -1.51379    -1.68824...
            -1.78223    -1.94949    -2.06185    -2.19330    -2.26314    -2.38047...
            -2.52530    -2.55233    -2.78523    -2.94210    -3.04406    -3.19714...
            -3.27602    -3.31878    -3.36106    -3.35824    -3.43310    -3.40938...
            -3.34276    -2.96769    -2.91374    -2.38690];
    c7   = [0.04640 0.05178 0.06226 0.07357 0.08160 0.09795 0.10744 0.12195...
            0.13054 0.13926 0.14359 0.15104 0.16033 0.16215 0.17649 0.18510...
            0.19102 0.20084 0.20733 0.21133 0.21467 0.21579 0.22124 0.22240...
            0.22097 0.20791 0.20455 0.19158];
    c10  = [-0.30371    -0.37951    -0.38860    -0.36699    -0.34549    -0.28426...
            -0.24230    -0.18473    -0.15738    -0.12919    -0.11198    -0.10052...
            -0.08963    -0.08711    -0.08022    -0.07565    -0.07192    -0.07142...
            -0.07091    -0.07040    -0.07031    -0.07078    -0.07027    -0.07041...
            -0.07204    -0.08054    -0.08156    -0.12481];
    sigp = [0.3573  0.3696  0.3852  0.4102  0.4239  0.4531  0.4684  0.4972  0.5207...
            0.5309  0.5314  0.5373  0.5514  0.5555  0.5755  0.5996  0.6155  0.6062...
            0.6069  0.6057  0.6044  0.6152  0.6271  0.6282  0.6231  0.5625  0.5568...
            0.4470];
    sigT = [1.3246  1.1942  1.0446  0.9565  0.8842  0.8027  0.8090  0.7714  0.7677...
            0.7689  0.7524  0.7481  0.7509  0.7547  0.7742  0.7801  0.7857  0.7783...
            0.7804  0.7755  0.7772  0.7830  0.7892  0.7869  0.7845  0.7374  0.7334...
            0.4470];
elseif SE == 0
    % single corner, constant medium stress drop
    c1   = [-20.75572   -17.19667   -14.06689   -11.50543   -10.01702   -7.05566...
            -5.49548    -3.32938    -2.17689    -0.91426    -0.25005    0.52720...
            1.40962 1.56684 2.84539 3.74250 4.30142 5.05068 5.34872 5.51993...
            5.67485 5.48446 5.79121 5.52760 5.04282 2.73988 2.44059 0.89599];
    c2   = [2.66436 2.37874 2.07919 1.80276 1.63758 1.29873 1.11266 0.87752...
            0.76471 0.64469 0.57474 0.50677 0.43574 0.42291 0.34310 0.28811...
            0.24798 0.20098 0.17298 0.15239 0.13971 0.14693 0.12122 0.12078...
            0.13496 0.22873 0.24664 0.82861];
    c4   = [1.4 1.5 1.7 1.8 1.9 2.0 2.0 2.1 2.2 2.3 2.3 2.4 2.5 2.5 2.7 2.8 2.8...
            2.9 2.9 2.9 2.9 2.8 2.8 2.7 2.6 2.4 2.4 1.9];
    c6   = [-1.08036    -1.15935    -1.28989    -1.41313    -1.50425    -1.67870...
            -1.77199    -1.93695    -2.04747    -2.17662    -2.24507    -2.36056...
            -2.50272    -2.52910    -2.75855    -2.91299    -3.01204    -3.16171...
            -3.23737    -3.27833    -3.31873    -3.31359    -3.38561    -3.36044...
            -3.29331    -2.92178    -2.86879    -2.34455];
    c7   = [0.04575 0.05081 0.06096 0.07203 0.07995 0.09627 0.10566 0.11987...
            0.12821 0.13662 0.14078 0.14798 0.15689 0.15864 0.17249 0.18076...
            0.18629 0.19564 0.20169 0.20546 0.20854 0.20937 0.21443 0.21541...
            0.21392 0.20135 0.19811 0.18556];
    c10  = [-0.26225    -0.33621    -0.34445    -0.32162    -0.29941    -0.23741...
            -0.19612    -0.14101    -0.11553    -0.08967    -0.07407    -0.06377...
            -0.05410    -0.05189    -0.04589    -0.04184    -0.03854    -0.03820...
            -0.03779    -0.03730    -0.03723    -0.03769    -0.03713    -0.03717...
            -0.03869    -0.04661    -0.04758    -0.08813];
    sigp = [0.3507  0.3670  0.3828  0.4058  0.4178  0.4440  0.4587  0.4886  0.5132...
            0.5249  0.5265  0.5331  0.5473  0.5512  0.5704  0.5949  0.6114  0.6016...
            0.6020  0.6010  0.5994  0.6096  0.6215  0.6227  0.6175  0.5568  0.5512...
            0.4429];
    sigT = [1.3227  1.1936  1.0435  0.9544  0.8813  0.7977  0.8033  0.7656  0.7630...
            0.7647  0.7488  0.7452  0.7479  0.7518  0.7705  0.7762  0.7826  0.7744...
            0.7773  0.7723  0.7733  0.7783  0.7844  0.7821  0.7798  0.7328  0.7292...
            0.4429];
else
    % single corner, constant medium stress drop with saturation
    c1   = [-19.49851   -15.76713   -12.68162   -10.05969   -8.51490    -5.47426...
            -3.89260    -1.64473    -0.41821    0.92932 1.61284 2.47822 3.46248...
            3.62759 5.11216 6.13834 6.73520 7.61948 7.94524 7.51087 7.67232...
            8.02069 8.35117 7.41237 6.86192 4.84985 4.53538 2.58628];
    c2   = [2.44358 2.14489 1.84290 1.55925 1.38716 1.03910 0.85098 0.60671...
            0.48551 0.35642 0.28534 0.20789 0.12632 0.11304 0.01138 -0.05642...
            -0.09898    -0.15985    -0.19015    -0.16870    -0.18185    -0.20800...
            -0.23555    -0.18438    -0.16191    -0.08535    -0.06647    0.55455];
    c4   = [1.6 1.8 1.9 2.0 2.1 2.2 2.2 2.3 2.4 2.5 2.5 2.6 2.7 2.7 2.9 3.0 3.0...
            3.1 3.1 3.0 3.0 3.0 3.0 2.8 2.7 2.6 2.6 2.1];
    c6   = [-1.33851    -1.44976    -1.57135    -1.70560    -1.80673    -1.99534...
            -2.09267    -2.27192    -2.39510    -2.53880    -2.61087    -2.74128...
```

```
            -2.90065    -2.92848    -3.19187    -3.36770    -3.47378    -3.64537...
            -3.72601    -3.66142    -3.70297    -3.79370    -3.86993    -3.72699...
            -3.64908    -3.33178    -3.27599    -2.68278];
        c7   = [0.09176 0.09921 0.10979 0.12218 0.13133 0.14929 0.15905 0.17484...
            0.18462 0.19457 0.19894 0.20773 0.21841 0.22023 0.23767 0.24805...
            0.25405 0.26565 0.27212 0.26868 0.27185 0.27856 0.28396 0.27609...
            0.27323 0.26390 0.26049 0.24143];
        c10  = [-0.27226    -0.34622    -0.35445    -0.33162    -0.30941    -0.24741...
            -0.20613    -0.15102    -0.12553    -0.09967    -0.08407    -0.07378...
            -0.06411    -0.06190    -0.05589    -0.05185    -0.04855    -0.04820...
            -0.04780    -0.04730    -0.04724    -0.04769    -0.04714    -0.04718...
            -0.04870    -0.05662    -0.05758    -0.09813];
        sigp = [0.3535  0.3736  0.3918  0.4162  0.4286  0.4556  0.4708  0.5011  0.5259...
            0.5377  0.5392  0.5456  0.5599  0.5639  0.5844  0.6093  0.6243  0.6149...
            0.6154  0.6137  0.6121  0.6224  0.6345  0.6346  0.6289  0.5686  0.5630...
            0.4489];
        sigT = [1.3235  1.1955  1.0469  0.9591  0.8866  0.8039  0.8102  0.7739  0.7711...
            0.7737  0.7580  0.7538  0.7568  0.7606  0.7809  0.7878  0.7928  0.7846...
            0.7874  0.7817  0.7834  0.7886  0.7948  0.7917  0.7885  0.7420  0.7382...
            0.4489];
    end
elseif SD_l == 0
    if SD_t == 0
        % single coner, variable low stress drop
        c1   = [-20.05231   -16.27482   -13.04615   -10.45871   -9.12302    -6.23478...
            -4.55982    -2.50090    -1.40924    -0.21574    0.40330     1.14750...
            1.99242 2.13993 3.38857 4.26612 4.80280 5.53531 5.81659 5.47728...
            5.61769 5.92208 6.21793 5.94977 5.46547 3.19108 2.89680 1.36709];
        c2   = [2.53227 2.19486 1.86751 1.57792 1.41677 1.08031 0.89047 0.66910...
            0.56460 0.45412 0.39049 0.32686 0.26076 0.24927 0.17291 0.12018...
            0.08289 0.03755 0.01153 0.02280 0.01155 -0.01071    -0.03527...
            -0.03501    -0.02078    0.06980 0.08717 0.68365];
        c4   = [1.4 1.5 1.7 1.8 1.8 1.9 2.0 2.1 2.2 2.3 2.3 2.4 2.5 2.5 2.7 2.8 2.8...
            2.9 2.9 2.8 2.8 2.8 2.8 2.7 2.6 2.4 2.4 1.9];
        c6   = [-1.07453    -1.16205    -1.29847    -1.42382    -1.48739    -1.65772...
            -1.78241    -1.94421    -2.05286    -2.17973    -2.24641    -2.36017...
            -2.49951    -2.52505    -2.75163    -2.90389    -2.99953    -3.14600...
            -3.21804    -3.16765    -3.20499    -3.28678    -3.35589    -3.32883...
            -3.26088    -2.89257    -2.84056    -2.31521];
        c7   = [0.04458 0.05129 0.06256 0.07424 0.08097 0.09727 0.10846 0.12242...
            0.13061 0.13883 0.14281 0.14988 0.15853 0.16018 0.17382 0.18190...
            0.18704 0.19608 0.20171 0.19979 0.20256 0.20844 0.21317 0.21388...
            0.21226 0.19998 0.19685 0.18396];
        c10  = [-0.33586    -0.38905    -0.38046    -0.34646    -0.31954    -0.25183...
            -0.21021    -0.15772    -0.13451    -0.11152    -0.09787    -0.08899...
            -0.08081    -0.07896    -0.07400    -0.07059    -0.06781    -0.06765...
            -0.06737    -0.06693    -0.06689    -0.06736    -0.06677    -0.06674...
            -0.06814    -0.07545    -0.07632    -0.12869];
        sigp = [0.3615  0.3781  0.4007  0.4264  0.4380  0.4608  0.4732  0.5006  0.5242...
            0.5346  0.5351  0.5408  0.5542  0.5579  0.5771  0.6009  0.6163  0.6068...
            0.6073  0.6058  0.6043  0.6149  0.6266  0.6277  0.6227  0.5626  0.5571...
            0.4495];
        sigT = [1.3257  1.1970  1.0503  0.9635  0.8914  0.8067  0.8119  0.7733  0.7704...
            0.7716  0.7552  0.7502  0.7531  0.7562  0.7757  0.7808  0.7865  0.7783...
            0.7812  0.7755  0.7772  0.7822  0.7884  0.7861  0.7837  0.7374  0.7337...
            0.4495];
    elseif SE == 0
        % single corner, constant low stress drop
        c1   = [-20.55815   -16.73947   -13.65946   -10.99282   -9.68073    -6.85855...
            -5.24001    -3.26924    -2.22508    -1.08416    -0.49842    0.21762...
            1.03212 1.17253 2.39286 3.25258 3.77291 4.48907 4.75723 4.41709...
            4.55068 4.84204 5.12821 4.85835 4.37562 2.12732 1.83761 0.46600];
        c2   = [2.60017 2.26764 1.95051 1.66012 1.50191 1.17422 0.99240 0.78397...
            0.68658 0.58402 0.52540 0.46599 0.40443 0.39399 0.32183 0.27171...
            0.23675 0.19370 0.16948 0.18082 0.17049 0.15000 0.12675 0.12717...
            0.14114 0.22793 0.24466 0.81692];
        c4   = [1.3 1.5 1.6 1.8 1.8 1.9 2.0 2.1 2.2 2.3 2.3 2.4 2.5 2.5 2.7 2.8 2.8...
            2.9 2.9 2.8 2.8 2.8 2.8 2.7 2.6 2.4 2.4 1.9];
        c6   = [-1.05537    -1.15760    -1.27073    -1.41718    -1.48069    -1.65049...
            -1.77350    -1.93239    -2.03913    -2.16376    -2.22892    -2.34043...
            -2.47694    -2.50179    -2.72488    -2.87481    -2.96790    -3.11130...
```

```
            -3.18064    -3.12981    -3.16561    -3.24440    -3.31113    -3.28306...
            -3.21479    -2.84970    -2.79850    -2.27508];
        c7   = [0.04356 0.05052 0.06054 0.07304 0.07973 0.09595 0.10692 0.12049...
            0.12843 0.13636 0.14015 0.14691 0.15518 0.15673 0.16988 0.17765...
            0.18244 0.19106 0.19633 0.19436 0.19693 0.20240 0.20681 0.20739...
            0.20573 0.19389 0.19087 0.17831];
        c10  = [-0.29353    -0.34549    -0.33566    -0.30030    -0.27288    -0.20544...
            -0.16520    -0.11585    -0.09454    -0.07370    -0.06141    -0.05349...
            -0.04627    -0.04465    -0.04034    -0.03729    -0.03480    -0.03473...
            -0.03449    -0.03406    -0.03402    -0.03447    -0.03383    -0.03371...
            -0.03501    -0.04184    -0.04268    -0.09206];
        sigp = [0.3564  0.3760  0.3974  0.4203  0.4303  0.4512  0.4640  0.4929  0.5175...
            0.5293  0.5307  0.5368  0.5502  0.5538  0.5721  0.5963  0.6122  0.6022...
            0.6024  0.6011  0.5994  0.6094  0.6211  0.6223  0.6173  0.5571  0.5515...
            0.4459];
        sigT = [1.3243  1.1964  1.0491  0.9608  0.8875  0.8016  0.8067  0.7681  0.7657...
            0.7682  0.7516  0.7473  0.7501  0.7532  0.7720  0.7778  0.7834  0.7752...
            0.7773  0.7723  0.7733  0.7783  0.7844  0.7821  0.7798  0.7336  0.7294...
            0.4459];
    else
        % single corner, constant low stress drop with saturation
        c1   = [-19.22315   -15.44147   -12.16021   -9.54716    -8.22053    -5.32394...
            -3.63748    -1.58622    -0.46884    0.75586 1.36003 2.16308 3.07766...
            3.22568 4.64940 5.63634 6.19239 7.04069 7.33406 6.89341 7.03853...
            7.35482 7.06323 6.73104 6.18299 4.21704 3.91273 2.14049];
        c2   = [2.37688 2.04218 1.70907 1.41649 1.25676 0.92033 0.73048 0.51303...
            0.40732 0.29579 0.23615 0.16737 0.09545 0.08459 -0.00917    -0.07192...
            -0.10902    -0.16563    -0.19183    -0.16928    -0.18041    -0.20260...
            -0.18554    -0.17676    -0.15452    -0.08408    -0.06646    0.54448];
        c4   = [1.6 1.7 1.9 2.0 2.0 2.1 2.2 2.3 2.4 2.5 2.5 2.6 2.7 2.7 2.9 3.0 3.0...
            3.1 3.1 3.0 3.0 3.0 2.9 2.8 2.7 2.6 2.6 2.1];
        c6   = [-1.32848    -1.42322    -1.57394    -1.70958    -1.77592    -1.95912...
            -2.09406    -2.26702    -2.38628    -2.52527    -2.59389    -2.72013...
            -2.87355    -2.89981    -3.15639    -3.32739    -3.42712    -3.59195...
            -3.66580    -3.59932    -3.63716    -3.72031    -3.68550    -3.64741...
            -3.56843    -3.25598    -3.20209    -2.61030];
        c7   = [0.09002 0.09738 0.11033 0.12320 0.13019 0.14797 0.16035 0.17549...
            0.18485 0.19430 0.19828 0.20662 0.21662 0.21825 0.23494 0.24478...
            0.24999 0.26081 0.26644 0.26271 0.26541 0.27118 0.26862 0.26785...
            0.26482 0.25607 0.25288 0.23387];
        c10  = [-0.30354    -0.35549    -0.34567    -0.31030    -0.28289    -0.21544...
            -0.17521    -0.12585    -0.10455    -0.08371    -0.07141    -0.06349...
            -0.05627    -0.05466    -0.05034    -0.04729    -0.04480    -0.04473...
            -0.04450    -0.04406    -0.04403    -0.04447    -0.04383    -0.04371...
            -0.04502    -0.05184    -0.05268    -0.10207];
        sigp = [0.3601  0.3837  0.4072  0.4309  0.4412  0.4625  0.4756  0.5049  0.5296...
            0.5415  0.5428  0.5488  0.5622  0.5660  0.5857  0.6102  0.6248  0.6152...
            0.6155  0.6135  0.6118  0.6220  0.6339  0.6339  0.6284  0.5685  0.5631...
            0.4513];
        sigT = [1.3254  1.1986  1.0529  0.9653  0.8929  0.8078  0.8131  0.7759  0.7738...
            0.7765  0.7602  0.7560  0.7590  0.7628  0.7816  0.7885  0.7928  0.7853...
            0.7874  0.7817  0.7826  0.7886  0.7940  0.7909  0.7885  0.7420  0.7382...
            0.4513];
    end
else
    if SD_t == 0
        % single coner, variable high stress drop
        c1   = [-20.56146   -17.04411   -14.08074   -11.50960   -9.98850    -6.91188...
            -5.02927    -2.58923    -1.50326    -0.04550    1.03708     1.63054...
            2.62840 2.81493 4.19608 5.16133 5.79219 6.60146 6.95517 7.15547...
            7.34032 7.73231 7.53570 7.28719 6.80166 4.80627 4.48217 2.45098];
        c2   = [2.65753 2.40199 2.12859 1.86114 1.69698 1.35161 1.13995 0.87023...
            0.74863 0.60048 0.49374 0.42844 0.34072 0.32360 0.22940 0.16491...
            0.11474 0.05996 0.02462 0.00024 -0.01632    -0.04885    -0.04513...
            -0.04751    -0.03323    0.04540 0.06607 0.69142];
        c4   = [1.4 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.2 2.3 2.4 2.4 2.5 2.5 2.7 2.8 2.8...
            2.9 2.9 2.9 2.9 2.9 2.8 2.7 2.6 2.5 2.5 2.0];
        c6   = [-1.10167    -1.19448    -1.30133    -1.42361    -1.51498    -1.68784...
            -1.81934    -1.99500    -2.06874    -2.20452    -2.32982    -2.39747...
            -2.54671    -2.57508    -2.81360    -2.97485    -3.08363    -3.24392...
            -3.33066    -3.37781    -3.42473    -3.52618    -3.51127    -3.49198...
```

```
          -3.42745    -3.11897    -3.06158    -2.50898];
    c7   = [0.04890 0.05392 0.06256 0.07335 0.08117 0.09700 0.10857 0.12371...
          0.13013 0.13930 0.14711 0.15166 0.16141 0.16340 0.17833 0.18742...
          0.19418 0.20485 0.21231 0.21686 0.22078 0.22900 0.22923 0.23099...
          0.22986 0.22107 0.21737 0.20312];
    c10  = [-0.26749    -0.36235    -0.38948    -0.38115    -0.36609    -0.31470...
          -0.27482    -0.21494    -0.18415    -0.15077    -0.12963    -0.11513...
          -0.10088    -0.09749    -0.08805    -0.08187    -0.07674    -0.07571...
          -0.07480    -0.07413    -0.07392    -0.07428    -0.07380    -0.07411...
          -0.07599    -0.08595    -0.08717    -0.12192];
    sigp = [0.3524  0.3633  0.3726  0.3938  0.4078  0.4427  0.4618  0.4938  0.5176...
          0.5273  0.5276  0.5338  0.5485  0.5528  0.5737  0.5981  0.6146  0.6057...
          0.6068  0.6058  0.6048  0.6159  0.6280  0.6292  0.6239  0.5626  0.5568...
          0.4447];
    sigT = [1.3233  1.1924  1.0399  0.9494  0.8766  0.7966  0.8050  0.7688  0.7657...
          0.7668  0.7495  0.7452  0.7487  0.7525  0.7727  0.7793  0.7849  0.7775...
          0.7804  0.7755  0.7772  0.7830  0.7900  0.7877  0.7845  0.7374  0.7334...
          0.4447];
elseif SE == 0
    % single corner, constant high stress drop
    c1   = [-20.96056   -17.49443   -14.56214   -12.02019   -10.51906   -7.48613...
          -5.64199    -3.49702    -2.23447    -0.83895    0.19834     0.75953...
          1.71843 2.24624 3.24012 4.18107 4.78769 5.57485 5.90954 6.09980...
          6.27420 6.64603 6.44287 6.18975 5.70463 3.73644 3.41869 1.56942];
    c2   = [2.71675 2.47125 2.20380 1.94074 1.77922 1.43919 1.23261 0.98628...
          0.85817 0.71930 0.61938 0.55896 0.47717 0.44033 0.37282 0.31199...
          0.26535 0.21375 0.18105 0.15805 0.14292 0.11313 0.11766 0.11580...
          0.12993 0.20458 0.22434 0.82163];
    c4   = [1.4 1.6 1.7 1.8 1.9 2.0 2.1 2.1 2.2 2.3 2.4 2.4 2.5 2.6 2.7 2.8 2.8...
          2.9 2.9 2.9 2.9 2.9 2.8 2.7 2.6 2.5 2.5 2.0];
    c6   = [-1.09530    -1.18623    -1.29165    -1.41253    -1.50306    -1.67573...
          -1.80682    -1.93942    -2.05340    -2.18694    -2.31041    -2.37683...
          -2.52375    -2.61513    -2.78683    -2.94569    -3.05138    -3.20785...
          -3.29094    -3.33603    -3.38074    -3.47773    -3.46082    -3.43970...
          -3.37433    -3.06845    -3.01216    -2.46320];
    c7   = [0.04814 0.05274 0.06102 0.07152 0.07918 0.09494 0.10642 0.11890...
          0.12760 0.13646 0.14402 0.14842 0.15785 0.16354 0.17423 0.18298...
          0.18933 0.19946 0.20644 0.21072 0.21434 0.22196 0.22193 0.22346...
          0.22223 0.21379 0.21025 0.19656];
    c10  = [-0.22730    -0.31935    -0.34577    -0.33650    -0.32073    -0.26795...
          -0.22804    -0.16965    -0.14044    -0.10939    -0.09000    -0.07686...
          -0.06412    -0.06112    -0.05284    -0.04739    -0.04289    -0.04210...
          -0.04136    -0.04075    -0.04059    -0.04099    -0.04049    -0.04070...
          -0.04245    -0.05171    -0.05284    -0.08546];
    sigp = [0.3442  0.3598  0.3703  0.3906  0.4034  0.4347  0.4524  0.4844  0.5092...
          0.5205  0.5221  0.5290  0.5441  0.5483  0.5685  0.5934  0.6105  0.6011...
          0.6019  0.6010  0.5997  0.6103  0.6223  0.6236  0.6182  0.5568  0.5510...
          0.4401];
    sigT = [1.3212  1.1912  1.0392  0.9481  0.8748  0.4922  0.7998  0.7630  0.7603...
          0.7620  0.7460  0.7423  0.7457  0.7496  0.7690  0.7755  0.7818  0.7744...
          0.7766  0.7723  0.7733  0.7791  0.7852  0.7829  0.7806  0.7328  0.7290...
          0.4401];
else
    % single corner, constant high stress drop with saturation
    c1   = [-19.69964   -16.16105   -13.17561   -10.39119   -9.01636    -5.90447...
          -3.98706    -1.53095    -0.47383    1.00761     2.13449     2.71500...
          3.77719 4.39753 5.51538 6.58742 7.23410 8.15944 8.52466 8.73233...
          8.92221 8.66995 9.02849 8.68242 7.53592 5.47014 5.14426 3.01933];
    c2   = [2.49541 2.24103 1.96739 1.68495 1.52890 1.17978 0.96465 0.69527...
          0.57909 0.43107 0.32163 0.26001 0.16754 0.12042 0.04067 -0.03320...
          -0.08251    -0.14834    -0.18367    -0.20849    -0.22488    -0.21066...
          -0.24163    -0.23353    -0.16817    -0.08443    -0.06415    0.56635];
    c4   = [1.6 1.8 1.9 2.1 2.1 2.2 2.3 2.4 2.4 2.5 2.6 2.6 2.7 2.8 2.9 3.0 3.0...
          3.1 3.1 3.1 3.1 3.0 3.0 2.9 2.7 2.6 2.6 2.1];
    c6   = [-1.35424    -1.45825    -1.57341    -1.73909    -1.80570    -1.99249...
          -2.13635    -2.32575    -2.40142    -2.54967    -2.68835    -2.75836...
          -2.92274    -3.02933    -3.22165    -3.40224    -3.51535    -3.69429...
          -3.78287    -3.83113    -3.87857    -3.86665    -3.94975    -3.91406...
          -3.73234    -3.40962    -3.35183    -2.75593];
    c7   = [0.09427 0.10047 0.10989 0.12390 0.13054 0.14792 0.16089 0.17750...
          0.18398 0.19440 0.20357 0.20818 0.21940 0.22679 0.23948 0.25038...
```

```
                        0.25724 0.26969 0.27715 0.28176 0.28560 0.28566 0.29191 0.29188...
                        0.28177 0.27179 0.26815 0.24888];
                c10  = [-0.23731    -0.32935    -0.35578    -0.34651    -0.33074    -0.27796...
                        -0.23804    -0.17966    -0.15044    -0.11939    -0.10000    -0.08687...
                        -0.07412    -0.07112    -0.06285    -0.05740    -0.05290    -0.05210...
                        -0.05137    -0.05076    -0.05060    -0.05100    -0.05050    -0.05071...
                        -0.05246    -0.06172    -0.06285    -0.09546];
                sigp = [0.3464  0.3653  0.3785  0.4005  0.4139  0.4465  0.4648  0.4974  0.5223...
                        0.5339  0.5354  0.5421  0.5572  0.5616  0.5830  0.6082  0.6238  0.6147...
                        0.6156  0.6140  0.6127  0.6232  0.6354  0.6356  0.6298  0.5689  0.5632...
                        0.4467];
                sigT = [1.3217  1.1930  1.0421  0.9523  0.8794  0.7988  0.8067  0.7714  0.7691...
                        0.7709  0.7552  0.7517  0.7553  0.7591  0.7801  0.7870  0.7920  0.7846...
                        0.7874  0.7825  0.7834  0.7893  0.7956  0.7925  0.7893  0.7420  0.7383...
                        0.4467];
            end
        end
    end
end
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = SGD_2003(T_low, M, G, Rjb, SE, CM, SD_l, SD_t);
    [sa_hi,  sigma_hi]  = SGD_2003(T_hi,  M, G, Rjb, SE, CM, SD_l, SD_t);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    Sa = exp(c1(i) + c2(i)*M + (c6(i) + c7(i)*M)*log(Rjb + exp(c4(i))) + c10(i)*(M-6)^2);
    sigma = sigT(i);
end
```

3.5 Atkinson and Boore - 2006

3.5.1 Reference

Atkinson, G. M., and D. M. Boore (2006). Earthquake Ground-Motion Prediction Equations for Eastern North America, *Bulletin of the Seismological Society of America* **96**, 2181-2205.

Atkinson, G. M., and D. M. Boore (2011). Modifications to Existing Ground-Motion Prediction Equations in Light of New Data, *Bulletin of the Seismological Society of America.* (*in process*)

Atkinson, G. M. (2009). The University of Western Ontario, London, Ontario, Canada. Written communication.

3.5.2 Abstract

Using the predictions of a stochastic finite-fault model, empirical ground-motion attenuation equations were developed. The model predicts peak ground acceleration (PGA, in cm/s^2), peak ground velocity (PGV, in cm/s) and 5%-damped spectral values (in cm/s^2) for periods ranging from 0.025 to 5 sec. The model is applicable for hard rock (shear wave velocity of 2000 m/s or greater at the surface, NEHRP site class A) or soil conditions. The relationship was developed for a stress drop of 140 bars and can be adjusted for stress drops between 35 and 560 bars. The model is applicable for earthquakes between M3.5 and M8.0 and distances up to 1000 km. Note: the MATLAB code converts all accelerations to g's.

Thousands of new records were recorded after the original GMPE publication warrenting a modification published in 2011 to include a magnitude dependent stress drop (as opposed to the original fixed stress drop). The modification is intended to replace the original GMPE but both options will be provided in the MATLAB code below. For M < 5.0, use stress drop calculated for M = 5.0.

3.5.3 Attenuation Relationship

The spectral acceleration is a function of:

T – Period (sec), use 0 for PGA, -1 for PGV
M – Moment magnitude
R_{rup} – Closest distance to rupture plane (km)
S – 1 soil conditions, 0 for rock (V_{S30} > 2000 m/s, NEHRP site class A)
V_{S30} – Average shear wave velocity in upper 30 m (m/s) (not required for rock sites)
F_{SAF} – 0 for magnitude dependant stress drop (does not use SAF), 1 for SAF
SAF – Stress Adjustment Factor (log(stress drop/140)/log(2), e.g. enter 0 for stress drop of 140 bars, 1 for stress drop of 280 bars, -1 for stress drop of 70 bars, etc.)

Original:

$$\log_{10}(Sa) = c_1 + c_2 M + c_3 M^2 + (c_4 + c_5 M) f_1 + (c_6 + c_7 M) f_2 + (c_8 + c_9 M) f_0 + c_{10} R_{rup} \\ +S1 + SAF \cdot \log_{10}(SF_2)$$

Modified:

$$\log_{10}(Sa) = c_1 + c_2 M + c_3 M^2 + (c_4 + c_5 M) f_1 + (c_6 + c_7 M) f_2 + (c_8 + c_9 M) f_0 + \ c_{10} R_{rup} + S1 + \frac{\log_{10}(\Delta\sigma/140)}{\log_{10}(2)} \cdot \log_{10}(SF_2)$$

where:

$$f_1 = \min\left[\log_{10}\left(R_{rup}\right), \log_{10}(R_1)\right]$$

$$f_2 = \max\left[\log_{10}\left(\frac{R_{rup}}{R_2}\right), 0\right]$$

$$f_0 = \max\left[\log_{10}\left(\frac{R_0}{R_{rup}}\right), 0\right]$$

$$S1 = \begin{cases} 0 & for\ rock\ sites \\ \log\left\{\exp\left[b_{lin}\ln\left(\frac{V_{S30}}{V_{ref}}\right) + b_{nl}\ln\left(\frac{\max(pgaBC, 60)}{100}\right)\right]\right\} & for\ soil\ sites \end{cases}$$

where:

$$b_{nl} = \begin{cases} b_1 & for\ V_{S30} \leq v_1 \\ (b_1 - b_2)\frac{\ln\left(\frac{V_{S30}}{v_2}\right)}{\ln\left(\frac{v_1}{v_2}\right)} + b_2 & for\ v_1 < V_{S30} \leq v_2 \\ b_2\frac{\ln\left(\frac{V_{S30}}{V_{ref}}\right)}{\ln\left(\frac{v_2}{V_{ref}}\right)} & for\ v_2 < V_{S30} \leq V_{ref} \\ 0 & for\ V_{S30} > V_{ref} \end{cases}$$

pgaBC = median predicted value of PGA for V_{S30} = 760 m/s (NEHRP site class B/C boundary) and stress drop of 140 bars.

$$\log_{10}\Delta\sigma = 3.45 - 0.2M$$

$$\log_{10}(SF_2) = \min\left\{[\Delta + 0.05], \left[0.05 + \Delta\frac{\max[(M - M_1), 0]}{M_h - M_1}\right]\right\}$$

Standard Deviation

$$\sigma_T = 0.3\ for\ all\ magnitudes, distances\ and\ periods$$

Coefficients

Table 3-45. Period independent coefficients.

R_0	R_1	R_2	v_1	v_2	V_{ref}
10	70	140	180	300	760

Table 3-46. Period dependant regression coefficients for rock sites.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}
5.000	-5.410	1.710	-0.0901	-2.54	0.227	-1.270	0.1160	0.9790	-0.1770	-0.0001760
4.000	-5.790	1.920	-0.1070	-2.44	0.211	-1.160	0.1020	1.0100	-0.1820	-0.0002010
3.130	-6.040	2.080	-0.1220	-2.37	0.200	-1.070	0.0895	1.0000	-0.1800	-0.0002310
2.500	-6.170	2.210	-0.1350	-2.30	0.190	-0.986	0.0786	0.9680	-0.1770	-0.0002820
2.000	-6.180	2.300	-0.1440	-2.22	0.177	-0.937	0.0707	0.9520	-0.1770	-0.0003220
1.590	-6.040	2.340	-0.1500	-2.16	0.166	-0.870	0.0605	0.9210	-0.1730	-0.0003750
1.250	-5.720	2.320	-0.1510	-2.10	0.157	-0.820	0.0519	0.8560	-0.1660	-0.0004330
1.000	-5.270	2.260	-0.1480	-2.07	0.150	-0.813	0.0467	0.8260	-0.1620	-0.0004860
0.794	-4.600	2.130	-0.1410	-2.06	0.147	-0.797	0.0435	0.7750	-0.1560	-0.0005790
0.629	-3.920	1.990	-0.1310	-2.05	0.142	-0.782	0.0430	0.7880	-0.1590	-0.0006950
0.500	-3.220	1.830	-0.1200	-2.02	0.134	-0.813	0.0444	0.8840	-0.1750	-0.0007700
0.397	-2.440	1.650	-0.1080	-2.05	0.136	-0.843	0.0448	0.7390	-0.1560	-0.0008510
0.315	-1.720	1.480	-0.0974	-2.08	0.138	-0.889	0.0487	0.6100	-0.1390	-0.0009540
0.251	-1.120	1.340	-0.0872	-2.08	0.135	-0.971	0.0563	0.6140	-0.1430	-0.0010600
0.199	-0.615	1.230	-0.0789	-2.09	0.131	-1.120	0.0679	0.6060	-0.1460	-0.0011300
0.158	-0.146	1.120	-0.0714	-2.12	0.130	-1.300	0.0831	0.5620	-0.1440	-0.0011800
0.125	0.214	1.050	-0.0666	-2.15	0.130	-1.610	0.1050	0.4270	-0.1300	-0.0011500
0.100	0.480	1.020	-0.0640	-2.20	0.127	-2.010	0.1330	0.3370	-0.1270	-0.0010500
0.079	0.691	0.997	-0.0628	-2.26	0.125	-2.490	0.1640	0.2140	-0.1210	-0.0008470
0.063	0.911	0.980	-0.0621	-2.36	0.126	-2.970	0.1910	0.1070	-0.1170	-0.0005790
0.050	1.110	0.972	-0.0620	-2.47	0.128	-3.390	0.2140	-0.1390	-0.0984	-0.0003170
0.040	1.260	0.968	-0.0623	-2.58	0.132	-3.640	0.2280	-0.3510	-0.0813	-0.0001230
0.031	1.440	0.959	-0.0628	-2.71	0.140	-3.730	0.2340	-0.5430	-0.0645	-0.0000323
0.025	1.520	0.960	-0.0635	-2.81	0.146	-3.650	0.2360	-0.6540	-0.0550	-0.0000485
PGA	0.907	0.983	-0.0660	-2.70	0.159	-2.800	0.2120	-0.3010	-0.0653	-0.0004480
PGV	-1.440	0.991	-0.0585	-2.70	0.216	-2.440	0.2660	0.0848	-0.0693	-0.0003730

Table 3-47. Period dependant regression coefficients for V_{S30} = 760 m/s sites.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	b_{lin}	b_1	b_2
5.000	-4.850	1.580	-0.0807	-2.53	0.222	-1.430	0.1360	0.6340	-0.1410	-0.000161	-0.752	-0.300	0.000
4.000	-5.260	1.790	-0.0979	-2.44	0.207	-1.310	0.1210	0.7340	-0.1560	-0.000196	-0.745	-0.310	0.000
3.130	-5.590	1.970	-0.1140	-2.33	0.191	-1.200	0.1100	0.8450	-0.1720	-0.000245	-0.740	-0.330	0.000
2.500	-5.800	2.130	-0.1280	-2.26	0.179	-1.120	0.0954	0.8910	-0.1800	-0.000260	-0.735	-0.352	0.000
2.000	-5.850	2.230	-0.1390	-2.20	0.169	-1.040	0.0800	0.8670	-0.1790	-0.000286	-0.730	-0.375	0.000
1.590	-5.750	2.290	-0.1450	-2.13	0.158	-0.957	0.0676	0.8670	-0.1790	-0.000343	-0.726	-0.395	0.000
1.250	-5.490	2.290	-0.1480	-2.08	0.150	-0.900	0.0579	0.8210	-0.1720	-0.000407	-0.713	-0.418	0.000
1.000	-5.060	2.230	-0.1450	-2.03	0.141	-0.874	0.0541	0.7920	-0.1700	-0.000489	-0.700	-0.440	0.000
0.794	-4.450	2.120	-0.1390	-2.01	0.136	-0.858	0.0498	0.7080	-0.1590	-0.000575	-0.690	-0.465	-0.002
0.629	-3.750	1.970	-0.1290	-2.00	0.131	-0.842	0.0482	0.6770	-0.1560	-0.000676	-0.670	-0.480	-0.031
0.500	-3.010	1.800	-0.1180	-1.98	0.127	-0.847	0.0470	0.6670	-0.1550	-0.000768	-0.600	-0.495	-0.060
0.397	-2.280	1.630	-0.1050	-1.97	0.123	-0.888	0.0503	0.6840	-0.1580	-0.000859	-0.500	-0.508	-0.095
0.315	-1.560	1.460	-0.0931	-1.98	0.121	-0.947	0.0558	0.6500	-0.1560	-0.000955	-0.445	-0.513	-0.130
0.251	-0.876	1.290	-0.0819	-2.01	0.123	-1.030	0.0634	0.5810	-0.1490	-0.001050	-0.390	-0.518	-0.160
0.199	-0.306	1.160	-0.0721	-2.04	0.122	-1.150	0.0738	0.5080	-0.1430	-0.001140	-0.306	-0.521	-0.185
0.158	0.119	1.060	-0.0647	-2.05	0.119	-1.360	0.0916	0.5160	-0.1500	-0.001180	-0.280	-0.528	-0.185
0.125	0.536	0.965	-0.0584	-2.11	0.121	-1.670	0.1160	0.3430	-0.1320	-0.001130	-0.260	-0.560	-0.140
0.100	0.782	0.924	-0.0556	-2.17	0.119	-2.100	0.1480	0.2850	-0.1320	-0.000990	-0.250	-0.595	-0.132
0.079	0.967	0.903	-0.0548	-2.25	0.122	-2.530	0.1780	0.1000	-0.1150	-0.000772	-0.232	-0.637	-0.117
0.063	1.110	0.888	-0.0539	-2.33	0.123	-2.880	0.2010	-0.0319	-0.1070	-0.000548	-0.249	-0.642	-0.105
0.050	1.210	0.883	-0.0544	-2.44	0.130	-3.040	0.2130	-0.2100	-0.0900	-0.000415	-0.286	-0.643	-0.105
0.040	1.260	0.879	-0.0552	-2.54	0.139	-2.990	0.2160	-0.3910	-0.0675	-0.000388	-0.314	-0.609	-0.105
0.031	1.190	0.888	-0.0564	-2.58	0.145	-2.840	0.2120	-0.4370	-0.0587	-0.000433	-0.322	-0.618	-0.108
0.025	1.050	0.903	-0.0577	-2.57	0.148	-2.650	0.2070	-0.4080	-0.0577	-0.000512	-0.330	-0.624	-0.115
PGA	0.523	0.969	-0.0620	-2.44	0.147	-2.340	0.1910	-0.0870	-0.0829	-0.000630	-0.361	-0.641	-0.144
PGV	-1.660	1.050	-0.0604	-2.50	0.184	-2.300	0.2500	0.1270	-0.0870	-0.000427	-0.600	-0.495	-0.060

Table 3-48. Coefficients for SF_2.

T (sec)	Δ	M_1	M_h
5.000	0.15	6.00	8.50
4.000	0.15	5.75	8.37
3.130	0.15	5.50	8.25
2.500	0.15	5.25	8.12
2.000	0.15	5.00	8.00
1.590	0.15	4.84	7.70
1.250	0.15	4.67	7.45
1.000	0.15	4.50	7.20
0.794	0.15	4.34	6.95
0.629	0.15	4.17	6.70
0.500	0.15	4.00	6.50
0.397	0.15	3.65	6.37
0.315	0.15	3.30	6.25
0.251	0.15	2.90	6.12
0.199	0.15	2.50	6.00
0.158	0.15	1.85	5.84
0.125	0.15	1.15	5.67
0.100	0.15	0.50	5.50
0.079	0.15	0.34	5.34
0.063	0.15	0.17	5.17
0.050	0.15	0.00	5.00
0.040	0.15	0.00	5.00
0.031	0.15	0.00	5.00
0.025	0.15	0.00	5.00
PGA	0.15	0.50	5.50
PGV	0.11	2.00	5.50

3.5.4 Calibration Plots (all plots are for fixed stress drop unless otherwise noted)

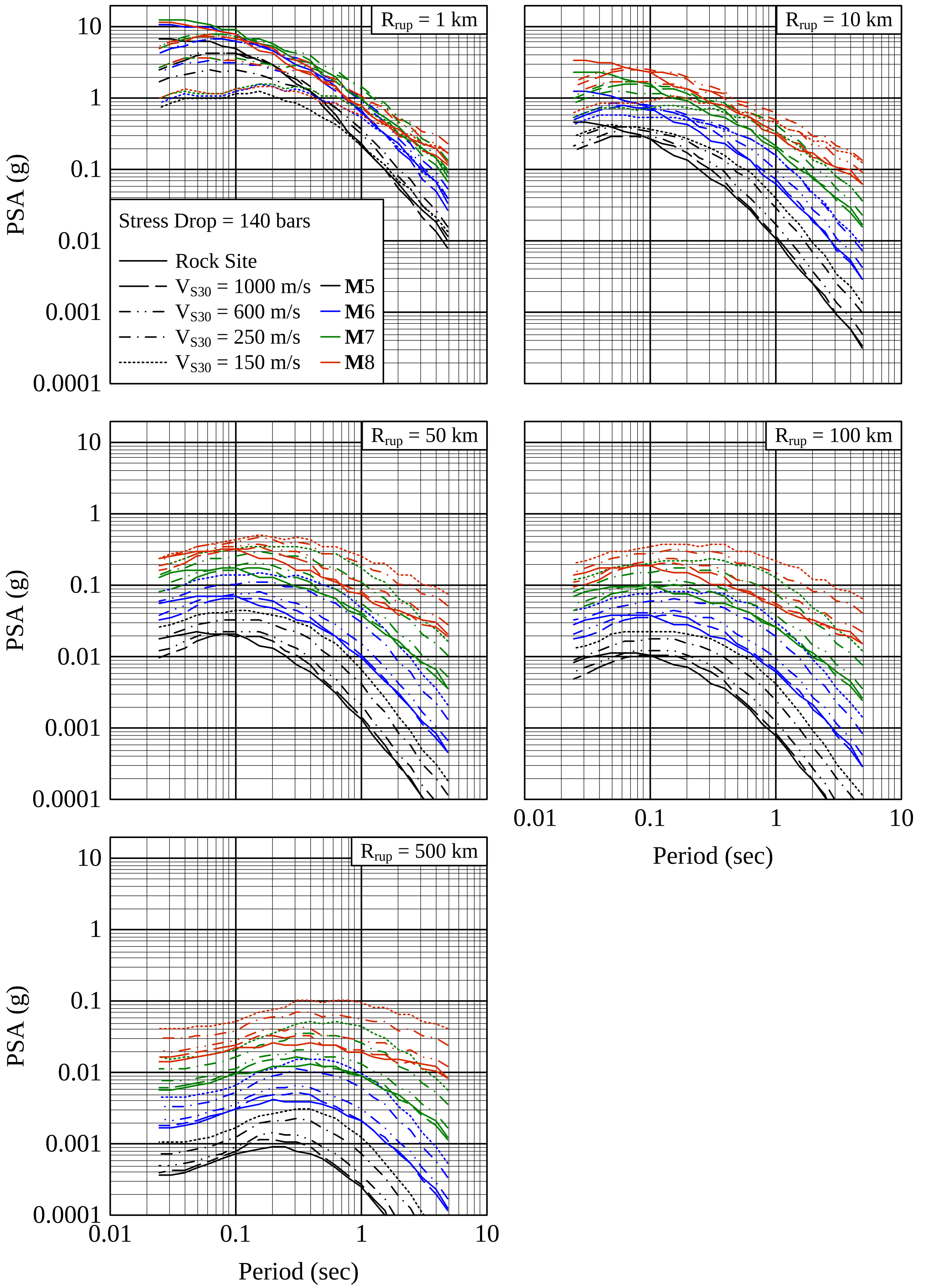


Figure 3-36. PSA as a function of period for various distances, magnitudes and site conditions.

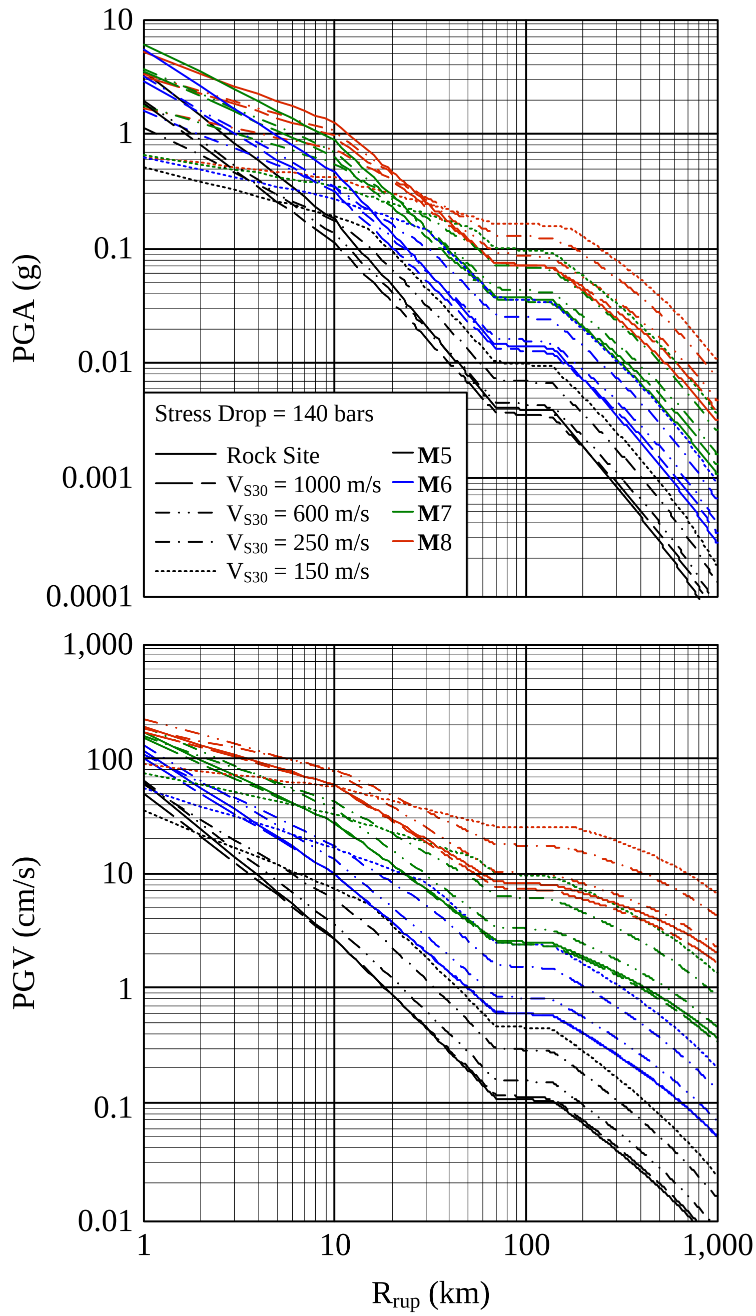


Figure 3-37. PGA and PGV as a function of distance for various magnitudes and site conditions.

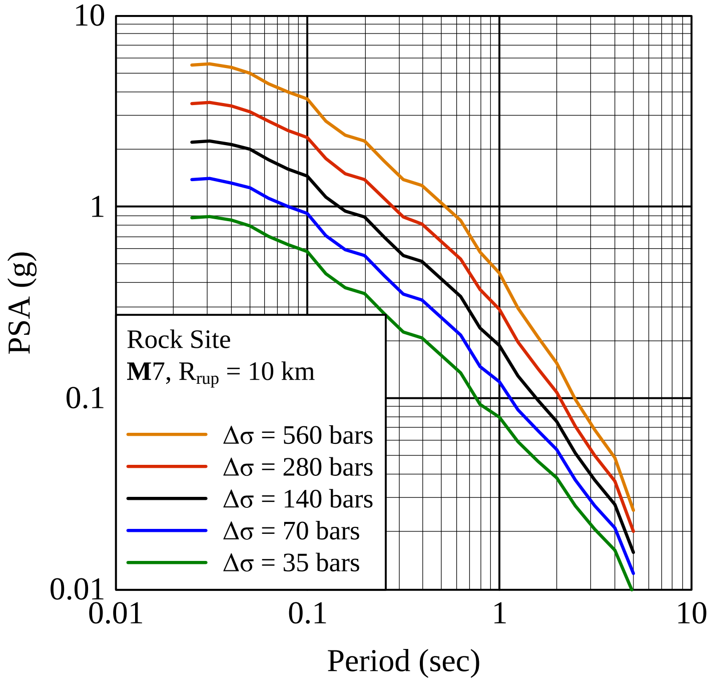


Figure 3-38. PSA estimated at various stress drops as a function of period for **M**7, rock site, and distance of 10 km.

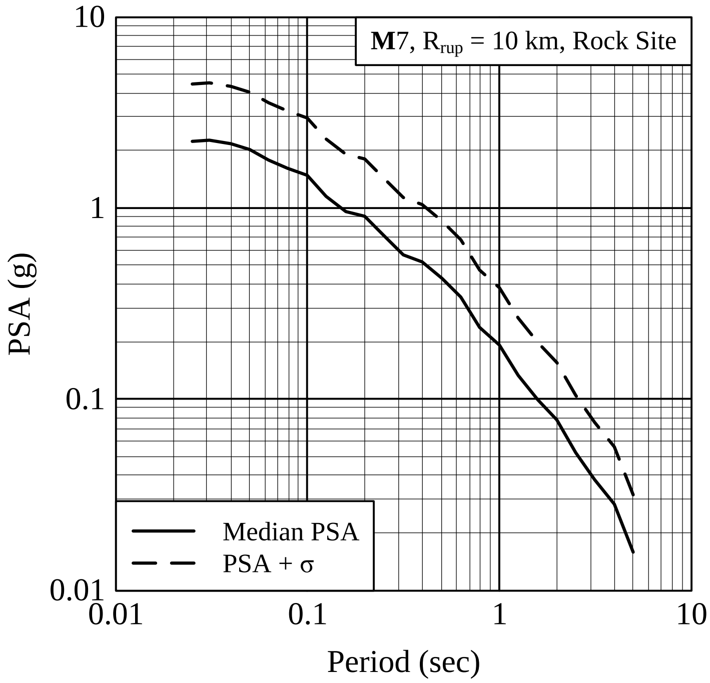


Figure 3-39. Example of application of median PSA plus one standard deviation.

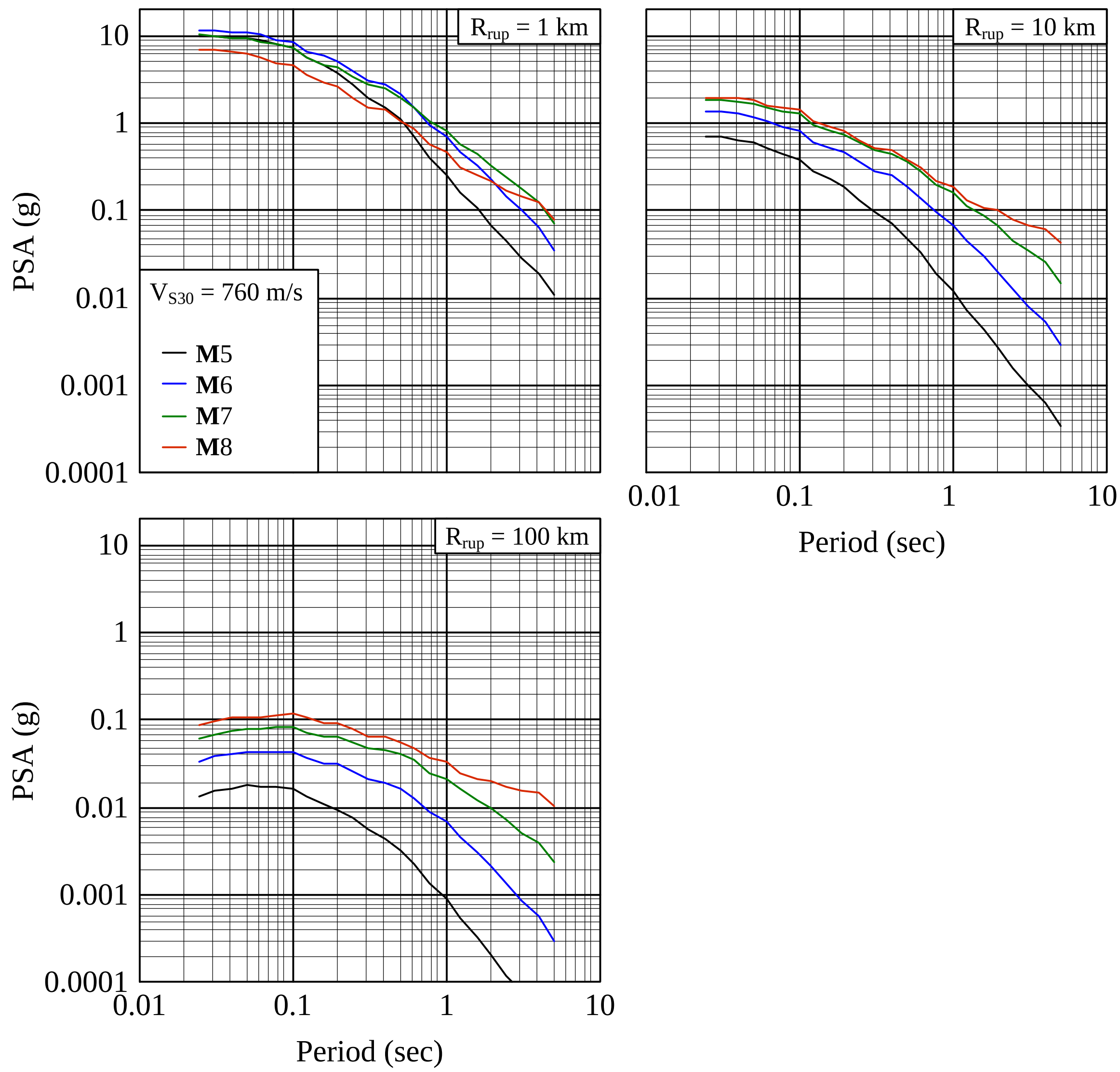


Figure 3-40. Calibration plots for magnitude dependent stress drop modification. PSA as a function of period for various distances and magnitudes.

3.5.5 Database

The database for the original attenuation equation is based on predictions of a stochastic finite-fault model. The modification used recent small-to-moderate magnitude earthquake records from central/eastern North America. No graphs were provided for either database.

3.5.6 MATLAB Code

```
% by Kathryn A. Gunberg 3/4/2008
% Virginia Tech
% kgunberg@vt.edu
%
% Atkinson and Boore attenuation equation, 2006
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T     = Period (sec), 0 for PGA, -1 for PGV
% M     = Moment magnitude
% Rrup  = Closest distance to the fault
% S     = 1 for soil conditions, 0 for rock (VS30 > 2000 m/s)
% VS30  = Average shear wave velocity in upper 30 m
%         (doesn't matter for rock conditions)
% F_SAF = 0 for magnitude dependent stress drop (no SAF), 1 for fixed
% SAF   = log(stress drop/140)/log(2) (e.g., 0 for stress drop of 140 bars,
%         1 for 280 bars, -1 for 70 bars)
% ---------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration or PGV prediction (g or cm/s)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = AB_2006(T, M, Rrup, S, VS30, F_SAF, SAF)
% Coefficients
period   = [5.000   4.000   3.130   2.500   2.000   1.590   1.250   1.000   0.794   0.629...
            0.500   0.397   0.315   0.251   0.199   0.158   0.125   0.100   0.079   0.063...
            0.050   0.040   0.031   0.025   0       -1];
R0 = 10;
R1 = 70;
R2 = 140;
if S == 0
    c1   = [-5.41   -5.79   -6.04   -6.17   -6.18   -6.04   -5.72   -5.27   -4.60   -3.92   ...
            -3.22   -2.44   -1.72   -1.12   -0.615  -0.146  0.214   0.480   0.691   0.911   ...
            1.11    1.26    1.44    1.52    0.907   -1.44];
    c2   = [1.71    1.92    2.08    2.21    2.30    2.34    2.32    2.26    2.13    1.99    ...
            1.83    1.65    1.48    1.34    1.23    1.12    1.05    1.02    0.997   0.980   ...
            0.972   0.968   0.959   0.960   0.983   0.991];
    c3   = [-0.0901 -0.107  -0.122  -0.135  -0.144  -0.150  -0.151  -0.148  -0.141  -0.131  ...
            -0.120  -0.108  -0.0974 -0.0872 -0.0789 -0.0714 -0.0666 -0.0640 -0.0628 -0.0621 ...
            -0.0620 -0.0623 -0.0628 -0.0635 -0.0660 -0.0585];
    c4   = [-2.54   -2.44   -2.37   -2.30   -2.22   -2.16   -2.10   -2.07   -2.06   -2.05   ...
            -2.02   -2.05   -2.08   -2.08   -2.09   -2.12   -2.15   -2.20   -2.26   -2.36   ...
            -2.47   -2.58   -2.71   -2.81   -2.70   -2.70];
    c5   = [0.227   0.211   0.200   0.190   0.177   0.166   0.157   0.150   0.147   0.142   ...
            0.134   0.136   0.138   0.135   0.131   0.130   0.130   0.127   0.125   0.126   ...
            0.128   0.132   0.140   0.146   0.159   0.216];
    c6   = [-1.27   -1.16   -1.07   -0.986  -0.937  -0.870  -0.820  -0.813  -0.797  -0.782  ...
            -0.813  -0.843  -0.889  -0.971  -1.12   -1.30   -1.61   -2.01   -2.49   -2.97   ...
            -3.39   -3.64   -3.73   -3.65   -2.80   -2.44];
    c7   = [0.116   0.102   0.0895  0.0786  0.0707  0.0605  0.0519  0.0467  0.0435  0.0430  ...
            0.0444  0.0448  0.0487  0.0563  0.0679  0.0831  0.105   0.133   0.164   0.191   ...
            0.214   0.228   0.234   0.236   0.212   0.266];
    c8   = [0.979   1.01    1.00    0.968   0.952   0.921   0.856   0.826   0.775   0.788   ...
            0.884   0.739   0.610   0.614   0.606   0.562   0.427   0.337   0.214   0.107   ...
            -0.139  -0.351  -0.543  -0.654  -0.301  0.0848];
    c9   = [-0.177  -0.182  -0.180  -0.177  -0.177  -0.173  -0.166  -0.162  -0.156  -0.159  ...
            -0.175  -0.156  -0.139  -0.143  -0.146  -0.144  -0.130  -0.127  -0.121  -0.117  ...
            -0.0984 -0.0813 -0.0645 -0.0550 -0.0653 -0.0693];
    c10  = [-0.000176 -0.000201 -0.000231 -0.000282 -0.000322 -0.000375 -0.000433 -0.000486 ...
            -0.000579 -0.000695 -0.000770 -0.000851 -0.000954 -0.00106 -0.00113 -0.00118 ...
            -0.00115 -0.00105 -0.000847 -0.000579 -0.000317 -0.000123 -0.0000323 -0.0000485 ...
            -0.000448 -0.000373];
else
    c1   = [-4.85   -5.26   -5.59   -5.80   -5.85   -5.75   -5.49   -5.06   -4.45   -3.75   ...
            -3.01   -2.28   -1.56   -0.876  -0.306  0.119   0.536   0.782   0.967   1.11    ...
            1.21    1.26    1.19    1.05    0.523   -1.66];
    c2   = [1.58    1.79    1.97    2.13    2.23    2.29    2.29    2.23    2.12    1.97    ...
```

```
            1.80    1.63    1.46    1.29    1.16    1.06    0.965   0.924   0.903   0.888   ...
            0.883   0.879   0.888   0.903   0.969   1.05];
    c3   = [-0.0807 -0.0979 -0.114  -0.128  -0.139  -0.145  -0.148  -0.145  -0.139  -0.129  ...
            -0.118  -0.105  -0.0931 -0.0819 -0.0721 -0.0647 -0.0584 -0.0556 -0.0548 -0.0539 ...
            -0.0544 -0.0552 -0.0564 -0.0577 -0.0620 -0.0604];
    c4   = [-2.53   -2.44   -2.33   -2.26   -2.20   -2.13   -2.08   -2.03   -2.01   -2.00   ...
            -1.98   -1.97   -1.98   -2.01   -2.04   -2.05   -2.11   -2.17   -2.25   -2.33   ...
            -2.44   -2.54   -2.58   -2.57   -2.44   -2.50];
    c5   = [0.222   0.207   0.191   0.179   0.169   0.158   0.150   0.141   0.136   0.131   ...
            0.127   0.123   0.121   0.123   0.122   0.119   0.121   0.119   0.122   0.123   ...
            0.130   0.139   0.145   0.148   0.147   0.184];
    c6   = [-1.43   -1.31   -1.20   -1.12   -1.04   -0.957  -0.900  -0.874  -0.858  -0.842  ...
            -0.847  -0.888  -0.947  -1.03   -1.15   -1.36   -1.67   -2.10   -2.53   -2.88   ...
            -3.04   -2.99   -2.84   -2.65   -2.34   -2.30];
    c7   = [0.136   0.121   0.110   0.0954  0.0800  0.0676  0.0579  0.0541  0.0498  0.0482  ...
            0.0470  0.0503  0.0558  0.0634  0.0738  0.0916  0.116   0.148   0.178   0.201   ...
            0.213   0.216   0.212   0.207   0.191   0.250];
    c8   = [0.634   0.734   0.845   0.891   0.867   0.867   0.821   0.792   0.708   0.677   ...
            0.667   0.684   0.650   0.581   0.508   0.516   0.343   0.285   0.100   -0.0319 ...
            -0.210  -0.391  -0.437  -0.408  -0.0870 0.127];
    c9   = [-0.141  -0.156  -0.172  -0.180  -0.179  -0.179  -0.172  -0.170  -0.159  -0.156  ...
            -0.155  -0.158  -0.156  -0.149  -0.143  -0.150  -0.132  -0.132  -0.115  -0.107  ...
            -0.0900 -0.0675 -0.0587 -0.0577 -0.0829 -0.0870];
    c10  = [-0.000161 -0.000196 -0.000245 -0.000260 -0.000286 -0.000343 -0.000407 -0.000489 ...
            -0.000575 -0.000676 -0.000768 -0.000859 -0.000955 -0.00105 -0.00114 -0.00118 ...
            -0.00113 -0.000990 -0.000772 -0.000548 -0.000415 -0.000388 -0.000433 -0.000512 ...
            -0.000630 -0.000427];
    blin = [-0.752  -0.745  -0.740  -0.735  -0.730  -0.726  -0.713  -0.700  -0.690  -0.670  ...
            -0.600  -0.500  -0.445  -0.390  -0.306  -0.280  -0.260  -0.250  -0.232  -0.249  ...
            -0.286  -0.314  -0.322  -0.330  -0.361  -0.600];
    b1   = [-0.300  -0.310  -0.330  -0.352  -0.375  -0.395  -0.418  -0.440  -0.465  -0.480  ...
            -0.495  -0.508  -0.513  -0.518  -0.521  -0.528  -0.560  -0.595  -0.637  -0.642  ...
            -0.643  -0.609  -0.618  -0.624  -0.641  -0.495];
    b2   = [0       0       0       0       0       0       0       0       -0.002  -0.031  ...
            -0.060  -0.095  -0.130  -0.160  -0.185  -0.185  -0.140  -0.132  -0.117  -0.105  ...
            -0.105  -0.105  -0.108  -0.115  -0.144  -0.060];
    Vref = 760;
    V1   = 180;
    V2   = 300;
end
delta    = [0.15    0.15    0.15    0.15    0.15    0.15    0.15    0.15    0.15    0.15    ...
            0.15    0.15    0.15    0.15    0.15    0.15    0.15    0.15    0.15    0.15    ...
            0.15    0.15    0.15    0.15    0.15    0.11];
M1       = [6.00    5.75    5.50    5.25    5.00    4.84    4.67    4.50    4.34    4.17    ...
            4.00    3.65    3.30    2.90    2.50    1.85    1.15    0.50    0.34    0.17    ...
            0       0       0       0       0.50    2.00];
Mh       = [8.50    8.37    8.25    8.12    8.00    7.70    7.45    7.20    6.95    6.70    ...
            6.50    6.37    6.25    6.12    6.00    5.84    5.67    5.50    5.34    5.17    ...
            5.00    5.00    5.00    5.00    5.50    5.50];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = AB_2006(T_low, M, Rrup, S, VS30, F_SAF, SAF);
    [sa_hi,  sigma_hi]  = AB_2006(T_hi,  M, Rrup, S, VS30, F_SAF, SAF);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    f0 = max(log10(R0/Rrup),0);
    f1 = min(log10(Rrup),log10(R1));
    f2 = max(log10(Rrup/R2),0);
    if S == 0
        S1 = 0;
    else
        j = find(abs((period - 0)) < 0.0001);
        pgaBC = 10^(c1(j) + c2(j)*M + c3(j)*M^2 + (c4(j) + c5(j)*M)*f1 + (c6(j) + ...
            c7(j)*M)*f2 + (c8(j) + c9(j)*M)*f0 + c10(j)*Rrup);
```

```
        if VS30 < V1
            bnl = b1(i);
        elseif VS30 <= V2
            bnl = (b1(i) - b2(i))*log(VS30/V2)/log(V1/V2) + b2(i);
        elseif VS30 <= Vref
            bnl = b2(i)*log(VS30/Vref)/log(V2/Vref);
        else
            bnl = 0;
        end
        S1 = log10(exp(blin(i)*log(VS30/Vref) + bnl*log(max(pgaBC,60)/100)));
    end
    logSF2 = min((delta(i) + 0.05),(0.05 + delta(i)*max((M-M1(i)),(0))/(Mh(i)-M1(i))));
    if F_SAF == 1
        Sapre = 10^(c1(i) + c2(i)*M + c3(i)*M^2 + (c4(i)+c5(i)*M)*f1 + (c6(i) + c7(i)*M)*f2 + ...
            (c8(i) + c9(i)*M)*f0 + c10(i)*Rrup + S1 + SAF*logSF2);
    else
        sd = min(280,10^(3.45-0.2*M));
        Sapre = 10^(c1(i) + c2(i)*M + c3(i)*M^2 + (c4(i)+c5(i)*M)*f1 + (c6(i) + c7(i)*M)*f2 + ...
            (c8(i) + c9(i)*M)*f0 + c10(i)*Rrup + S1 + log10(sd/140)/log10(2)*logSF2);
    end
    if T == -1
        Sa = Sapre;
    else
        Sa = Sapre/980.665;
    end
    sigma = 0.3;
end
```

3.6 Atkinson – 2008

3.6.1 Reference

Atkinson, G. M. (2008). Ground-Motion Prediction Equations for Eastern North America from a Referenced Empirical Approach: Implications for Epistemic Uncertainty, *Bulletin of the Seismological Society of America* **98**(3), 1304-1318.

Atkinson, G. M., and D. M. Boore. (2011). Modifications to Existing Ground-Motion Prediction Equations in Light of New Data, *Bulletin of the Seismological Society of America.* (*in process*)

3.6.2 Abstract

The Boore and Atkinson (2008; see section 2.9 of this report) ground-motion prediction equation is modified to fit eastern North America ground motion data. The original Atkinson (2008) model was updated in 2011 (Atkinson and Boore). Both versions are presented below. The 2008 model does not include the small-to-medium magnitude (SMM) adjustment and the 2011 model does. The model predicts 5%-damped spectral values (in g) for periods ranging from 0.1 to 5 s for the 2008 model and 0.05 to 5 s for the 2011 model. The model is applicable at distances less than 700 km and based on the bounds of the earthquakes in the database, this model is most applicable for earthquakes between M4.3 and M7.6. Standard deviations were only provided with the 2008 model.

3.6.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA, -1 for PGV
- **M** – Moment magnitude
- F – 1 for unspecified, 2 for strike-slip, 3 for normal or 4 for reverse
- R_{jb} – Joyner-Boore distance (km)
- V_{S30} – Shear wave velocity (m/s) averaged over top 30 m
- SMM – 1 for SMM adjustment (2011 model), 0 othewise (2008 model)
- w – 0 for c_0, 1 to replace with c_{0w} (weighted average) (used in 2008 version only)

$$Sa = F \cdot Sa_{BA08}$$

where:

2008 model: $\log(F) = c_0 + c_1 R_{jb} + c_2 {R_{jb}}^2$

2011 model: $\log(F) = c + dR_{jb}$

Sa_{BA08} = PSA, PGA or PGV value from Boore and Atkinson (2008) (see section 2.9)

Coefficients

Table 3-49. Coefficients and standard deviations for 2008 model.

Period	c_0	c_{0w}	c_1	c_2	σ
0.10	0.143	0.093	0.001240	0.000001990	0.234
0.20	-0.102	-0.155	0.001440	0.000001270	0.290
0.50	-0.364	-0.356	0.001130	0.000000698	0.368
1.0	-0.376	-0.404	0.000556	0.000000744	0.288
2.0	-0.419	-0.379	0.000520	0.000000376	0.379
5.0	-0.271	-0.319	-0.001070	0.000001490	0.284
PGA	0.287	0.163	0.001200	0.000002300	0.331
PGV	-0.029	0.047	-0.001110	0.000001890	0.223

Table 3-50. Coefficients for 2011 model.

Period	c	d
0.05	0.417	0.00192
0.10	0.245	0.00273
0.20	0.042	0.00232
0.30	-0.078	0.00190
0.50	-0.180	0.00180
1.0	-0.248	0.00153
2.0	-0.214	0.00117
3.0	-0.084	0.00091
5.0	0	0
PGA	0.419	0.00211
PGV	0.450	0.00039

3.6.4 Calibration Plots

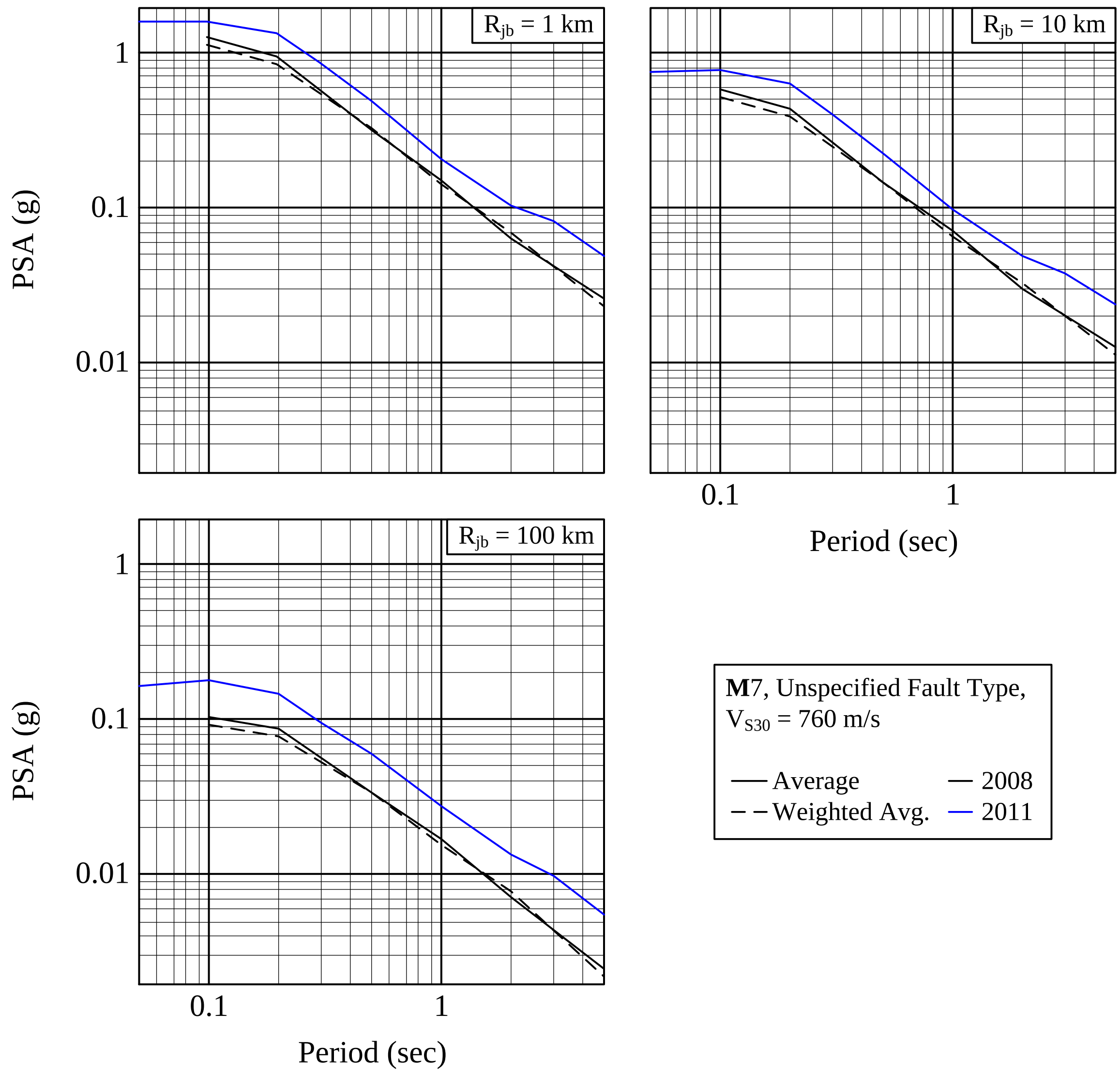


Figure 3-41. PSA as a function of period for the weighted and non-weight averages of the 2008 model and the 2011 model. Note that the other input parameters do not need to be calibrated as long as the Boore and Atkinson (2008) model is correct.

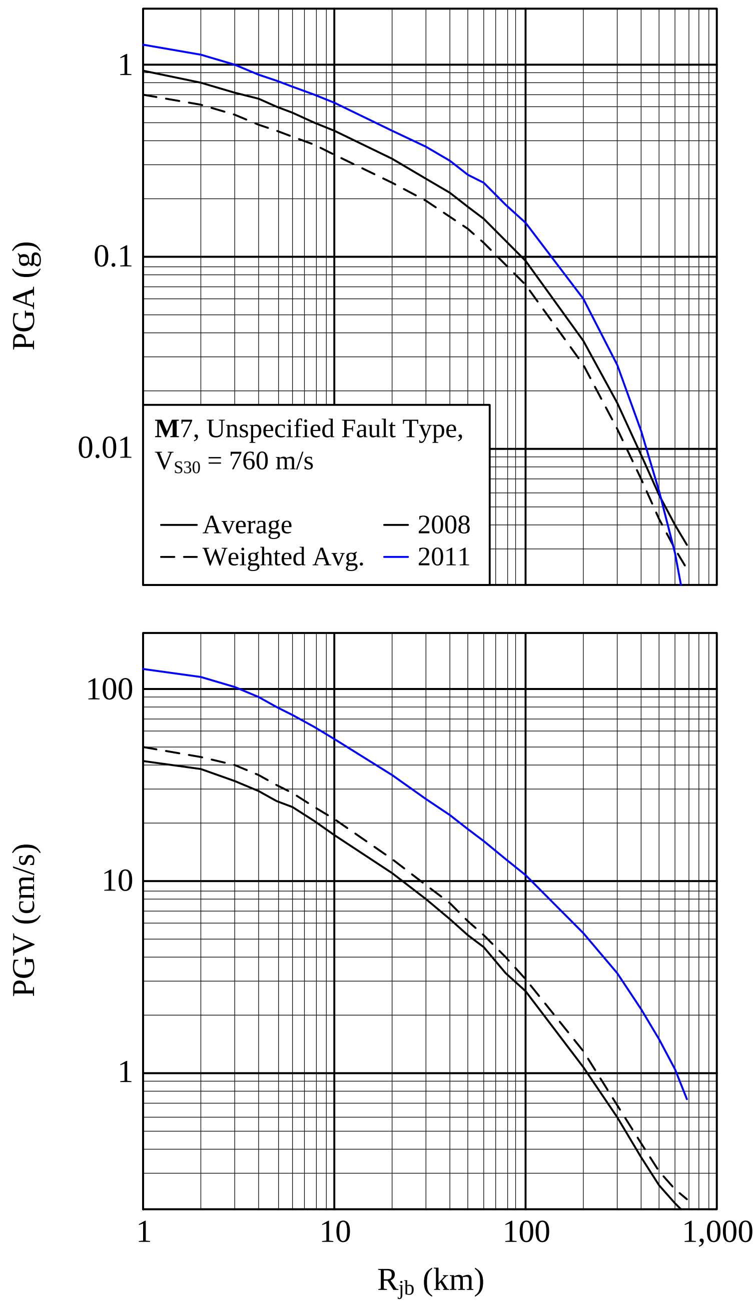


Figure 3-42. PGA and PGV as a function of distace for the weighted and non-weight averages of the 2008 model and the 2011 model.

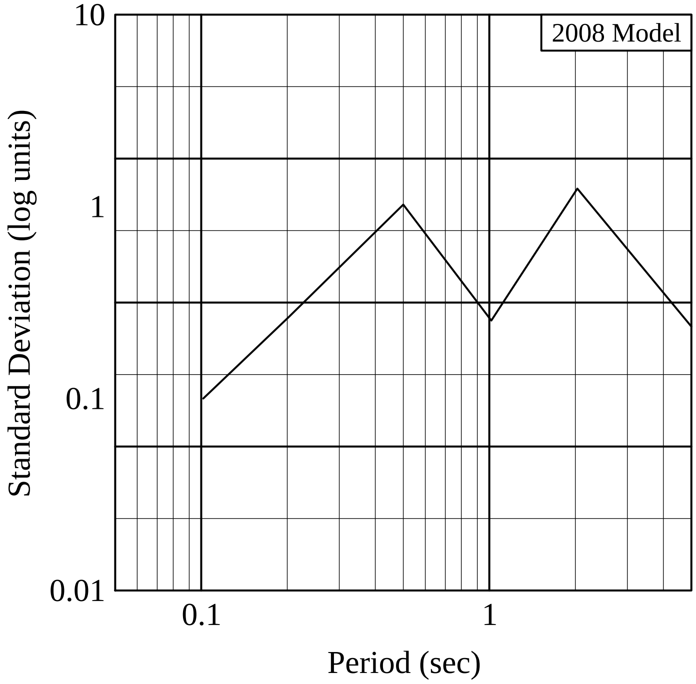


Figure 3-43. Standard deviation as a function of period.

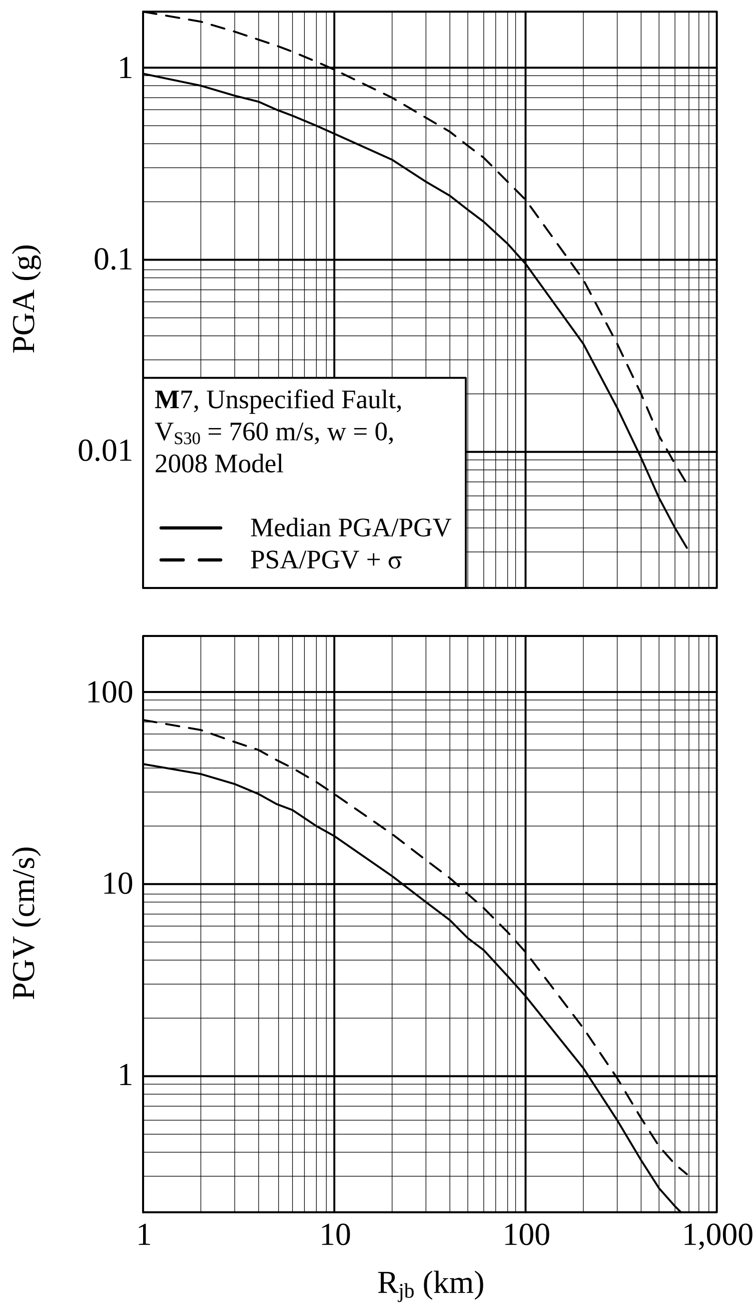


Figure 3-44. Example of application of median PGA/PGV plus one standard deviation.

3.6.5 Database

As discussed in the abstract, these models used a modified Boore and Atkinson (2008) model to fit eastern North America strong ground motions. The 2008 model used the same database as Atkinson and Boore (2006). The 2011 model used more recent ground motions. No graphs were provided.

3.6.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/12/20011
% Virginia Tech
% kgunberg@vt.edu
%
% Atkinson attenuation equation, 2008, with updates from Atkinson and
% Boore, 2011
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T             = Period (sec), 0 for PGA, -1 for PGV
% M             = Moment magnitude
% F             = Faut type: 1 for unspecified, 2 for strike-slip, 3 for
%                 normal, 4 for reverse
% Rjb           = Joyner-Boore distance (km)
% Vs30          = shear wave velocity averaged over top 30 m (m/s)
% SMM           = 1 to include SMM adjument (2011), 0 otherwise (2008)
% w             = 0 for c0, 1 to replace with c0w (weighted average) (used
%                 in 2008 version only)
% ---------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration or PGV prediction (g or cm/s)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = A_2008(T, M, F, Rjb, Vs30, SMM, w)
% Coefficients
if SMM == 0
    period   = [0.1 0.2 0.5 1   2   5   0   -1];
    if w == 0
        c0       = [0.143   -0.102  -0.364  -0.376  -0.419  -0.271  0.287   -0.029];
    else
        c0       = [0.093   -0.155  -0.356  -0.404  -0.379  -0.319  0.163   0.047];
    end
    c1       = [0.001240    0.001440    0.001130    0.000556    0.000520    -0.001070...
                0.001200    -0.001110];
    c2       = [0.000001990 0.000001270 0.000000698 0.000000744 0.000000376 0.000001490...
                0.000002300 0.000001890];
    sig      = [0.234   0.290   0.368   0.288   0.379   0.284   0.331   0.223];
else
    period   = [0.05    0.1 0.2 0.3 0.5 1   2   3   5   0   -1];
    c        = [0.417   0.245   0.042   -0.078  -0.180  -0.248  -0.214  -0.084  0   0.419...
                0.450];
    d        = [0.00192 0.00273 0.00232 0.00190 0.00180 0.00153 0.00117 0.00091 0   0.00211...
                0.00039];
end
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = A_2008(T_low, M, F, Rjb, Vs30, SMM, w);
    [sa_hi,  sigma_hi]  = A_2008(T_hi,  M, F, Rjb, Vs30, SMM, w);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    SABA08 = BA_2008_nga(T, M, F, Rjb, Vs30, SMM);
    if SMM == 0
        F = 10^(c0(i) + c1(i)*Rjb + c2(i)*Rjb^2);
        sigma = sig(i);
    else
        F = 10^(c(i) + d(i)*Rjb);
        sigma = 0;
    end
    Sa = F*SABA08;
end
```

4 SUBDUCTION ZONES

The attenuation relations in this section apply to subduction zones such as the northwestern United States. They do not apply to shallow active regions.

Table 4-1. List of parameters used in this section by each relationship. Definitions below.

Input Parameter	YCSH97	GSWY02	AB03
T	●	●	●
M	●	●	●
G			●
H	●		●
F	●		●
R_{rup}	●	●	●
S	●	●	●

T – Period (sec), PGA, PGV or PGD
M – Moment magnitude
G – Region region indicator
H – Focal depth (km)
F – Fault type indicator (0 for interface, 1 for intraslab)
R_{rup} – Closest distance to rupture plane (km)
S – Soil condition indicator

Table 4-2. List of parameters provided by relationships in this section. Definitions below.

Output Parameter	YCSH97	GSWY02	AB03
PSA	●	●	●
PGA	●	●	●

PSA – 5%-damped pseudo-spectral acceleration (g)
PGA – Peak ground acceleration (g)

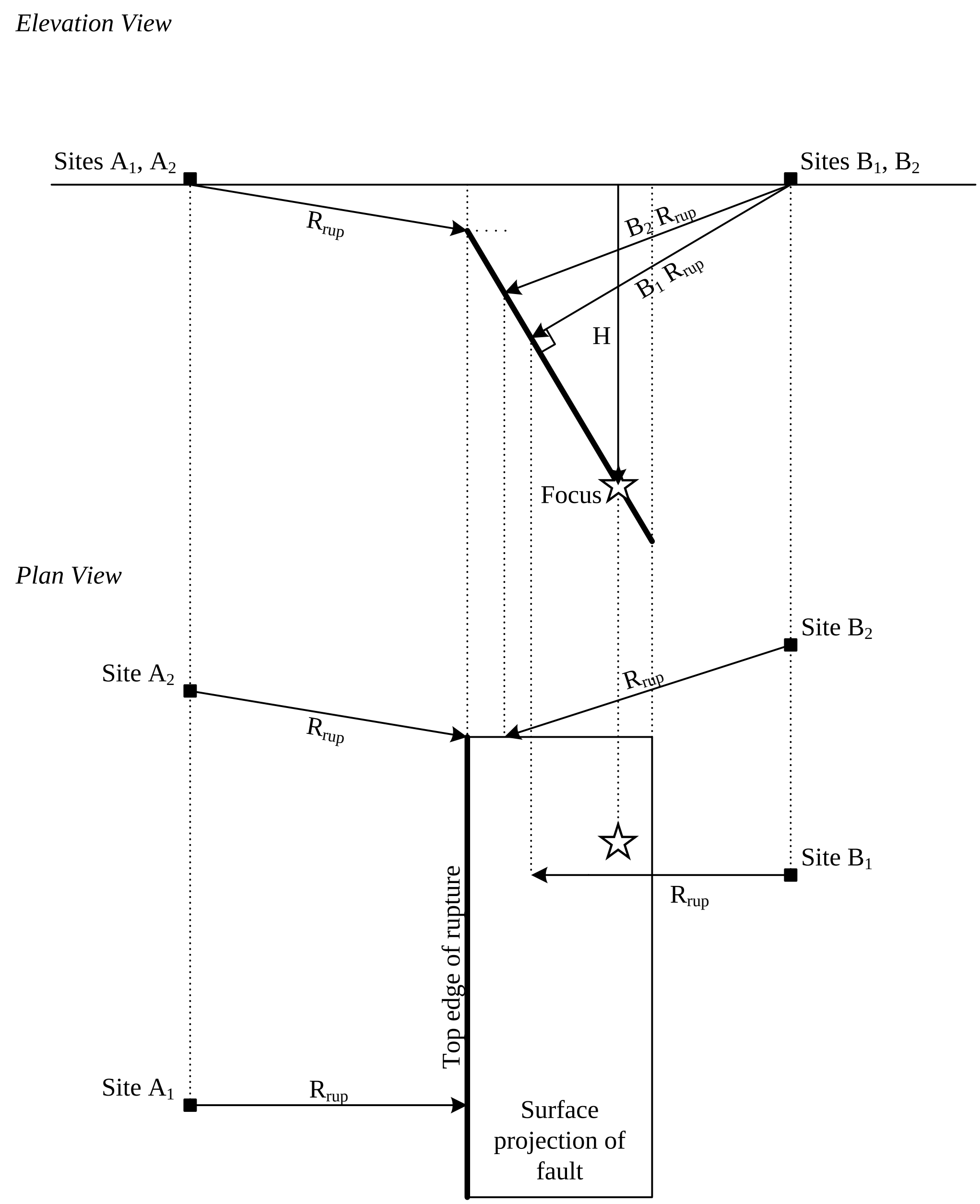


Figure 4-1. Fault geometry graphical definitions.

4.1 Youngs, Chiou, Silva and Humphrey - 1997

4.1.1 Reference

Youngs, R. R., S.-J. Chiou, W. G. Silva, and J. R. Humphrey (1997). Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquakes, *Seismological Research Letters* **68**, 58-73.

4.1.2 Abstract

Using 476 records from 161 subduction zone earthquakes, empirical ground-motion attenuation equations were developed for peak ground acceleration (PGA, in g) and 5%-damped spectral values (PSA, in g) for periods ranging from 0.075 to 3 sec. for rock sites and 0.075 to 4 sec. for soil sites. The model is applicable earthquakes greater than M5.0 and distances from 10 to 500 km.

4.1.3 Attenuation Relationship

The spectral acceleration is a function of:

T – Period (sec), use 0 or PGA
M – Moment magnitude
H – Focal depth (km)
F – 0 for interface (between overriding and subducting plates, 1 for intraslab (within subducting plate)
R_{rup} – Closest distance to rupture plane (km)
S – 0 for rock sites, 1 for soil sites

Rock Sites

$$\ln(Sa) = 0.2418 + 1.414M + c_1 + c_2(10 - M)^3 + c_3 \ln\left(R_{rup} + 1.7818e^{0.554M}\right) + 0.00607H + 0.3846F$$

Soil Sites

$$\ln(Sa) = -0.6687 + 1.438M + c_1 + c_2(10 - M)^3 + c_3 \ln\left(R_{rup} + 1.097e^{0.617M}\right) + 0.00648H + 0.3643F$$

Standard Deviation

$$\sigma = c_4 + c_5 \min(M, 8)$$

Coefficients

Table 4-3. Coefficients for attenuation relationship.

T (sec)	Rock			Soil			c_4
	c_1	c_2	c_3	c_1	c_2	c_3	
PGA	0.000	0.0000	-2.552	0.000	0.0000	-2.329	1.45
0.075	1.275	0.0000	-2.707	2.400	-0.0019	-2.697	1.45
0.10	1.188	-0.0011	-2.655	2.516	-0.0019	-2.697	1.45
0.20	0.722	-0.0027	-2.528	1.549	-0.0019	-2.464	1.45
0.30	0.246	-0.0036	-2.454	0.793	-0.0020	-2.327	1.45
0.40	-0.115	-0.0043	-2.401	0.144	-0.0020	-2.230	1.45
0.50	-0.400	-0.0048	-2.360	-0.438	-0.0035	-2.140	1.45
0.75	-1.149	-0.0057	-2.286	-1.704	-0.0048	-1.952	1.45
1.0	-1.736	-0.0064	-2.234	-2.870	-0.0066	-1.785	1.45
1.5	-2.634	-0.0073	-2.160	-5.101	-0.0114	-1.470	1.50
2.0	-3.328	-0.0080	-2.107	-6.433	-0.0164	-1.290	1.55
3.0	-4.511	-0.0089	-2.033	-6.672	-0.0221	-1.347	1.65
4.0	-	-	-	-7.618	-0.0235	-1.272	1.65

Note: c_5 = -0.1 for all periods and site conditions

4.1.4 Calibration Plots

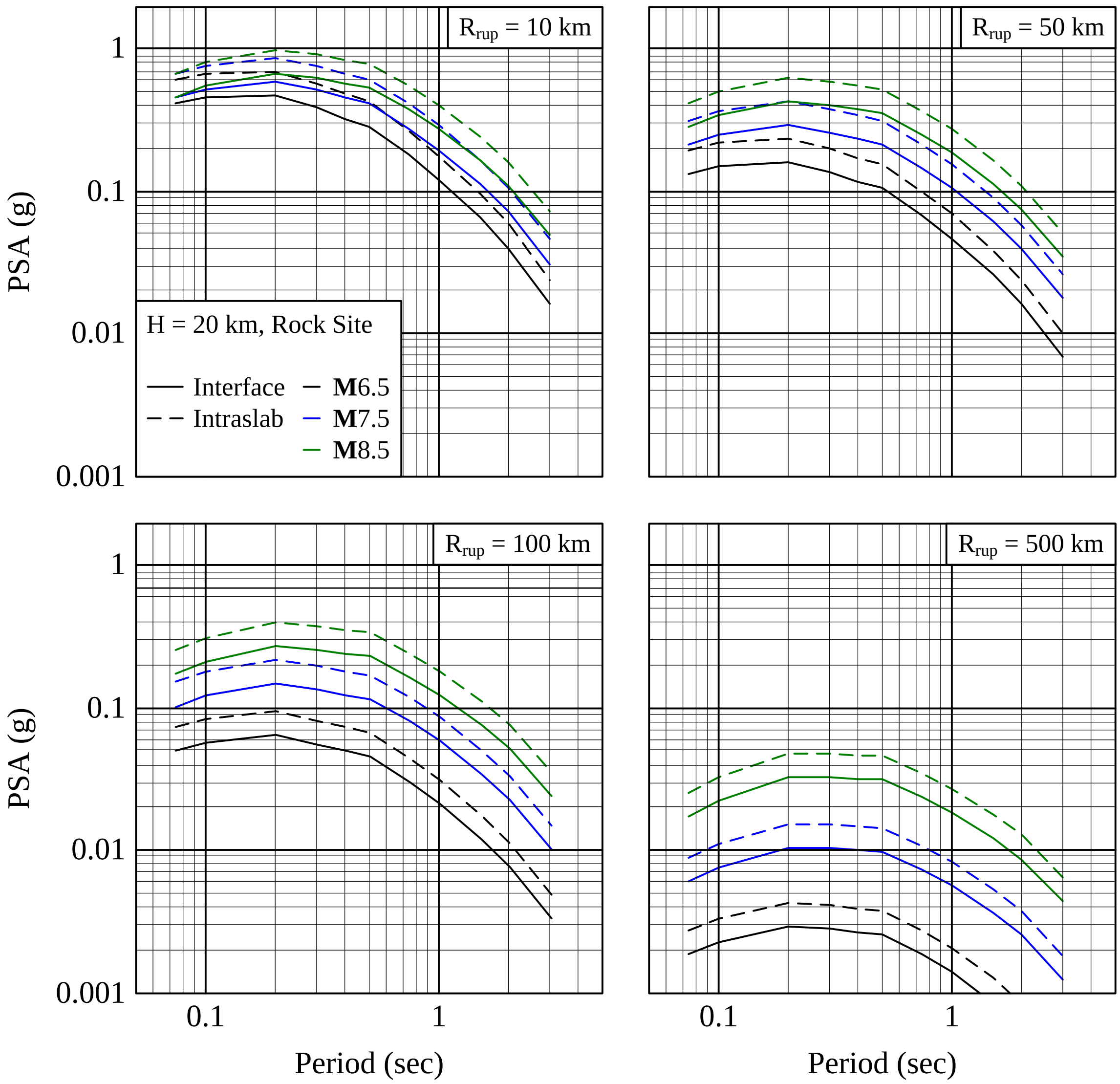


Figure 4-2. PSA as a function of period for various conditions.

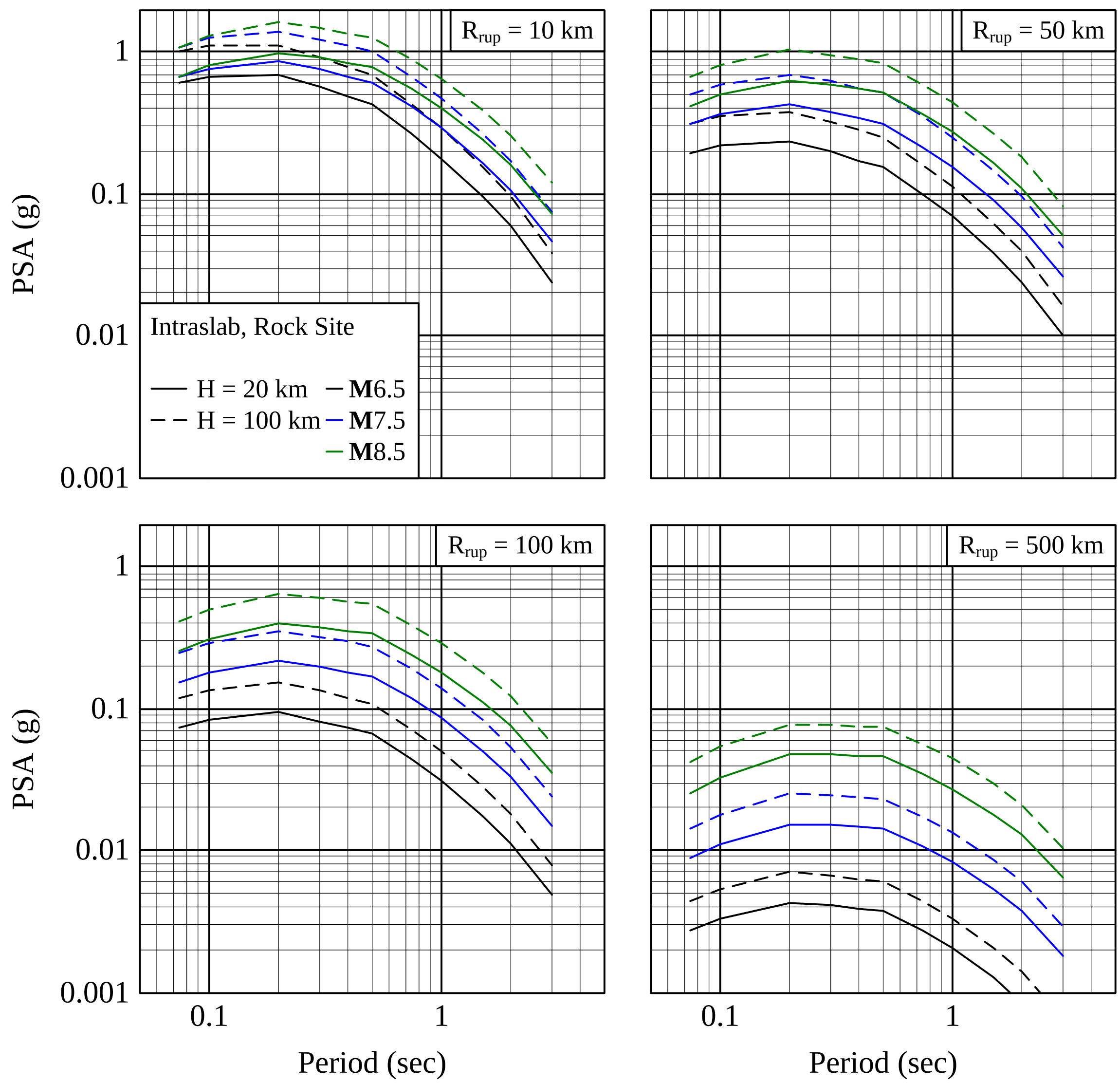


Figure 4-3. PSA as a function of period for various conditions.

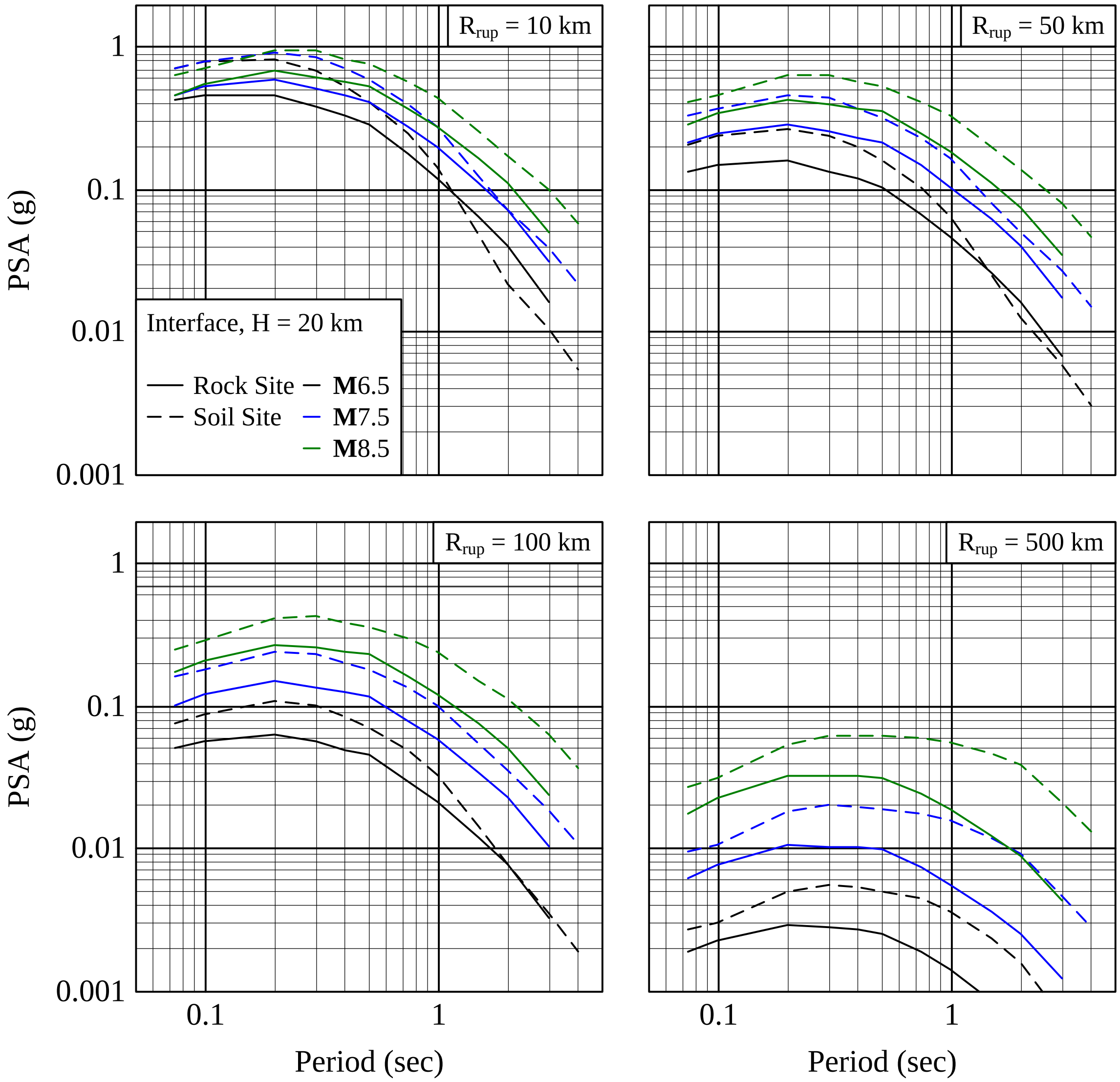


Figure 4-4. PSA as a function of period for various conditions.

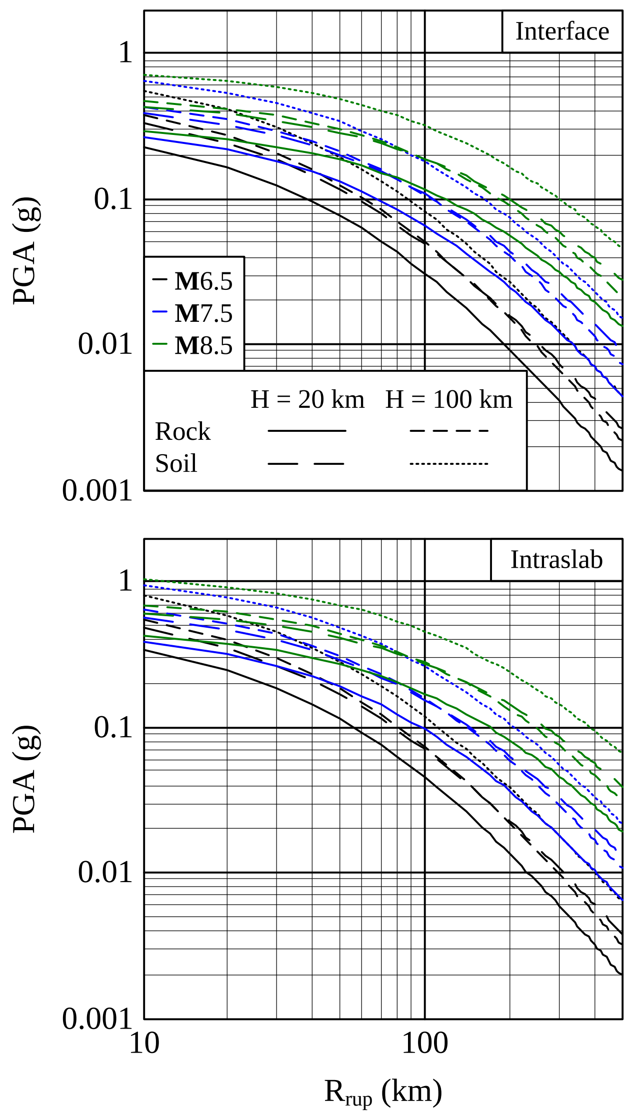


Figure 4-5. PGA as a function of distance for various conditions.

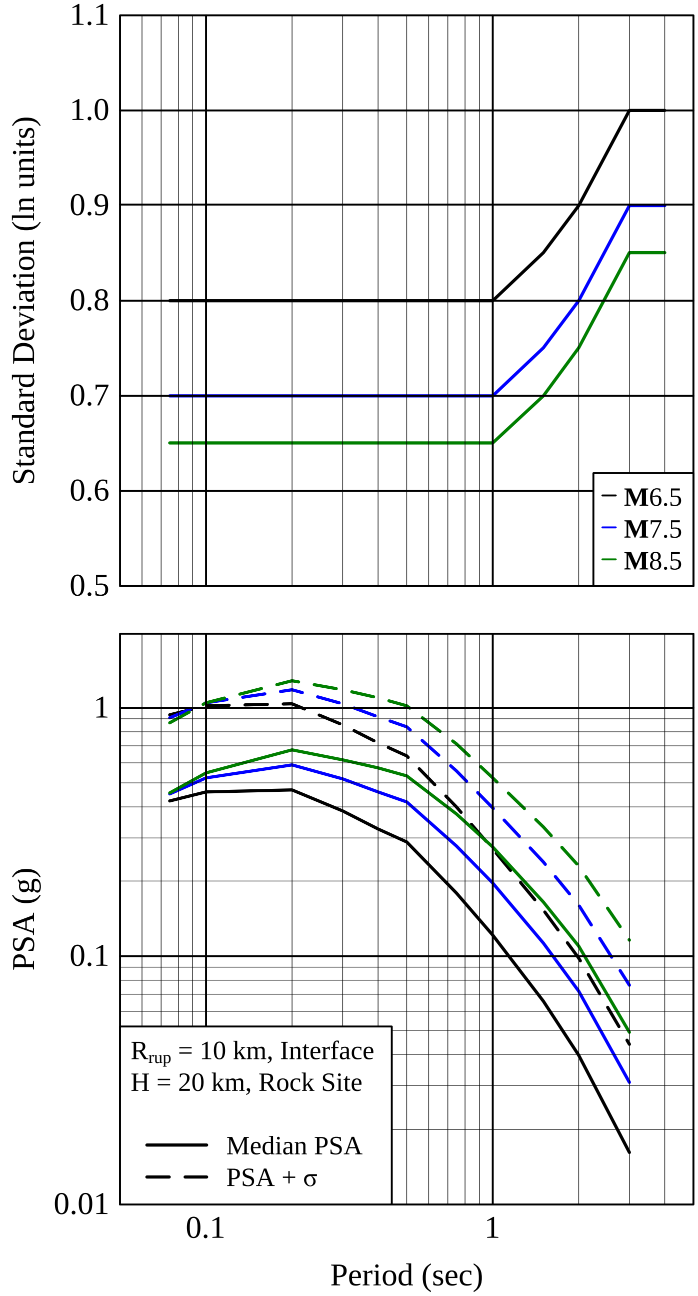


Figure 4-6. Above: standard deviation as a function of period for different magnitudes. Below: Example of application of median PSA plus one standard deviation at different magnitudes.

4.1.5 Database

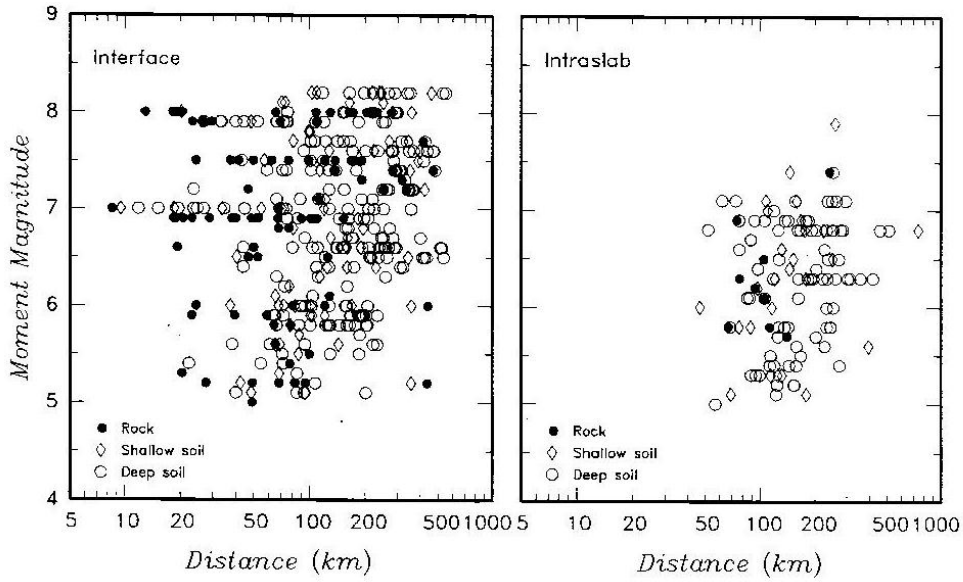


Figure 4-7. Scattergram of subduction zone PGA data set.

4.1.6 MATLAB Code

```
% by Kathryn A. Gunberg 4/28/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Youngs, Chiou, Silva and Humphrey attenuation equation, 1997
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0 for PGA
% M         = Moment magnitude
% H         = Focal depth (km)
% F         = Fault type: 0 for interface events, 1 for intraslab
% Rrup      = Closest distance to rupture plane (km)
% S         = 0 for rock, 1 for soil
% ----------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = YCSH_1997(T, M, H, F, Rrup, S)
% Coefficients
if S == 0
    period   = [0.000   0.075   0.100   0.200   0.300   0.400   0.500   0.750   1.000   1.500...
                2.000   3.000];
    c1   = [0.000   1.275   1.188   0.722   0.246   -0.115  -0.400  -1.149  -1.736  -2.634...
            -3.328  -4.511];
    c2   = [0.000   0.000   -0.0011 -0.0027 -0.0036 -0.0043 -0.0048 -0.0057 -0.0064 -0.0073...
            -0.0080 -0.0089];
    c3   = [-2.552  -2.707  -2.655  -2.528  -2.454  -2.401  -2.360  -2.286  -2.234  -2.160...
            -2.107  -2.033];
else
    period   = [0.000   0.075   0.100   0.200   0.300   0.400   0.500   0.750   1.000   1.500...
                2.000   3.000   4.000];
    c1   = [0.000   2.400   2.516   1.549   0.793   0.144   -0.438  -1.704  -2.870  -5.101...
            -6.433  -6.672  -7.618];
    c2   = [0.000   -0.0019 -0.0019 -0.0019 -0.0020 -0.0020 -0.0035 -0.0048 -0.0066 -0.0114...
            -0.0164 -0.0221 -0.0235];
    c3   = [-2.329  -2.697  -2.697  -2.464  -2.327  -2.230  -2.140  -1.952  -1.785  -1.470...
            -1.290  -1.347  -1.272];
end
c4  =  [1.45    1.45    1.45    1.45    1.45    1.45    1.45    1.45    1.45    1.50    1.55...
        1.65    1.65];
c5  =  -0.1;
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = YCSH_1997(T_low, M, H, F, Rrup, S);
    [sa_hi,  sigma_hi]  = YCSH_1997(T_hi,  M, H, F, Rrup, S);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(period == T);
    if S == 0
        Sa = exp(0.2418 + 1.414*M + c1(i) + c2(i)*(10 - M)^3 + c3(i)*log(Rrup + ...
                 1.7818*exp(0.554*M)) + 0.00607*H + 0.3846*F);
    else
        Sa = exp(-0.6687 + 1.438*M + c1(i) + c2(i)*(10 - M)^3 + c3(i)*log(Rrup + ...
                 1.097*exp(0.617*M)) + 0.00648*H + 0.3643*F);
    end
    sigma = c4(i) + c5*min(M,8);
end
```

4.2 Gregor, Silva, Wong and Youngs - 2002

4.2.1 Reference

Gregor, N. J., W. J. Silva, I. G. Wong, R. R. Youngs (2002). Ground-Motion Attenuation Relationships for Cascadia Subduction Zone Megathrust Earthquakes Based on a Stochastic Finite-Fault Model, *Bulletin of the Seismological Society of America* **92**, 1923-1932.

Gregor, N. J. (2009). Pacific Engineering and Analysis, El Cerrito, CA. Written communication.

4.2.2 Abstract

Using a stochastic finite-fault ground motion model for Cascadia subduction zone megathrust earthquakes, empirical ground-motion attenuation equations were developed for peak ground acceleration (PGA, in g) and 5%-damped spectral values (PSA, in g) for periods ranging from 0.01 to 5 sec. for both rock and soil sites. The model is applicable earthquakes between M8.0 and M9.0, and distances from 10 to 500 km.

4.2.3 Attenuation Relationship

The spectral acceleration is a function of:

T – Period (sec), use 0 for PGA
M – Moment magnitude
R_{rup} – Closest distance to rupture plane (km)
S – 0 for rock sites, 1 for soil sites

$$\ln(Sa) = c_1 + c_2M + (c_3 + c_4M)\ln\left(R_{rup} + e^{c_5}\right) + c_6(M - 10)^3$$

Coefficients

Table 4-4. Coefficients for rock sites.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	$\sigma_{Param.}$	σ_{Model}	σ_{Total}
PGA	21.0686	-1.7712	-5.0631	0.4153	4.2	0.0017	0.6083	0.3926	0.7240
0.010	20.9932	-1.7658	-5.0404	0.4132	4.2	0.0226	0.6031	0.3926	0.7195
0.020	21.072	-1.772	-5.0529	0.4142	4.2	0.0025	0.6036	0.3926	0.7195
0.025	21.152	-1.779	-5.0663	0.4154	4.2	0.0023	0.6042	0.3983	0.7235
0.032	21.366	-1.797	-5.1036	0.4187	4.2	0.0017	0.6062	0.3926	0.7221
0.040	17.525	-1.339	-4.8602	0.3868	4.2	-0.0318	0.5836	0.3818	0.6969
0.050	19.347	-1.519	-4.9731	0.3960	4.2	-0.0155	0.5908	0.3925	0.7086
0.056	20.774	-1.625	-5.1875	0.4118	4.3	-0.0155	0.5974	0.4052	0.7215
0.063	21.331	-1.672	-5.2561	0.4173	4.3	-0.0146	0.6028	0.4132	0.7302
0.071	24.221	-1.924	-5.6250	0.4478	4.4	-0.0071	0.6116	0.4042	0.7326
0.083	24.950	-1.979	-5.6696	0.4493	4.4	-0.0018	0.6337	0.4584	0.7815
0.100	30.005	-2.349	-6.3862	0.5009	4.7	-0.0019	0.6448	0.4668	0.7954
0.125	39.719	-3.090	-7.8541	0.6161	5.1	-0.0064	0.6654	0.5461	0.8605
0.143	43.414	-3.385	-8.3122	0.6513	5.2	-0.0001	0.6769	0.5225	0.8544
0.167	39.579	-2.957	-7.9723	0.6139	5.2	-0.0264	0.6810	0.5050	0.8478
0.200	39.345	-3.087	-7.6002	0.5972	5.1	0.0060	0.7034	0.5089	0.8679
0.250	37.690	-2.960	-7.3790	0.5842	5.1	-0.0023	0.7121	0.4539	0.8444
0.333	34.787	-2.899	-6.7855	0.5616	4.9	0.0256	0.7372	0.4764	0.8776
0.400	33.393	-2.776	-6.9595	0.5863	4.9	-0.0039	0.7110	0.5187	0.8801
0.500	29.159	-2.424	-6.2114	0.5216	4.7	0.0161	0.6745	0.4382	0.8039
0.769	15.279	-1.220	-4.3240	0.3618	3.9	-0.0011	0.6111	0.5611	0.8295
1.000	6.528	-0.406	-3.1991	0.2589	3.2	-0.0225	0.5898	0.4751	0.7567
1.667	7.467	-0.676	-2.6465	0.2193	2.8	0.0416	0.4931	0.4889	0.6943
2.000	8.657	-0.851	-2.7398	0.2339	2.8	0.0370	0.4666	0.4247	0.6305
2.500	6.637	-0.651	-2.3124	0.1879	2.8	0.0364	0.4163	0.5198	0.6657
5.000	8.013	-0.943	-2.4087	0.2154	2.3	0.0647	0.3931	0.6656	0.7730

Table 4-5. Coefficients for soil sites.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	$\sigma_{Param.}$	σ_{Model}	σ_{Total}
PGA	23.8613	-2.2742	-4.8803	0.4399	4.7	0.0366	0.3760	0.3926	0.5436
0.010	25.4516	-2.4206	-5.1071	0.4605	4.8	0.0372	0.3742	0.3926	0.5422
0.020	25.4339	-2.4185	-5.1044	0.4602	4.8	0.0370	0.3742	0.3926	0.5422
0.025	25.4200	-2.4168	-5.1026	0.4600	4.8	0.0369	0.3743	0.3983	0.5464
0.032	25.3849	-2.4127	-5.0977	0.4594	4.8	0.0366	0.3743	0.3926	0.5422
0.040	22.7042	-2.1004	-4.9006	0.4353	4.8	0.0164	0.3590	0.3818	0.5241
0.050	23.2948	-2.1619	-4.8855	0.4332	4.8	0.0263	0.3592	0.3925	0.5319
0.056	23.2165	-2.1528	-4.8744	0.4319	4.8	0.0255	0.3598	0.4052	0.5413
0.063	24.7067	-2.2814	-5.0947	0.4509	4.9	0.0245	0.3607	0.4132	0.5480
0.070	24.9425	-2.3045	-5.0672	0.4476	4.9	0.0295	0.3609	0.4042	0.5413
0.083	26.5395	-2.4402	-5.3025	0.4677	5.0	0.0276	0.3617	0.4584	0.5835
0.100	29.9693	-2.7254	-5.8054	0.5098	5.2	0.0226	0.3654	0.4668	0.5926
0.125	35.6660	-3.1853	-6.6251	0.5769	5.5	0.0123	0.3821	0.5461	0.6665
0.143	50.7368	-4.5292	-8.7213	0.7649	5.9	0.0108	0.3923	0.5225	0.6532
0.167	55.6402	-4.9662	-9.5555	0.8435	6.0	-0.0070	0.3927	0.5050	0.6393
0.200	75.8218	-6.8396	-12.0687	1.0753	6.3	0.0096	0.4231	0.5089	0.6618
0.250	100.3357	-9.0324	-15.3511	1.3731	6.6	-0.0043	0.4472	0.4539	0.6371
0.330	71.7967	-6.4990	-11.6056	1.0415	6.2	0.0102	0.4324	0.4764	0.6431
0.400	67.3720	-6.1755	-11.1567	1.0167	6.1	0.0035	0.4243	0.5187	0.6699
0.500	56.0088	-5.1176	-9.5083	0.8632	5.9	0.0164	0.4305	0.4382	0.6139
0.770	26.3013	-2.4482	-5.3818	0.4957	4.8	0.0259	0.4601	0.5611	0.7256
1.000	17.2330	-1.5506	-4.3287	0.3930	4.2	0.0133	0.4599	0.4751	0.6606
1.670	11.9971	-1.1180	-2.9451	0.2639	3.7	0.0538	0.4781	0.4889	0.6837
2.000	17.9124	-1.7505	-3.8150	0.3574	4.1	0.0583	0.4628	0.4247	0.6276
2.500	16.1666	-1.5091	-3.7101	0.3344	4.1	0.0473	0.4193	0.5198	0.6676
5.000	7.4856	-0.8360	-2.0627	0.1779	-0.2	0.0821	0.4802	0.6656	0.8207

4.2.4 Calibration Plots

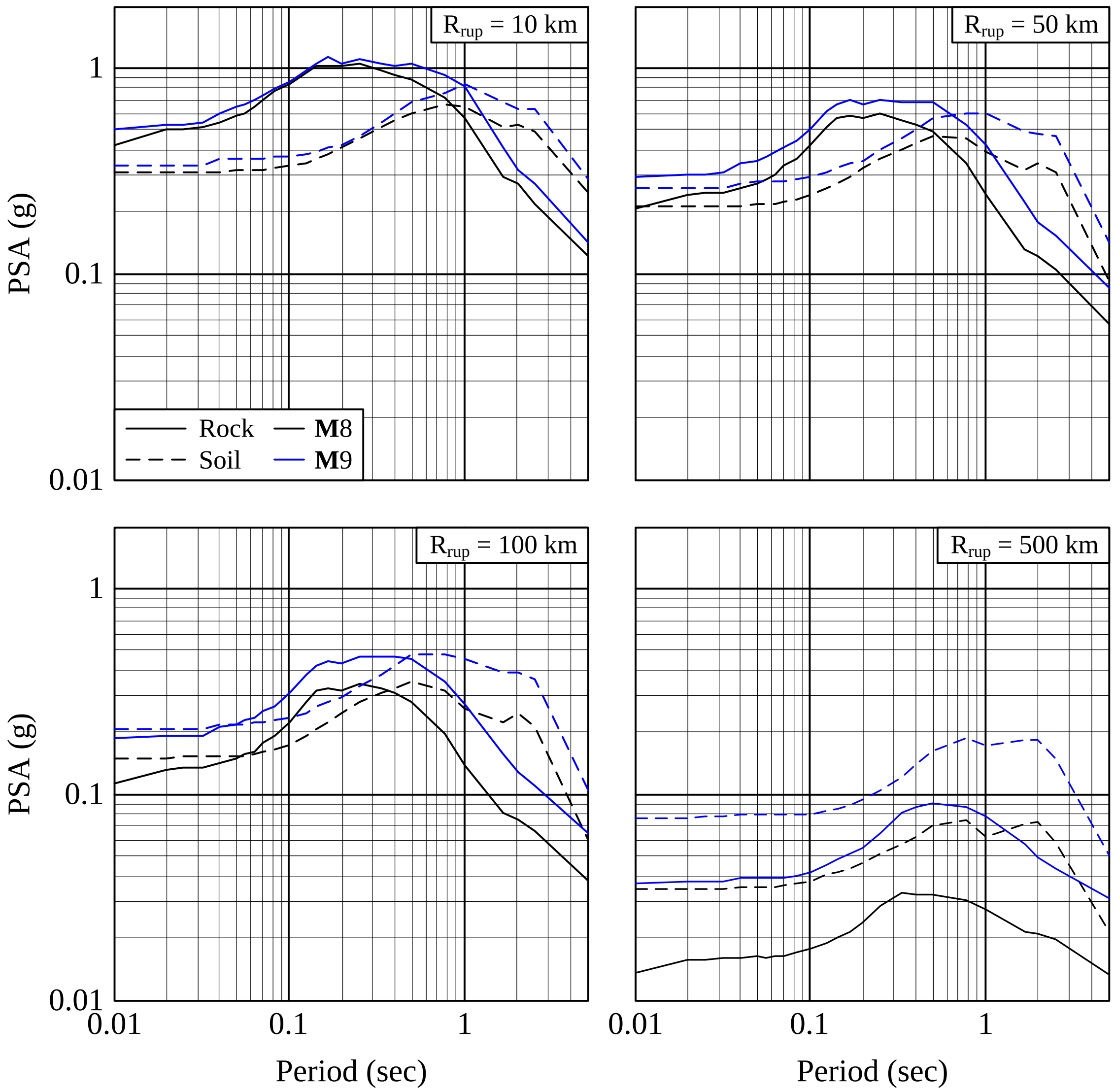


Figure 4-8. PSA as a function of period for given conditions.

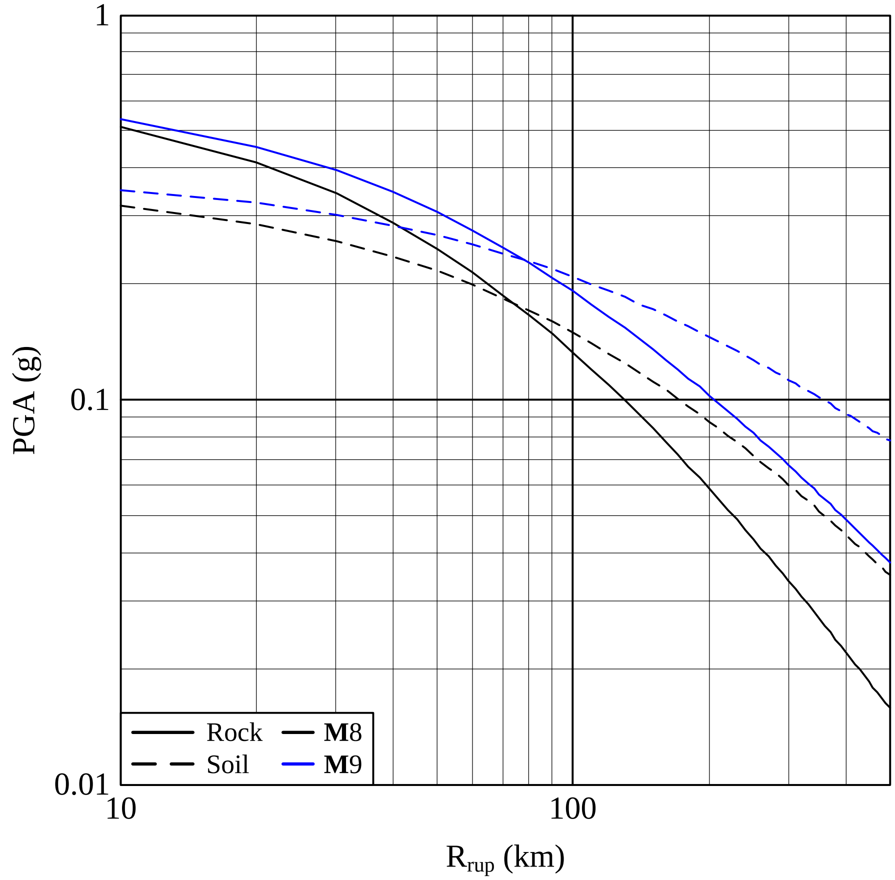


Figure 4-9. PGA as a function of distance for given conditions.

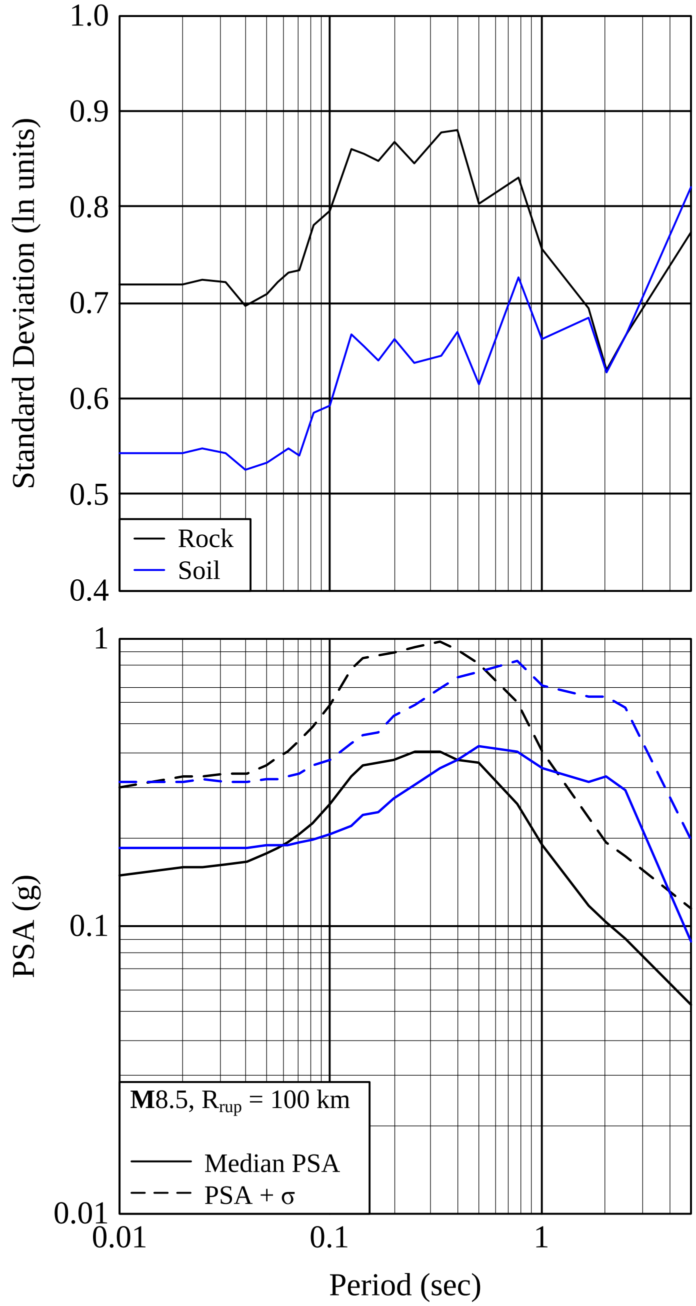


Figure 4-10. Above: standard devitation as a fucnction of period for rock and soil. Below: Example of application of median PSA plus one standard deviation.

4.2.5 Database

This study was based on a stochastic finite-fault ground motin model similating subduction zone megathrust events of **M** 8.0, 8.5 and 9.0 on the Cascadia subduction zone.

4.2.6 MATLAB Code

```
% by Kathryn A. Gunberg 4/30/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Gregor, Silva, Wong and Youngs attenuation equation, 2002
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), use 0 fo PGA
% M         = Magnitude
% Rrup      = Closest distance to rupture plane (km)
% S         = 0 for rock, 1 for soil
% --------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = GSWY_2002(T, M, Rrup, S)
% Coefficients
period   = [0.000   0.010   0.020   0.025   0.032   0.040   0.050   0.056   0.063   0.071...
            0.083   0.100   0.125   0.143   0.167   0.200   0.250   0.333   0.400   0.500...
            0.769   1.000   1.667   2.000   2.500   5.000];
if S == 0
    c1   = [21.0686 20.9932 21.072  21.152  21.366  17.525  19.347  20.774  21.331  24.221...
            24.950  30.005  39.719  43.414  39.579  39.345  37.690  34.787  33.393  29.159...
            15.279  6.528   7.467   8.657   6.637   8.013];
    c2   = [-1.7712 -1.7658 -1.772  -1.779  -1.797  -1.339  -1.519  -1.625  -1.672  -1.924...
            -1.979  -2.349  -3.090  -3.385  -2.957  -3.087  -2.960  -2.899  -2.776  -2.424...
            -1.220  -0.406  -0.676  -0.851  -0.651  -0.943];
    c3   = [-5.0631 -5.0404 -5.0529 -5.0663 -5.1036 -4.8602 -4.9731 -5.1875 -5.2561 -5.6250...
            -5.6696 -6.3862 -7.8541 -8.3122 -7.9723 -7.6002 -7.3790 -6.7855 -6.9595 -6.2114...
            -4.3240 -3.1991 -2.6465 -2.7398 -2.3124 -2.4087];
    c4   = [0.4153  0.4132  0.4142  0.4154  0.4187  0.3868  0.3960  0.4118  0.4173  0.4478...
            0.4493  0.5009  0.6161  0.6513  0.6139  0.5972  0.5842  0.5616  0.5863  0.5216...
            0.3618  0.2589  0.2193  0.2339  0.1879  0.2154];
    c5   = [4.2 4.2 4.2 4.2 4.2 4.2 4.2 4.3 4.3 4.4 4.4 4.7 5.1 5.2 5.2 5.1 5.1 4.9 4.9 4.7...
            3.9 3.2 2.8 2.8 2.8 2.3];
    c6   = [0.0017  0.0226  0.0025  0.0023  0.0017  -0.0318 -0.0155 -0.0155 -0.0146 -0.0071...
            -0.0018 -0.0019 -0.0064 -0.0001 -0.0264 0.0060  -0.0023 0.0256  -0.0039 0.0161...
            -0.0011 -0.0225 0.0416  0.0370  0.0364  0.0647];
    sigp = [0.6083  0.6031  0.6036  0.6042  0.6062  0.5836  0.5908  0.5974  0.6028  0.6116...
            0.6337  0.6448  0.6654  0.6769  0.6810  0.7034  0.7121  0.7372  0.7110  0.6745...
            0.6111  0.5898  0.4931  0.4666  0.4163  0.3931];
    sigm = [0.3926  0.3926  0.3926  0.3983  0.3926  0.3818  0.3925  0.4052  0.4132  0.4042...
            0.4584  0.4668  0.5461  0.5225  0.5050  0.5089  0.4539  0.4764  0.5187  0.4382...
            0.5611  0.4751  0.4889  0.4247  0.5198  0.6656];
    sigt = [0.7240  0.7195  0.7195  0.7235  0.7221  0.6969  0.7086  0.7215  0.7302  0.7326...
            0.7815  0.7954  0.8605  0.8544  0.8478  0.8679  0.8444  0.8776  0.8801  0.8039...
            0.8295  0.7567  0.6943  0.6305  0.6657  0.7730];
else
    c1   = [23.8613 25.4516 25.4339 25.4200 25.3849 22.7042 23.2948 23.2165 24.7067 24.9425...
            26.5395 29.9693 35.6660 50.7368 55.6402 75.8218 100.3357    71.7967 67.3720...
            56.0088 26.3013 17.2330 11.9971 17.9124 16.1666 7.4856];
    c2   = [-2.2742 -2.4206 -2.4185 -2.4168 -2.4127 -2.1004 -2.1619 -2.1528 -2.2814 -2.3045...
            -2.4402 -2.7254 -3.1853 -4.5292 -4.9662 -6.8396 -9.0324 -6.4990 -6.1755 -5.1176...
            -2.4482 -1.5506 -1.1180 -1.7505 -1.5091 -0.8360];
    c3   = [-4.8803 -5.1071 -5.1044 -5.1026 -5.0977 -4.9006 -4.8855 -4.8744 -5.0947 -5.0672...
            -5.3025 -5.8054 -6.6251 -8.7213 -9.5555 -12.0687    -15.3511    -11.6056...
            -11.1567    -9.5083 -5.3818 -4.3287 -2.9451 -3.8150 -3.7101 -2.0627];
    c4   = [0.4399  0.4605  0.4602  0.4600  0.4594  0.4353  0.4332  0.4319  0.4509  0.4476...
            0.4677  0.5098  0.5769  0.7649  0.8435  1.0753  1.3731  1.0415  1.0167  0.8632...
            0.4957  0.3930  0.2639  0.3574  0.3344  0.1779];
    c5   = [4.7 4.8 4.8 4.8 4.8 4.8 4.8 4.8 4.9 4.9 5.0 5.2 5.5 5.9 6.0 6.3 6.6 6.2 6.1 5.9...
            4.8 4.2 3.7 4.1 4.1 -0.2];
    c6   = [0.0366  0.0372  0.0370  0.0369  0.0366  0.0164  0.0263  0.0255  0.0245  0.0295...
            0.0276  0.0226  0.0123  0.0108  -0.0070 0.0096  -0.0043 0.0102  0.0035  0.0164...
            0.0259  0.0133  0.0538  0.0583  0.0473  0.0821];
```

```
    sigp = [0.3760  0.3742  0.3742  0.3743  0.3743  0.3590  0.3592  0.3598  0.3607  0.3609...
            0.3617  0.3654  0.3821  0.3923  0.3927  0.4231  0.4472  0.4324  0.4243  0.4305...
            0.4601  0.4599  0.4781  0.4628  0.4193  0.4802];
    sigm = [0.3926  0.3926  0.3926  0.3983  0.3926  0.3818  0.3925  0.4052  0.4132  0.4042...
            0.4584  0.4668  0.5461  0.5225  0.5050  0.5089  0.4539  0.4764  0.5187  0.4382...
            0.5611  0.4751  0.4889  0.4247  0.5198  0.6656];
    sigt = [0.5436  0.5422  0.5422  0.5464  0.5422  0.5241  0.5319  0.5413  0.5480  0.5413...
            0.5835  0.5926  0.6665  0.6532  0.6393  0.6618  0.6371  0.6431  0.6699  0.6139...
            0.7256  0.6606  0.6837  0.6276  0.6676  0.8207];
end
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = GSWY_2002(T_low, M, Rrup, S);
    [sa_hi,  sigma_hi]  = GSWY_2002(T_hi,  M, Rrup, S);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(period == T);
    Sa = exp(c1(i) + c2(i)*M + (c3(i) + c4(i)*M)*log(Rrup + exp(c5(i))) + c6(i)*(M-10)^3);
    sigma = sigt(i);
end
```

4.3 Atkinson and Boore - 2003

4.3.1 References

Atkinson, G. M. and D. M. Boore (2003). Empirical Ground-Motion Relations for Subduction-Zone Earthquakes and Their Application to Cascadia and Other Regions, *Bulletin of the Seismological Society of America* **93**, 1703-1729.

Atkinson, G. M. and D. M. Boore (2008). Erratum to Empirical Ground-Motion Relations for Subduction-Zone Earthquakes and Their Application to Cascadia and Other Regions, *Bulletin of the Seismological Society of America* **98**, 2567-2569.

4.3.2 Abstract

Using 1200 records from worldwide subduction zone earthquakes, empirical ground-motion attenuation equations were developed for peak ground acceleration (PGA, in cm/s^2) and 5%-damped spectral values (PSA, in cm/s^2) for periods ranging from 0.04 to 3 sec. for both rock and soil sites. The model is applicable for earthquakes greater than M5.0, and distances out to a couple hundred kilometers. Notes: when calculating PSA for 0.2 or 0.4 seconds, please see the "changes due to erratum" portion of section 4.3.3. The MATLAB code converts all accelerations to g's.

4.3.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA
- M – Moment magnitude
- G – Region: 1 for Cascadia specific, 2 for Japan specific, 0 otherwise
- H – Focal depth (km) (Note: if H > 100 km, use H = 100 km)
- F – Fault type: 0 for interface (between overriding and subducting plates), 1 for intraslab (within subducting plate)
- R_{rup} – Closest distance to rupture plane (km)
- S – Soil type: 0 for NEHRP site class B sites, 1 for NEHRP C, 2 for NEHRP D, and 3 for NEHRP E

$$\log_{10}(Sa) = fn(M) + c_3 H + c_4 R - g \log_{10} R + c_5 slS_C + c_6 slS_D + c_7 slS_E$$

where:

for interface events, if M > 8.5, use 8.5, for intraslab events, if M > 8, use 8

$$fn(M) = c_1 + c_2 M$$

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

where:

$$\Delta = 0.00724 \times 10^{0.507M}$$

$$S_C = \begin{cases} 1 & for\ NEHRP\ C\ soils \\ 0 & otherwise \end{cases}$$

$$S_D = \begin{cases} 1 & for\ NEHRP\ D\ soils \\ 0 & otherwise \end{cases}$$

$$S_E = \begin{cases} 1 & for\ NEHRP\ E\ soils \\ 0 & otherwise \end{cases}$$

$$g = \begin{cases} 10^{1.2-0.18M} & for\ interface\ events \\ 10^{0.301-0.01M} & for\ intraslab\ events \end{cases}$$

$$sl = \begin{cases} 1 & for\ PGA_{rx} \leq 100\ cm/s^2\ OR\ \ T \geq 1\ sec \\ 1 - \left(\frac{1}{T} - 1\right)\frac{PGA_{rx} - 100}{400} & for\ 100 < PGA_{rx} < 500 cm/s^2\ AND\ 1 > T > 0.5\ sec \\ 1 - \left(\frac{1}{T} - 1\right) & for\ PGA_{rx} \geq 500 cm/s^2\ AND\ 1 > T > 0.5\ sec \\ 1 - \frac{PGA_{rx} - 100}{400} & for\ 100 < PGA_{rx} < 500 cm/s^2\ AND\ T \leq 0.5\ sec \\ 0 & for\ PGA_{rx} \geq 500 cm/s^2\ AND\ T \leq 0.5\ sec \end{cases}$$

where:

PGA_{rx} is the median predicted PGA on rock (S = 0)

Changes due to erratum:

An error was made in the original publication regarding the PSA at periods of 0.2 sec and 0.4 sec. To correct for this error, when calculating PSA for either of these periods, PSA for both periods need to be calculated and appropriate weighting factors applied. The correction does not apply to the Cascadia region or to intraslab events. Please see the equations below for how to correct for the error.

$$\log[PSA(0.2\ sec)_{corrected}] = 0.333 \log[PSA(0.2\ sec)_{AB03}] + 0.667 \log[PSA(0.4\ sec)_{AB03}]$$

$$\log[PSA(0.4\ sec)_{corrected}] = 0.333 \log[PSA(0.4\ sec)_{AB03}] + 0.667 \log[PSA(0.2\ sec)_{AB03}]$$

Coefficients

Table 4-6. Coefficients with specific c_1 adjustments for the Cascadia and Japan regions.

T (sec)	Interface										Intraslab										c_5	c_6	c_7
	c_1			c_2	c_3	c_4	σ	σ_{reg}	σ_1	σ_2	c_1			c_2	c_3	c_4	σ	σ_{reg}	σ_1	σ_2			
	All	Casc.	Japan								All	Casc.	Japan										
3.00	2.3010	2.36	2.27	0.02237	0.00012	0.00000	0.36	0.36	0.31	0.18	-3.70012	-3.64	-3.73	1.11690	0.00615	-0.00045	0.30	0.23	0.29	0.08	0.10	0.25	0.36
2.00	2.1907	2.33	2.14	0.07148	0.00224	0.00000	0.34	0.33	0.29	0.18	-2.39234	-2.25	-2.44	0.99640	0.00364	-0.00118	0.30	0.23	0.28	0.11	0.10	0.25	0.40
1.00	2.1442	2.18	2.18	0.13450	0.00521	-0.00110	0.34	0.31	0.28	0.19	-1.02133	-0.98	-0.98	0.87890	0.00130	-0.00173	0.29	0.25	0.27	0.11	0.10	0.30	0.55
0.40	2.5249	2.50	2.58	0.14770	0.00728	-0.00235	0.29	0.26	0.25	0.15	0.005445	-0.01	0.07	0.77270	0.00173	-0.00178	0.28	0.26	0.26	0.10	0.13	0.37	0.38
0.20	2.6638	2.54	2.84	0.12386	0.00884	-0.00280	0.28	0.28	0.25	0.13	0.51589	0.40	0.70	0.69186	0.00572	-0.00192	0.28	0.23	0.26	0.10	0.15	0.27	0.25
0.10	2.7789	2.50	2.95	0.09841	0.00974	-0.00287	0.27	0.30	0.25	0.10	0.43928	0.16	0.61	0.66675	0.01080	-0.00219	0.28	0.25	0.27	0.07	0.15	0.23	0.20
0.04	2.8753	2.60	3.05	0.07052	0.01004	-0.00278	0.26	0.26	0.22	0.14	0.50697	0.23	0.68	0.63273	0.01275	-0.00234	0.25	0.23	0.24	0.07	0.15	0.20	0.20
PGA	2.9910	2.79	3.14	0.03525	0.00759	-0.00206	0.23	0.24	0.20	0.11	-0.04713	-0.25	0.10	0.69090	0.01130	-0.00202	0.27	0.23	0.23	0.14	0.19	0.24	0.29

Note: σ_{reg} only applies for Casc. or Japan regions for the following input parameters: for interface when $M \geq 7.5$ and $R_{rup} < 300$ km, for intraslab when $M \geq 6.5$ and $R_{rup} < 100$ km.

4.3.4 Calibration Plots

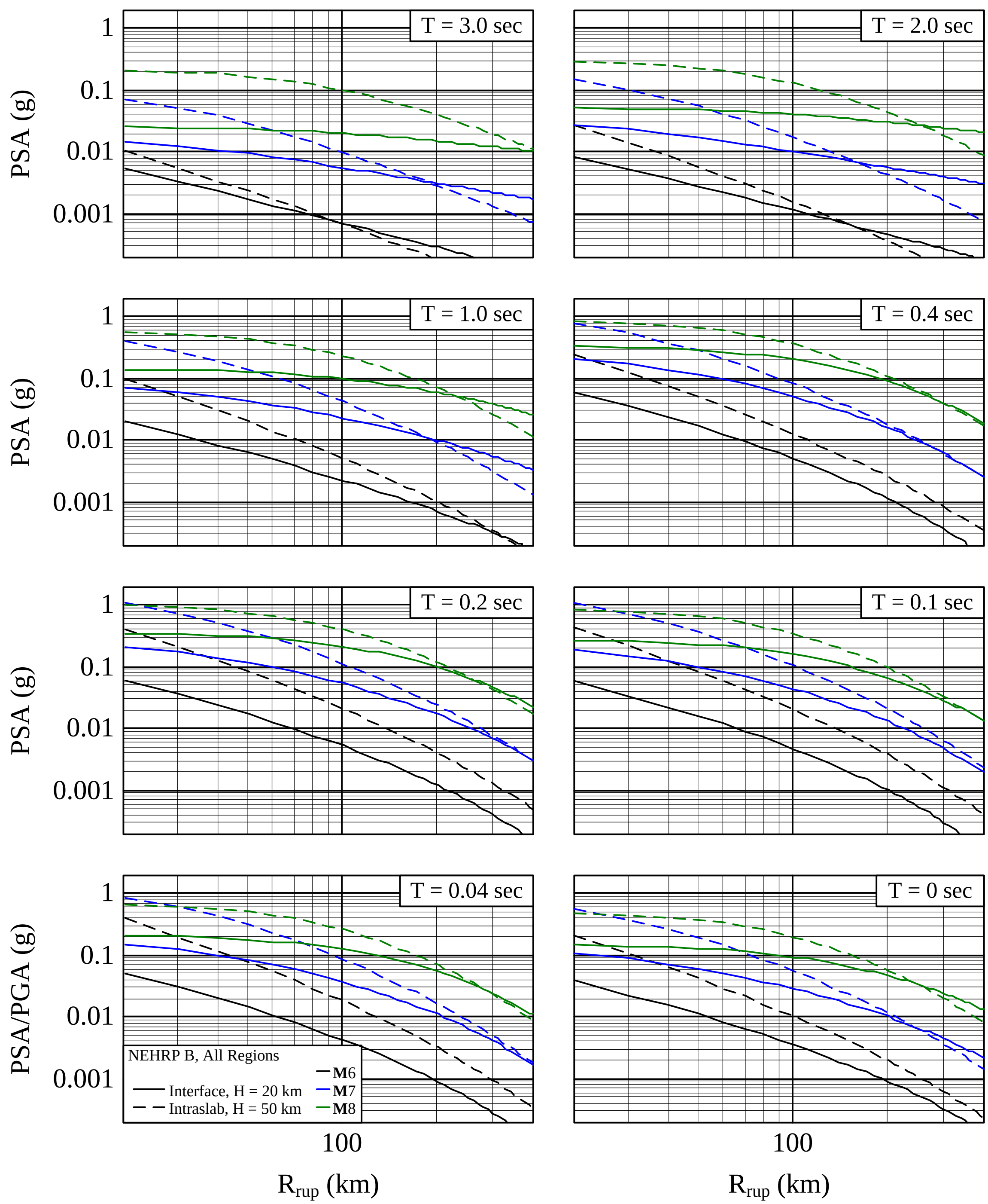


Figure 4-11. Spectral acceleration as a function of distance for given conditions.

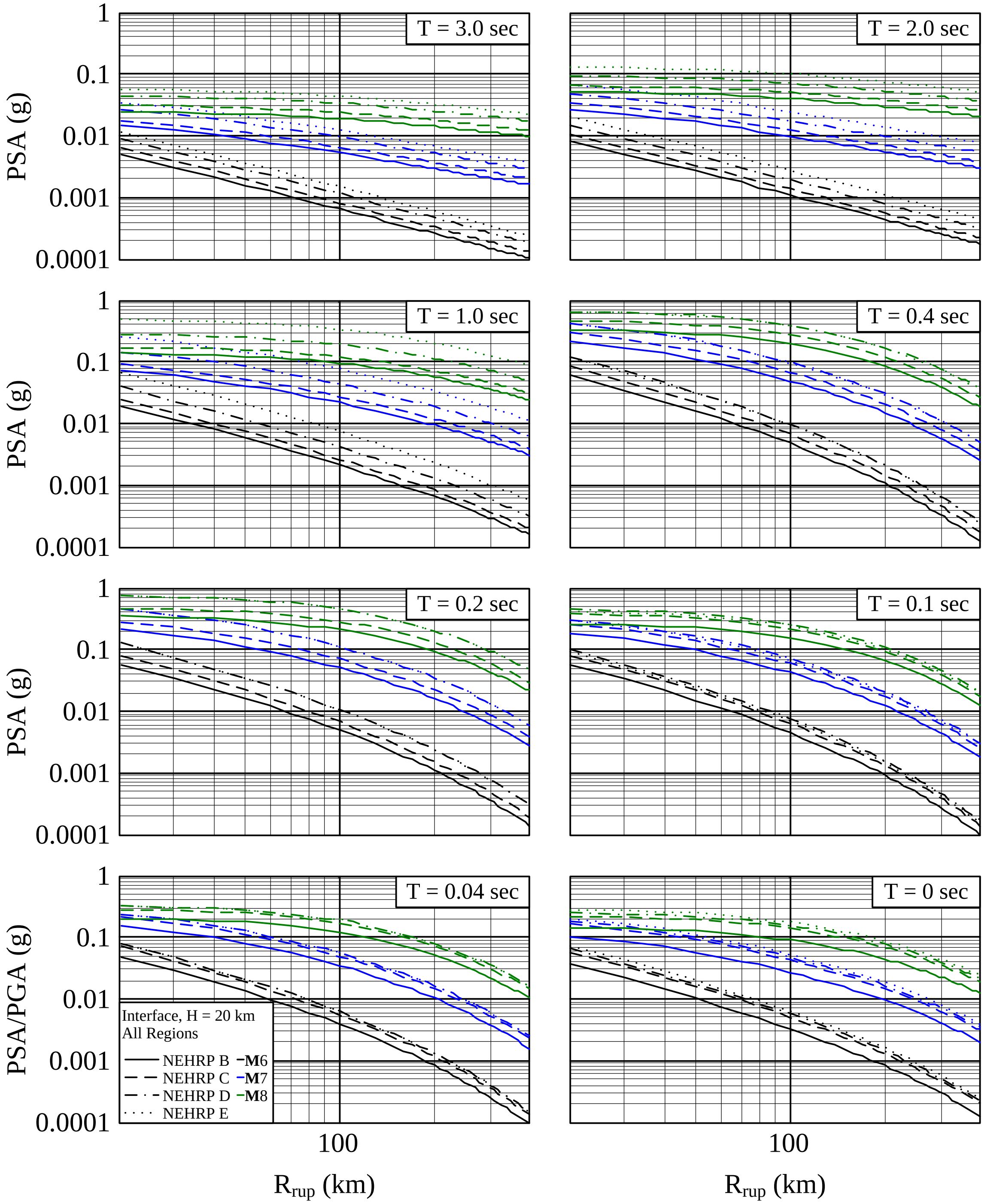


Figure 4-12. Spectral acceleration as a function of distance for given conditions.

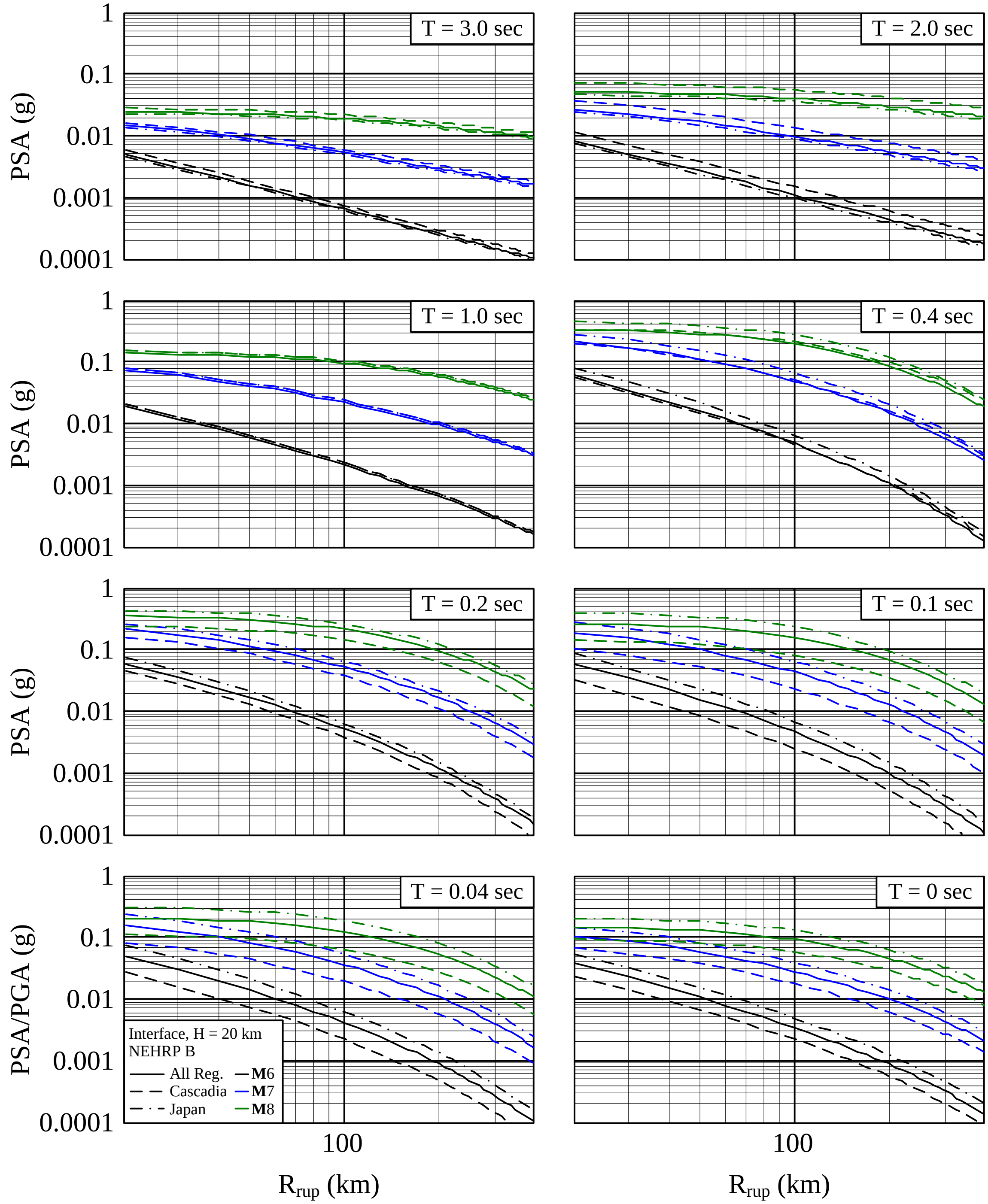


Figure 4-13. Spectral acceleration as a function of distance for given conditions.

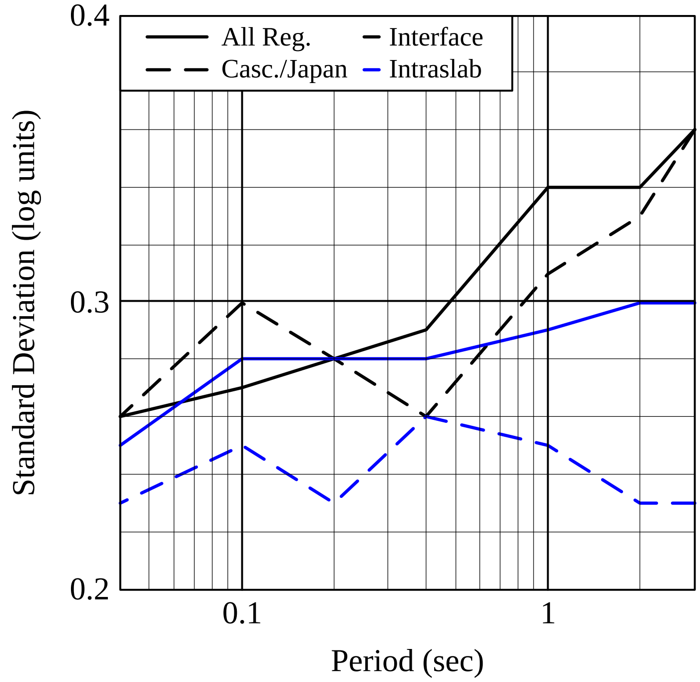


Figure 4-14. Standard deviation as a function of period for difference cases.

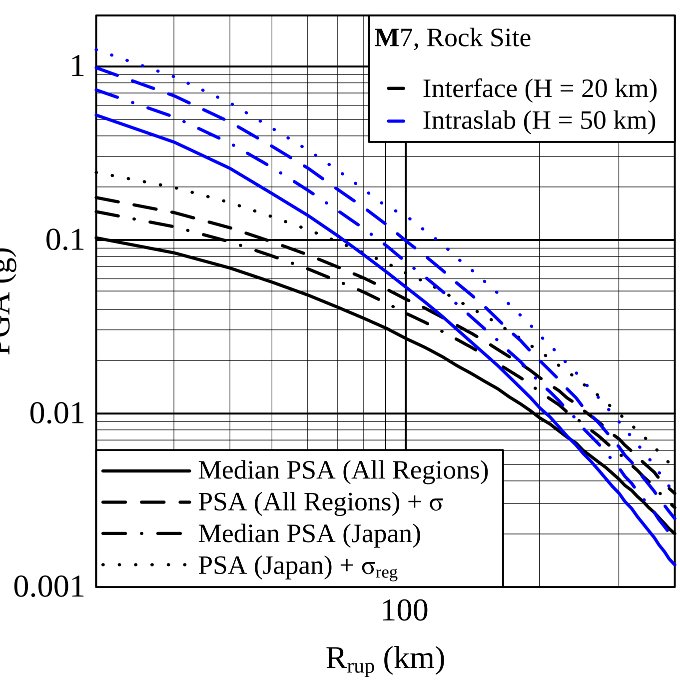


Figure 4-15. Example of application of median PSA plus one standard deviation.

4.3.5 Database

This database is four times larger than the previous largest database used for attenuation relationship development in subduction zone regions. The database includes ground motions from subduction zone earthquakes recorded worldwide.

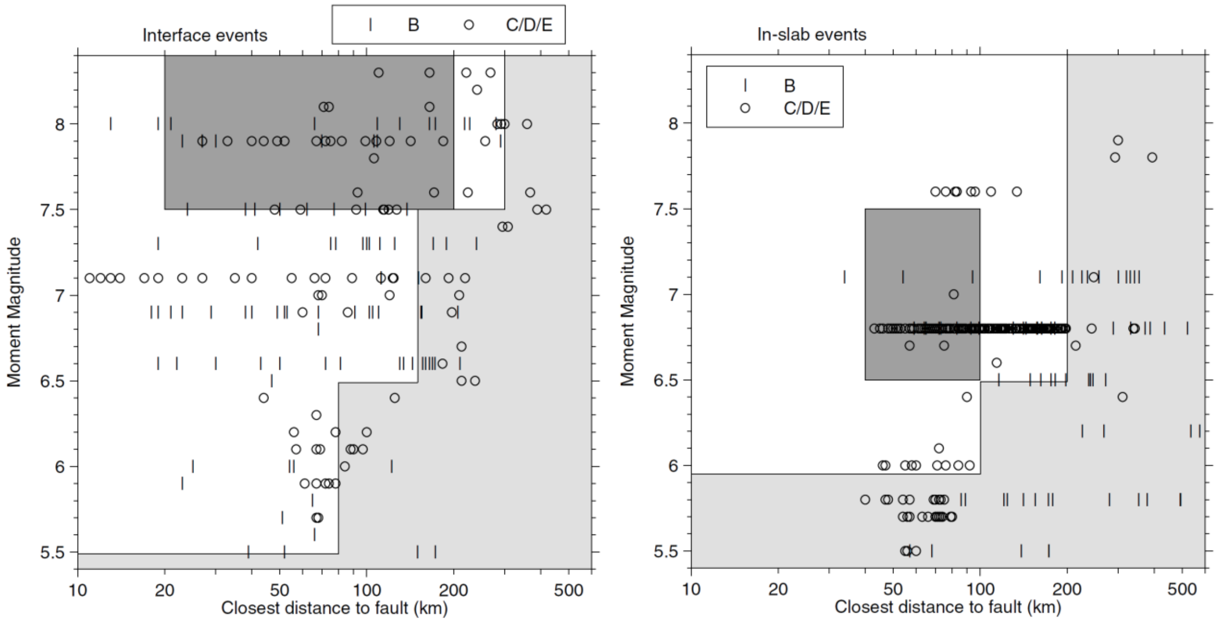


Figure 4-16. Database for subduction –zone earthquakes. The left frame shows data available for interface events, by NEHRP site class; the right frame shows data available for in-slab events, by NEHRP site class. Data of **M** < 5.4 are not shown. The magnitude-distance range of most engineering interest is shaded dark gray. Magnitude-distance cutoffs imposed on final regressions are shaded light gray. KNET data that are believed to be inreliable at higher frequencies (moderate magnitudes at large distances) are not included.

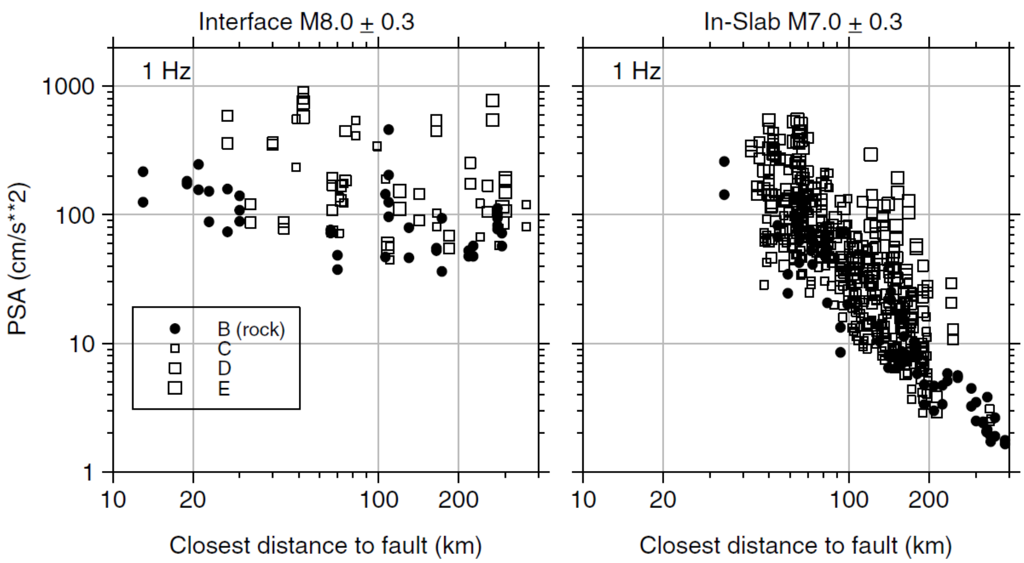


Figure 4-17. Illustration of the difference in attenuation behavior of interface events versus intraslab events. Plot shows 1-Hz PSA data for interface events of M8 ± 0.3 (left) in comparison to 1-Hz PSA data for intraslab events of M7 ± 0.3 (right).

4.3.6 MATLAB Code

```
% by Kathryn A. Gunberg 4/30/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Atkinson and Boore attenuation equation, 2003
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), use 0 for PGA
% M         = Moment magnitude
% G         = Region: 1 for Cascadia, 2 for Japan, 0 otherwise
% H         = Focal depth (km)
% F         = Fault type: 0 for interface, 1 for intraslab
% Rrup      = Closest distance to rupture plane (km)
% S         = 0 for NEHRP B, 1 for C, 2 for D, 3 for E
% E         = equal to 1 for T = 0.2 or 0.4, 0 otherwise
% ---------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = AB_2003(T, M, G, H, F, Rrup, S, E)
% Coefficients
period      = [3.0     2.0     1.0     0.4     0.2     0.1     0.04    0.0];
if F == 0
    if G == 0
        c1   = [2.3010  2.1907  2.1442  2.5249  2.6638  2.7789  2.8753  2.9910];
    elseif G == 1
        c1   = [2.36    2.33    2.18    2.50    2.54    2.50    2.60    2.79];
    else
        c1   = [2.27    2.14    2.18    2.58    2.84    2.95    3.05    3.14];
    end
    c2       = [0.02237 0.07148 0.13450 0.14770 0.12386 0.09841 0.07052 0.03525];
    c3       = [0.00012 0.00224 0.00521 0.00728 0.00884 0.00974 0.01004 0.00759];
    c4       = [0.000   0.000   -0.0011 -0.00235 -0.0028 -0.00287 -0.00278 -0.00206];
    sig      = [0.36    0.34    0.34    0.29    0.28    0.27    0.26    0.23];
    sigreg   = [0.36    0.33    0.31    0.26    0.28    0.30    0.26    0.24];
    sig1     = [0.31    0.29    0.28    0.25    0.25    0.25    0.22    0.20];
    sig2     = [0.18    0.18    0.19    0.15    0.13    0.10    0.14    0.11];
else
    if G == 0
        c1   = [-3.70012 -2.39234 -1.02133 0.005445 0.51589 0.43928 0.50697 -0.04713];
    elseif G == 1
        c1   = [-3.64   -2.25   -0.98   -0.01   0.40    0.16    0.23    -0.25];
    else
        c1   = [-3.73   -2.44   -0.98   0.07    0.70    0.61    0.68    0.10];
    end
    c2       = [1.1169  0.9964  0.8789  0.7727  0.69186 0.66675 0.63273 0.6909];
    c3       = [0.00615 0.00364 0.00130 0.00173 0.00572 0.01080 0.01275 0.01130];
    c4       = [-0.00045 -0.00118 -0.00173 -0.00178 -0.00192 -0.00219 -0.00234 -0.00202];
    sig      = [0.30    0.30    0.29    0.28    0.28    0.28    0.25    0.27];
    sigreg   = [0.23    0.23    0.25    0.26    0.23    0.25    0.23    0.23];
    sig1     = [0.29    0.28    0.27    0.26    0.26    0.27    0.24    0.23];
    sig2     = [0.08    0.11    0.11    0.10    0.10    0.07    0.07    0.14];
end
c5       = [0.10    0.10    0.10    0.13    0.15    0.15    0.15    0.19];
c6       = [0.25    0.25    0.30    0.37    0.27    0.23    0.20    0.24];
c7       = [0.36    0.40    0.55    0.38    0.25    0.20    0.20    0.29];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = AB_2003(T_low, M, G, H, F, Rrup, S, E);
    [sa_hi,  sigma_hi]  = AB_2003(T_hi,  M, G, H, F, Rrup, S, E);
    x = [log10(T_low) log10(T_hi)];
    Y_sa = [log10(sa_low) log10 (sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
```

```
    Sa = 10^(interp1(x,Y_sa,log10(T)));
    sigma = interp1(x,Y_sigma,log10(T));
else
    if or(F == 1, G == 1)
        E = 0;
    end
    i = find(period == T);
    if and(and(G ~= 0, F == 0), and(M >= 7.5, Rrup < 300))
        sigma = sigreg(i);
    elseif and(and(G ~= 0, F == 1), and(M >= 6.5, Rrup < 100))
        sigma = sigreg(i);
    else
        sigma = sig(i);
    end
    if F == 0
        M = min(M,8.5);
        g = 10^(1.2 - 0.18*M);
    else
        M = min(M,8);
        g = 10^(0.301 - 0.01*M);
    end
    fnM = c1(i) + c2(i)*M;
    if H > 100
        H = 100;
    end
    D = 0.00724*10^(0.507*M);
    R = sqrt(Rrup^2 + D^2);
    logSarock = fnM + c3(i)*H + c4(i)*R - g*log10(R);
    if and(T == 0, S == 0)
        Sa = 10^(logSarock)/980.665;
        return
    end
    SC = 0;
    SD = 0;
    SE = 0;
    if S == 1
        SC = 1;
    elseif S == 2
        SD = 1;
    elseif S == 3
        SE = 1;
    end
    [PGArx sigPGA] = AB_2003(0, M, G, H, F, Rrup, 0, E);
    if or(PGArx <= 100, T >= 1)
        sl = 1;
    elseif T > 0.5
        if PGArx < 500
            sl = 1 - (1/T - 1)*(PGArx - 100)/400;
        else
            sl = 1 - (1/T - 1);
        end
    else
        if PGArx < 500
            sl = 1 - (PGArx - 100)/400;
        else
            sl = 0;
        end
    end
    if E == 0
        Sa = 10^(logSarock + c5(i)*sl*SC + c6(i)*sl*SD + c7(i)*sl*SE)/980.665;
    elseif T == 0.4
        Sa = 10^(0.333*log10(AB_2003(0.4, M, G, H, F, Rrup, S, 0)) +...
                 0.667*log10(AB_2003(0.2, M, G, H, F, Rrup, S, 0)));
    elseif T == 0.2
        Sa = 10^(0.333*log10(AB_2003(0.2, M, G, H, F, Rrup, S, 0)) +...
                 0.667*log10(AB_2003(0.4, M, G, H, F, Rrup, S, 0)));
    end
end
```

5 OTHER PARTS OF THE WORLD

This section includes attenuation relationships for Europe and the Middle East, Greece, India, Japan, Puerto Rico, Taiwan and Turkey. They are organized first alphabetically by region then by year.

Table 5-1. List of parameters used in this section by each relationship. Definitions below.

Input	Sea09	Fea03	Aea05	AB10	DT07	S98	Kea06	Zea06	Mea06 Crustal	Mea06 Sub. Z.	MA05	LL08	GK02	KG04
T	●	●	●	●	●		●	●	●	●	●	●	●	●
M	●	●	●	●	●	●	●	●	●	●	●	●	●	●
C			●											
C_H									●	●				
G	●													
H							●	●		●		●		
F			●	●	●			●	●	●		●		
R_{rup}							●	●	●	●	●			
R_{jb}	●		●	●									●	●
R_{hypo}		●				●						●		
R_{epi}					●									
R_{tr}							●							
R_{VOL}									●	●				
V_{S30}							●						●	
S		●	●	●	●			●	●	●		●		●

T – Period (sec), PGA, PGV or PGD
M – Magnitude
C – Component indicator (0 for horizontal, 1 for vertical)
C_H – Horizontal component: 1 for geometric mean, 0 for maximum
G – Region indicator
H – Focal depth (km)
F – Fault type indicator (e.g. strike-slip, reverse, normal, unspecified)
R_{rup} – Closest distance to rupture plane (km)
R_{jb} – Joyner-Boore distance (i.e. closest horizontal distance to surface projection of fault rupture) (km)
R_{hypo} – Hypocentral distance (km)
R_{epi} – Epicentral distance (km)
R_{tr} – Distance to trench axis (km), enter 0 for unapplicable events
R_{VOL} – Length of the part of the source-to-site path in the volcanic zone (km)
V_{S30} – Shear wave velocity (m/s) averaged over top 30 m
S – Soil type indicator

Table 5-2. List of parameters provided by relationships in this section. Definitions below.

Output	Sea09	Fea03	Aea05	AB10	DT07	S98	Kea06	Zea06	Mea06 Crustal	Mea06 Sub. Z.	MA05	LL08	GK02	KG04
PSA	●	●	●	●	●		●	●	●	●	●	●	●	●
PGA	●	●	●	●	●	●	●	●	●	●	●	●	●	●
PGV				●			●				●			

PSA – 5%-damped pseudo-spectral acceleration (g)
PGA – Peak ground acceleration (g)
PGV – Peak ground velocity (cm/s)

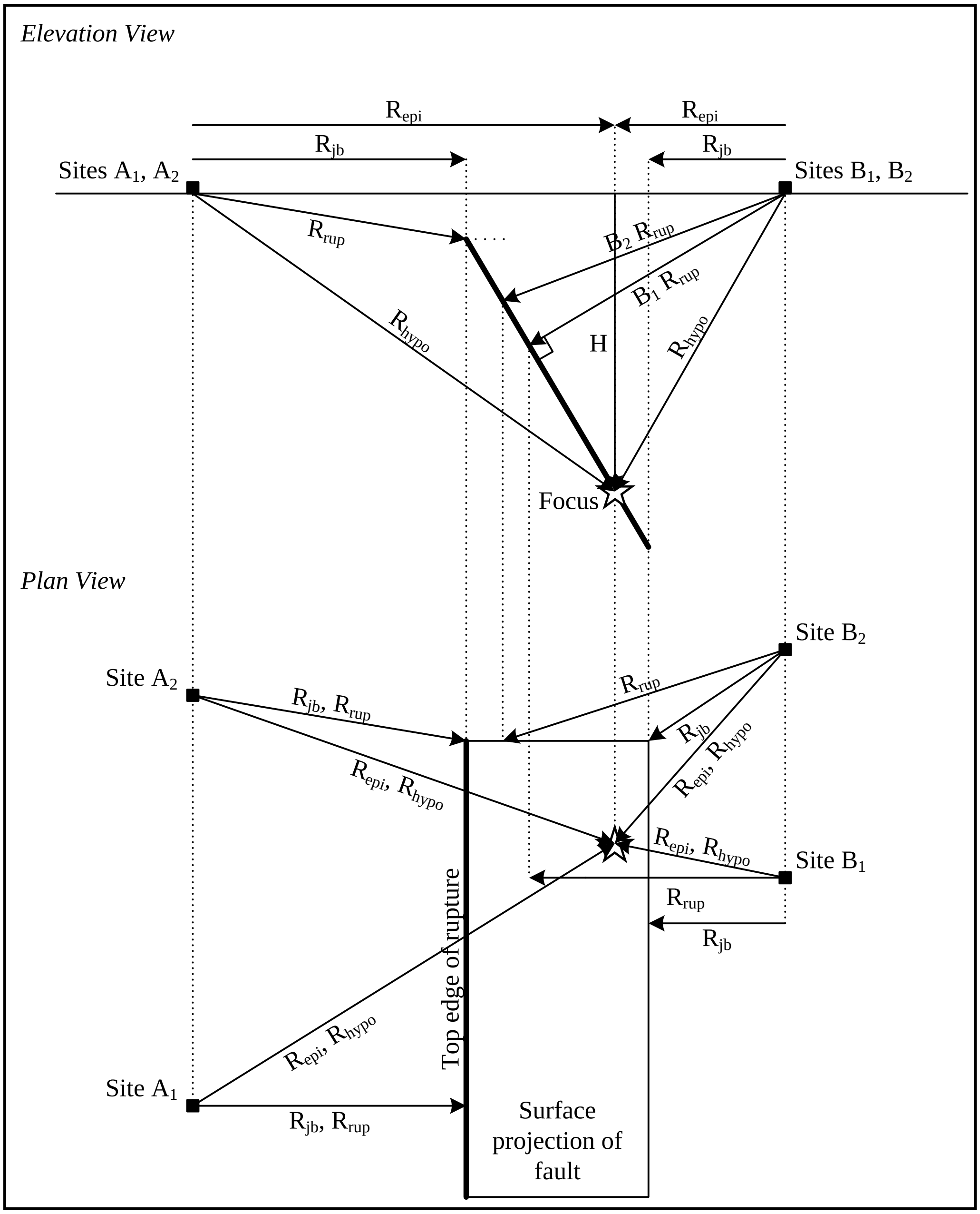


Figure 5-1. Fault geometry graphical definitions.

5.1 Australia: Somerville, Graves, Collins, Song, Ni, and Commins – 2009

5.1.1 Reference

Somerville, P., R. Graves, N. Collins, S. G. Song, S. Ni, and P. Cummins (2009). Source and Ground Motion Models for Austrailian Earthquakes, Commonwealth of Austrailia (Geoscience Australia).

Somerville, P. (2011). URS Corporation, Los Angeles, CA. Written communication.

5.1.2 Abstract

Using a combination of ground motions from recent earthquakes and a stochastic approach ground-motion models for the average horizontal component was developed for non-cratonic regions and the Yilgarn Craton in Australia. The model predicts peak ground acceleration (PGA, in g), peak ground velocity (in cm/s) and 5%-damped spectral values (in g) for periods ranging from 0.01 to 10 s. The model was developed for rock site conditions having a VS30 of 865 m/s. This model is most applicable for earthquakes between M5.0 and M7.5 and distances up to 500 km.

5.1.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA and -1 for PGV
- M – Moment magnitude
- G – Region indicator: 0 for non-cratonic Australia, 1 for Yilgarn Craton
- R_{jb} – Joyner-Boore distance (km)

$$\ln(Sa) = c_1 + c_{2,7}(M - 6.4) + c_3 \ln\sqrt{\min(R_{jb}, 50)^2 + 6^2} + c_4(M - 6.4)\ln\sqrt{{R_{jb}}^2 + 6^2} + c_5 R_{jb} + c_6\left(\ln\sqrt{\max(R_{jb}, 50)^2 + 6^2} - \ln\sqrt{50^2 + 6^2}\right) + c_8(8.5 - M)^2$$

Note for $c_{2,7}$: use c_2 for M < 6.4, and c_7 for M ≥ 6.4.

Coefficients

Table 5-3. Coefficients and standard deviations for non-cratonic Australia.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	σ
0.01	1.0536	-0.0419	-0.7939	0.1445	-0.00619	-0.7266	-0.0394	-0.0974	0.5684
0.02	1.0568	-0.0392	-0.7968	0.1455	-0.00617	-0.7323	-0.0393	-0.0960	0.5684
0.03	1.1353	-0.0479	-0.8092	0.1500	-0.00610	-0.7641	-0.0571	-0.0921	0.5681
0.04	1.3000	-0.0702	-0.8315	0.1592	-0.00599	-0.8285	-0.0981	-0.0853	0.5676
0.05	1.4768	-0.0931	-0.8333	0.1560	-0.00606	-0.8674	-0.1274	-0.0913	0.5670
0.075	1.7022	-0.0516	-0.8072	0.1456	-0.00655	-0.8769	-0.1097	-0.0869	0.5663
0.10	1.6572	0.1508	-0.7759	0.1310	-0.00708	-0.7783	0.0169	-0.0598	0.5659
0.15	1.9444	-0.0962	-0.7500	0.1167	-0.00698	-0.6949	-0.1332	-0.1253	0.5659
0.20	1.8272	-0.0623	-0.7343	0.1194	-0.00677	-0.6438	-0.0957	-0.1192	0.5669
0.25	1.7438	-0.0253	-0.7248	0.1195	-0.00646	-0.6374	-0.0625	-0.1165	0.5678
0.30	1.8056	-0.2702	-0.7319	0.1349	-0.00606	-0.6644	-0.1747	-0.1434	0.5708
0.40	1.8875	-0.3782	-0.7058	0.0996	-0.00589	-0.5877	-0.2442	-0.2189	0.5697
0.50	2.0376	-0.7959	-0.6973	0.1147	-0.00565	-0.5999	-0.4867	-0.2969	0.5739
0.75	1.9306	-0.8028	-0.7451	0.1122	-0.00503	-0.5946	-0.5012	-0.3499	0.5876
1.0	1.6038	-0.4780	-0.8695	0.0732	-0.00569	-0.4159	0.0636	-0.3373	0.6269
1.5	0.4774	0.9096	-1.0244	0.1106	-0.00652	-0.1900	1.0961	-0.1066	0.7517
2.0	-0.2581	1.3777	-1.0100	0.1031	-0.00539	-0.2734	1.5033	-0.0453	0.8036
3.0	-0.9636	1.1469	-0.8853	0.1038	-0.00478	-0.4042	1.5413	-0.1102	0.8219
4.0	-1.4614	1.0795	-0.8049	0.1096	-0.00395	-0.4604	1.4196	-0.1470	0.8212
5.0	-1.6116	0.7486	-0.7810	0.0965	-0.00307	-0.4649	1.2409	-0.2217	0.8240
7.5	-2.3531	0.3519	-0.6434	0.0959	-0.00138	-0.6826	0.9288	-0.3123	0.7957
10	-3.2614	0.6973	-0.6276	0.1292	-0.00155	-0.6198	1.0105	-0.2455	0.7602
PGA	1.0378	-0.0397	-0.7943	0.1445	-0.00618	-0.7254	-0.0359	-0.0973	0.5685
PGV	5.0709	0.5278	-0.8574	0.1770	-0.00501	-0.6119	0.8066	-0.0380	0.6417

Table 5-4. Coefficients and standard deviations for the Yilgarn Craton, Australia.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	σ
0.01	1.5551	1.4638	-1.1146	0.1662	-0.00568	-1.0484	1.0585	0.2014	0.5512
0.02	2.3380	1.3806	-1.2297	0.1801	-0.00467	-1.3985	0.9599	0.2013	0.5510
0.03	2.4809	1.3754	-1.1762	0.1712	-0.00542	-1.3872	0.9693	0.1928	0.5508
0.04	2.3145	1.6025	-1.1260	0.1715	-0.00629	-1.2791	1.0704	0.2356	0.5509
0.05	2.2686	1.5584	-1.0734	0.1471	-0.00709	-1.0891	1.1075	0.2067	0.5510
0.075	1.9707	1.6803	-1.0154	0.1456	-0.00737	-0.9193	1.1829	0.2217	0.5514
0.10	1.7103	1.7507	-0.9933	0.1382	-0.00746	-0.7814	1.2939	0.2379	0.5529
0.15	1.5231	1.6916	-0.9631	0.1333	-0.00713	-0.6733	1.2243	0.2102	0.5544
0.20	1.3683	1.5794	-0.9472	0.1364	-0.00677	-0.6269	1.1776	0.1895	0.5558
0.25	1.4018	1.2894	-0.9441	0.1436	-0.00617	-0.6707	1.0561	0.1459	0.5583
0.30	1.4500	1.0463	-0.9488	0.1476	-0.00581	-0.6870	0.9404	0.1104	0.5602
0.40	1.4415	0.9282	-0.9183	0.1132	-0.00576	-0.5952	0.8628	0.0406	0.5614
0.50	1.4038	0.6916	-0.9101	0.1348	-0.00557	-0.6239	0.7123	0.0062	0.5636
0.75	1.5084	0.7580	-0.9901	0.1126	-0.00458	-0.6904	0.6859	-0.0563	0.5878
1.0	2.1063	0.3818	-1.0868	0.0795	-0.00406	-0.9034	0.6185	-0.1825	0.6817
1.5	2.5579	-0.8427	-0.8181	0.0765	-0.00220	-1.3532	-0.2544	-0.4666	0.8514
2.0	2.3960	-1.3995	-0.7044	0.0677	-0.00366	-0.9086	-0.6432	-0.5960	0.8646
3.0	0.9604	-0.4612	-0.7045	0.0645	-0.00429	-0.5119	-0.1643	-0.4631	0.8424
4.0	0.1219	-0.0698	-0.7591	0.0849	-0.00374	-0.4145	0.1235	-0.3925	0.8225
5.0	-0.8424	0.5316	-0.7960	0.1033	-0.00180	-0.6213	0.5368	-0.2757	0.8088
7.5	-1.9226	0.6376	-0.8190	0.1455	-0.00066	-0.7574	0.6902	-0.2329	0.7808
10	-2.6033	0.5906	-0.8094	0.1609	-0.00106	-0.6855	0.7035	-0.2291	0.7624
PGA	1.5456	1.4565	-1.1151	0.1664	-0.00567	-1.0490	1.0553	0.2000	0.5513
PGV	5.2344	1.5853	-1.0154	0.2140	-0.00341	-0.9161	1.1298	0.1481	0.6606

5.1.4 Calibration Plots

5.1.5 Database

This model is largely based on simulations and synthetic seismograms. No database was provided.

5.1.6 MATLAB Code

5.2 Europe: Fukushima, Berge-Thierry, Volant, Griot-Pommera, and Cotton – 2003

5.2.1 Reference

Fukushima, Y., C. Berge-Thierry, P. Volant, D.-A. Griot-Pommera, and F. Cotton (2003). Attenuation Relation for West Eurasia Determined with Recent Near-Fault Records from California, Japan and Turkey, *Journal of Earthquake Engineering* **7**(4), 573-598.

5.2.2 Abstract

Using 740 horizontal ground motion recordings (west Eurasia: 399, US: 162, Hyogo-ken Nanbu: 154, Kocaeli:25) from 50 earthquakes, an empirical ground-motion model for the average horizontal component was developed. The model predicts peak ground acceleration (PGA, in cm/s^2) and 5%-damped spectral values (in cm/s^2) for periods ranging from 0.1 to 2.0 s. Based on the bounds of the earthquakes in the database, this model is most applicable for earthquakes between M5.5 and M7.4 and distances from 0.5 to 235 km. Note: the MATLAB code converts all accelerations to g's.

5.2.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA
- M – Surface wave magnitude
- R_{hypo} – Hypocentral distance (km)
- S – Soil Type: 0 for rock (V_{S30} > 800 m/s), 1 for alluvium (300 m/s < V_{S30} < 800 m/s),

$$\log_{10}(Sa) = aM + bR_{hypo} + c - \log_{10}\left(R_{hypo} + d10^{0.42M}\right)$$

Coefficients

Table 5-5. Attenuation relationship coefficients and standard deviations.

T (sec)	a	b	c_{rock}	c_{soil}	d	σ
PGA	0.307	-0.001170	1.640	1.734	0.01300	0.261
0.10	0.256	-0.002160	2.325	2.338	0.01740	0.280
0.15	0.247	-0.001930	2.433	2.502	0.01930	0.293
0.20	0.272	-0.001500	2.270	2.349	0.01970	0.290
0.30	0.332	-0.001320	1.780	1.906	0.01750	0.301
0.40	0.369	-0.001050	1.438	1.613	0.01510	0.300
0.50	0.410	-0.000763	1.073	1.275	0.01350	0.308
0.75	0.444	-0.000731	0.671	0.893	0.01060	0.324
1.00	0.485	-0.000139	0.212	0.464	0.00860	0.328
1.50	0.535	-0.000516	-0.282	-0.072	0.00754	0.341
2.00	0.537	-0.000604	-0.435	-0.268	0.00667	0.345

5.2.4 Calibration Plots

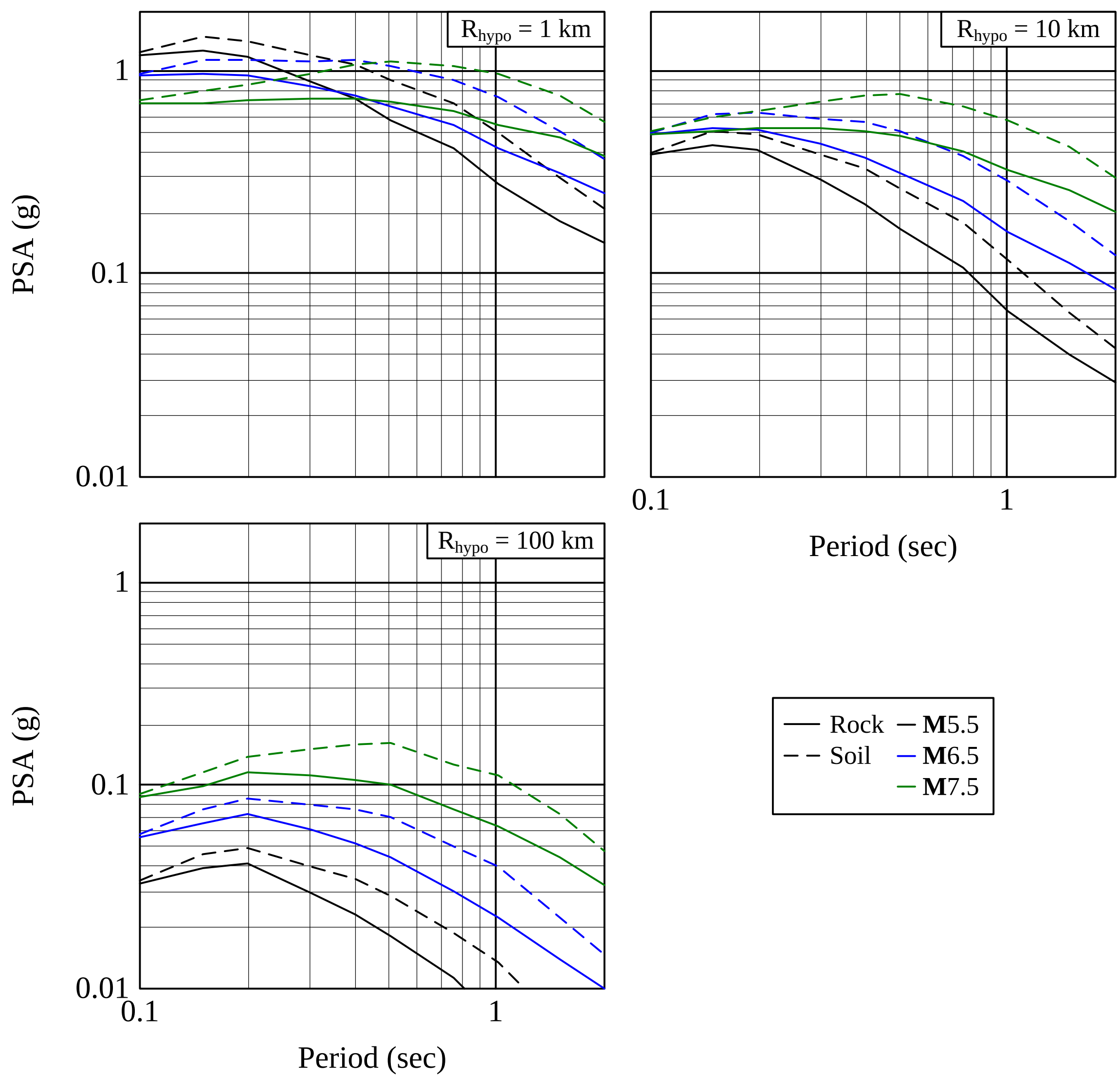


Figure 5-2. PSA as a function of period for given conditions.

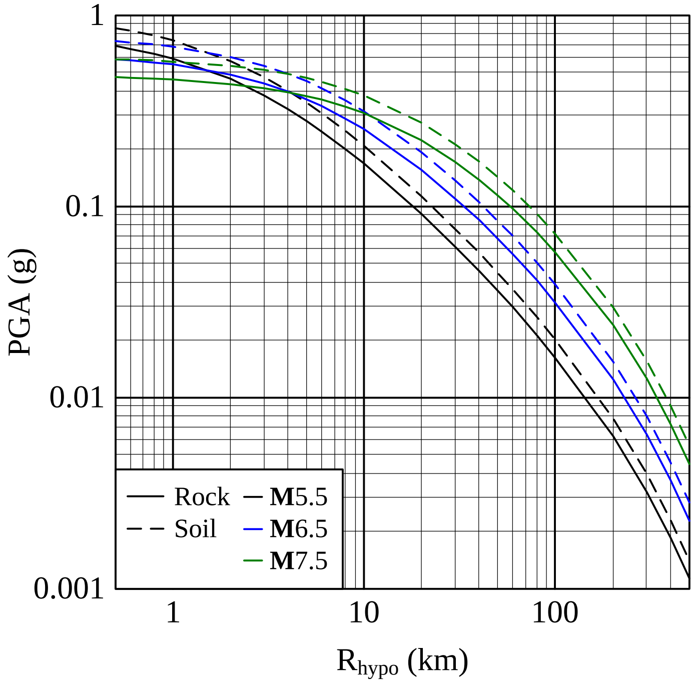


Figure 5-3. PGA as a function of distance for given conditions.

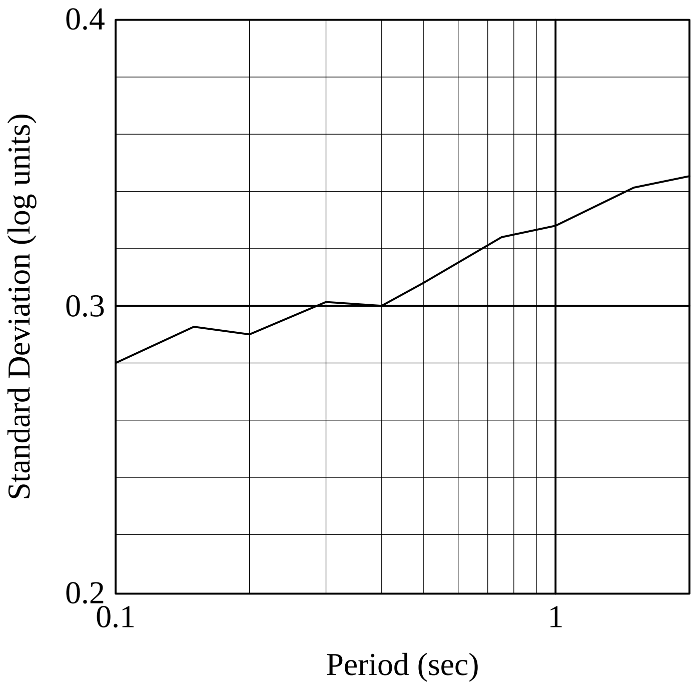


Figure 5-4. Standard deviation as a function of period.

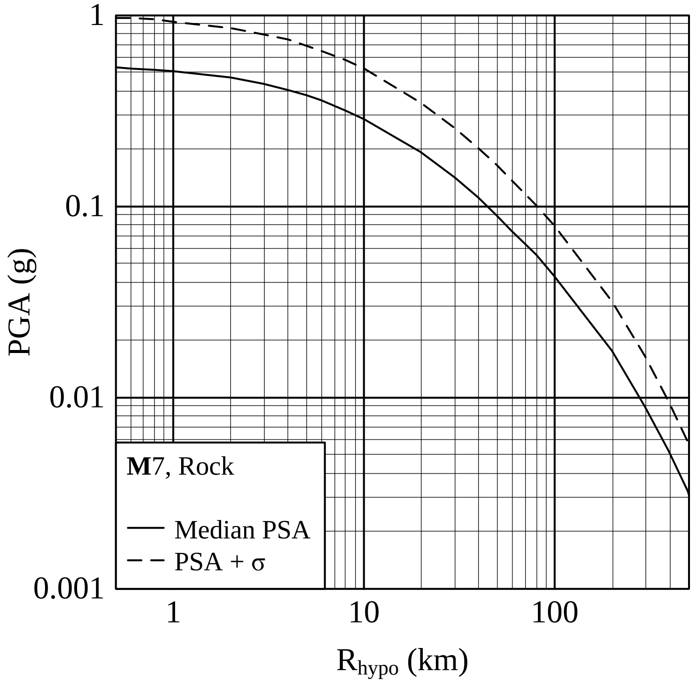


Figure 5-5 Example of application of median PGA plus one standard deviation.

5.2.5 Database

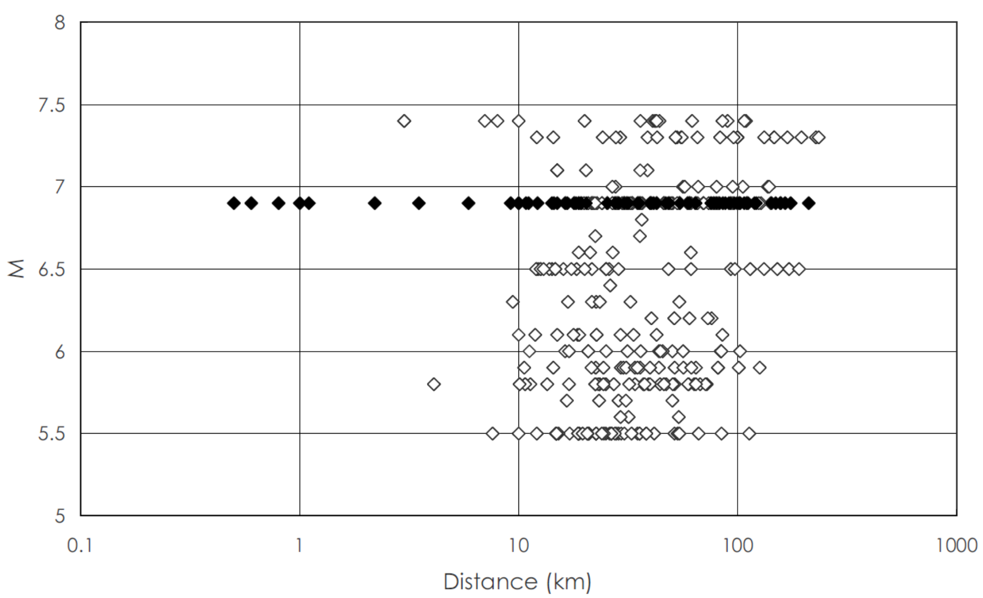


Figure 5-6. Distribution of magnitude and distance for records used in this study. Dark points indicate the Hyogo-ken Nanbu earthquake.

5.2.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/7/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Fukushima et al. attenuation equation, 2003
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0 for PGA
% M         = Surface wave magnitude
% Rh        = Hypocentral distance (km)
% S         = Soil type: 0 for rock (VS30 > 800 m/s), 1 for soil
%             (300 < VS30 < 800 m/s)
% -------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration or PGA prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = FBVGC_2003(T, M, Rh, S)
% Coefficients
period = [0.00  0.10    0.15    0.20    0.30    0.40    0.50    0.75    1.00    1.50    2.00];
a    = [0.307   0.256   0.247   0.272   0.332   0.369   0.410   0.444   0.485   0.535   0.537];
b    = [-0.00117    -0.00216    -0.00193    -0.00150    -0.00132    -0.00105    -0.000763...
        -0.000731   -0.000139   -0.000516   -0.000604];
if S == 0
    c = [1.640  2.325   2.433   2.270   1.780   1.438   1.073   0.671   0.212   -0.282  -0.435];
else
    c = [1.734  2.338   2.502   2.349   1.906   1.613   1.275   0.893   0.464   -0.072  -0.268];
end
d    = [0.0130  0.0174  0.0193  0.0197  0.0175  0.0151  0.0135  0.0106  0.00860 0.00754 0.00667];
sig  = [0.261   0.280   0.293   0.290   0.301   0.300   0.308   0.324   0.328   0.341   0.345];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi  = min(period(find(period>T)));
    [sa_low, sigma_low] = FBVGC_2003(T_low, M, Rh, S);
    [sa_hi,  sigma_hi]  = FBVGC_2003(T_hi,  M, Rh, S);
    x = [log10(T_low) log10(T_hi)];
    Y_sa = [log10(sa_low) log10(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = 10^(interp1(x,Y_sa,log10(T)));
    sigma = interp1(x,Y_sigma,log10(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    Sa = 10^(a(i)*M + b(i)*Rh - log10(Rh + d(i)*10^(0.42*M)) + c(i))/980.665;
    sigma = sig(i);
end
```

5.3 Europe/Middle East: Ambraseys, Douglas, Sarma and Smit – 2005

5.3.1 References

Ambrayseys, N. N., J. Douglas, S. K. Sarma, P. M. Smit (2005). Equations for the Estimation of Strong Ground Motions from Shallow Crustal Earthquakes Using Data from Europe and the Middle East: Horizontal Peak Ground Acceleration and Spectral Acceleration, *Bulletin of Earthquake Engineering* **3**, 1-53.

Ambrayseys, N. N., J. Douglas, S. K. Sarma, P. M. Smit (2005). Equations for the Estimation of Strong Ground Motions from Shallow Crustal Earthquakes Using Data from Europe and the Middle East: Vertical Peak Ground Acceleration and Spectral Acceleration, *Bulletin of Earthquake Engineering* **3**, 55-73.

5.3.2 Abstract

Using 595 strong ground motions records (from 135 earthquakes and 338 stations) from Europe and the Middle East, empirical ground-motion models for the average horizontal and vertical components were developed. The model predicts peak ground acceleration (PGA, in g) and 5%-damped spectral values (in g) for periods ranging from 0.05 to 2.5 s. Based on the bounds of the earthquakes in the database, this model is most applicable for earthquakes between M5.0 and M7.6, and distances up to 100 km.

5.3.3 Attenuation Relationship

The spectral acceleration is a function of:

T	– Period (sec), use 0 for PGA
M	– Moment magnitude
C	– 1 for vertical motion, 0 for horizontal
F	– Fault Type: 1 for strike-slip, 2 for normal, 3 for reverse/thrust, 4 for odd
R_{jb}	– Joyner-Boore distance (km)
S	– Soil Type: 1 for soft soil, 2 for stiff soil, 3 for rock

$$\log_{10}(Sa) = a_1 + a_2 M + (a_3 + a_4 M)\log_{10}\sqrt{{R_{jb}}^2 + {a_5}^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O$$

where:

$$S_S = \begin{cases} 1 & for\ soft\ soil\ sites \\ 0 & otherwise \end{cases}$$

$$S_A = \begin{cases} 1 & for\ stiff\ soil\ sites \\ 0 & otherwise \end{cases}$$

$$F_N = \begin{cases} 1 & for\ normal\ fault \\ 0 & otherwise \end{cases}$$

$$F_T = \begin{cases} 1 & for\ reverse/thrust\ fault \\ 0 & otherwise \end{cases}$$

$$F_O = \begin{cases} 1 & for\ odd\ fault \\ 0 & otherwise \end{cases}$$

Standard Error

$$\sigma_T = \sqrt{(\sigma_{1A} - \sigma_{1B} M)^2 + (\sigma_{2A} - \sigma_{2B} M)^2}$$

Coefficients

Table 5-6. Coefficients for Horizontal Component

T (sec)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	σ_{1A}	σ_{1B}	σ_{2A}	σ_{2B}
PGA	2.522	-0.142	-3.184	0.314	7.6	0.137	0.050	-0.084	0.062	-0.044	0.665	0.065	0.222	0.022
0.050	3.247	-0.225	-3.525	0.359	7.4	0.098	0.005	-0.096	0.078	-0.048	0.708	0.069	0.249	0.024
0.055	3.125	-0.206	-3.418	0.345	7.1	0.085	0.004	-0.096	0.072	-0.050	0.672	0.063	0.235	0.022
0.060	3.202	-0.212	-3.444	0.347	7.4	0.079	0.002	-0.103	0.073	-0.047	0.687	0.065	0.237	0.023
0.065	3.442	-0.242	-3.571	0.365	7.7	0.069	0.001	-0.104	0.076	-0.035	0.693	0.067	0.241	0.023
0.070	3.504	-0.249	-3.576	0.367	7.9	0.064	-0.002	-0.114	0.068	-0.043	0.647	0.059	0.225	0.021
0.075	3.472	-0.240	-3.521	0.358	8.0	0.064	-0.003	-0.121	0.063	-0.046	0.674	0.063	0.227	0.021
0.080	3.526	-0.248	-3.520	0.358	8.1	0.069	-0.002	-0.116	0.074	-0.040	0.756	0.076	0.252	0.025
0.085	3.320	-0.215	-3.381	0.336	8.0	0.067	0.010	-0.116	0.075	-0.039	0.750	0.076	0.258	0.026
0.090	3.309	-0.211	-3.353	0.332	7.9	0.064	0.014	-0.119	0.065	-0.048	0.727	0.072	0.249	0.025
0.095	3.479	-0.240	-3.420	0.345	7.8	0.062	0.014	-0.107	0.073	-0.051	0.772	0.079	0.262	0.027
0.100	3.596	-0.258	-3.511	0.360	7.9	0.065	0.025	-0.095	0.076	-0.047	0.747	0.075	0.249	0.025
0.110	3.453	-0.239	-3.398	0.345	7.9	0.077	0.041	-0.082	0.072	-0.052	0.810	0.084	0.256	0.027
0.120	3.330	-0.214	-3.300	0.329	8.0	0.070	0.045	-0.081	0.065	-0.046	0.753	0.075	0.240	0.024
0.130	3.249	-0.195	-3.254	0.321	8.2	0.069	0.043	-0.084	0.056	-0.059	0.712	0.068	0.236	0.023
0.140	2.993	-0.154	-3.088	0.297	8.2	0.065	0.042	-0.074	0.053	-0.067	0.650	0.059	0.218	0.020
0.150	2.725	-0.111	-2.909	0.270	8.3	0.067	0.044	-0.074	0.067	-0.060	0.634	0.057	0.223	0.020
0.160	2.738	-0.120	-2.912	0.274	8.2	0.085	0.049	-0.069	0.090	-0.061	0.734	0.072	0.251	0.025
0.170	2.692	-0.114	-2.907	0.275	8.2	0.091	0.053	-0.059	0.087	-0.055	0.760	0.077	0.257	0.026
0.180	2.665	-0.110	-2.907	0.276	8.1	0.098	0.049	-0.057	0.087	-0.054	0.736	0.073	0.251	0.025
0.190	2.713	-0.118	-2.989	0.288	8.1	0.112	0.059	-0.050	0.090	-0.054	0.752	0.076	0.250	0.025
0.200	2.632	-0.109	-2.990	0.289	8.1	0.124	0.070	-0.033	0.090	-0.039	0.784	0.080	0.251	0.026
0.220	2.483	-0.088	-2.941	0.281	7.9	0.136	0.078	-0.033	0.086	-0.024	0.778	0.079	0.244	0.025
0.240	2.212	-0.051	-2.823	0.265	7.6	0.156	0.087	-0.037	0.090	-0.020	0.770	0.077	0.235	0.024
0.260	2.058	-0.036	-2.787	0.263	7.3	0.179	0.077	-0.024	0.120	0.010	0.917	0.101	0.278	0.030
0.280	1.896	-0.010	-2.732	0.251	7.5	0.193	0.074	-0.023	0.112	0.027	0.947	0.104	0.285	0.031
0.300	1.739	0.009	-2.667	0.244	7.1	0.192	0.069	-0.034	0.104	0.012	0.890	0.095	0.267	0.028
0.320	1.728	0.001	-2.688	0.251	7.1	0.207	0.073	-0.021	0.118	0.008	0.917	0.098	0.273	0.029
0.340	1.598	0.020	-2.667	0.246	7.2	0.216	0.078	-0.010	0.118	0.005	0.896	0.095	0.261	0.028
0.360	1.477	0.034	-2.641	0.244	6.9	0.230	0.091	-0.013	0.107	-0.011	0.846	0.087	0.254	0.026
0.380	1.236	0.071	-2.534	0.227	6.7	0.247	0.100	-0.010	0.106	-0.018	0.803	0.080	0.250	0.025
0.400	1.070	0.091	-2.474	0.219	6.3	0.256	0.097	-0.013	0.115	-0.020	0.793	0.078	0.244	0.024
0.420	0.998	0.096	-2.469	0.220	5.9	0.259	0.100	-0.021	0.116	-0.024	0.757	0.072	0.233	0.022
0.440	1.045	0.085	-2.540	0.231	6.3	0.269	0.114	-0.016	0.114	-0.028	0.787	0.077	0.241	0.024
0.460	0.980	0.093	-2.564	0.234	6.3	0.278	0.122	-0.011	0.108	-0.029	0.766	0.074	0.238	0.023
0.480	0.874	0.103	-2.530	0.231	6.2	0.286	0.130	0.001	0.118	-0.024	0.778	0.076	0.240	0.023
0.500	0.624	0.139	-2.410	0.212	6.1	0.289	0.133	0.004	0.126	-0.026	0.798	0.079	0.246	0.024
0.550	0.377	0.174	-2.317	0.196	6.1	0.293	0.137	-0.004	0.118	-0.035	0.841	0.085	0.268	0.027
0.600	0.359	0.158	-2.343	0.206	5.4	0.311	0.136	0.008	0.118	-0.028	0.919	0.099	0.308	0.033
0.650	0.130	0.182	-2.294	0.202	5.0	0.318	0.149	0.005	0.107	-0.031	0.867	0.090	0.301	0.031
0.700	-0.014	0.198	-2.305	0.205	4.8	0.327	0.154	-0.011	0.105	-0.032	0.803	0.080	0.298	0.030
0.750	-0.307	0.236	-2.201	0.191	4.7	0.318	0.148	-0.001	0.114	-0.032	0.774	0.076	0.278	0.027
0.800	-0.567	0.279	-2.083	0.170	5.2	0.332	0.178	-0.003	0.083	-0.062	0.661	0.059	0.240	0.021
0.850	-0.519	0.262	-2.177	0.186	4.9	0.341	0.183	0.005	0.085	-0.070	0.694	0.064	0.253	0.023
0.900	-0.485	0.249	-2.246	0.199	4.5	0.354	0.191	-0.003	0.072	-0.082	0.714	0.067	0.263	0.025
0.950	-1.133	0.369	-1.957	0.143	5.5	0.353	0.204	-0.025	0.024	-0.109	0.309	0.000	0.121	0.000
1.000	-1.359	0.403	-1.848	0.124	6.0	0.357	0.211	-0.013	0.024	-0.101	0.305	0.000	0.120	0.000
1.100	-1.675	0.437	-1.711	0.108	5.5	0.373	0.213	-0.029	-0.007	-0.108	0.306	0.000	0.118	0.000
1.200	-1.982	0.477	-1.636	0.095	5.4	0.389	0.226	-0.014	-0.017	-0.095	0.297	0.000	0.120	0.000
1.300	-2.226	0.511	-1.605	0.089	5.5	0.395	0.215	-0.004	-0.025	-0.085	0.296	0.000	0.119	0.000
1.400	-2.419	0.533	-1.541	0.080	6.0	0.408	0.237	0.028	-0.040	-0.091	0.290	0.000	0.115	0.000
1.500	-2.639	0.550	-1.443	0.074	4.9	0.405	0.229	0.020	-0.053	-0.133	0.292	0.000	0.111	0.000
1.600	-2.900	0.587	-1.351	0.060	5.2	0.387	0.216	0.019	-0.056	-0.131	0.296	0.000	0.114	0.000
1.700	-2.695	0.564	-1.564	0.086	6.5	0.380	0.212	0.001	-0.081	-0.141	0.302	0.000	0.117	0.000
1.800	-3.209	0.630	-1.410	0.069	5.4	0.391	0.174	0.012	-0.035	-0.154	0.291	0.000	0.128	0.000
1.900	-3.313	0.647	-1.424	0.067	5.9	0.386	0.175	0.030	-0.033	-0.145	0.290	0.000	0.133	0.000
2.000	-3.063	0.586	-1.372	0.070	4.2	0.421	0.177	0.008	-0.019	-0.174	0.282	0.000	0.134	0.000
2.100	-3.043	0.578	-1.435	0.080	4.3	0.404	0.171	0.002	-0.026	-0.164	0.281	0.000	0.134	0.000
2.200	-3.068	0.575	-1.448	0.083	4.2	0.394	0.160	-0.007	-0.034	-0.169	0.283	0.000	0.136	0.000
2.300	-3.996	0.740	-0.829	-0.025	5.1	0.349	0.135	-0.010	-0.031	-0.125	0.282	0.000	0.137	0.000
2.400	-4.108	0.758	-0.755	-0.038	5.3	0.338	0.119	-0.024	-0.050	-0.147	0.284	0.000	0.137	0.000
2.500	-4.203	0.768	-0.714	-0.044	5.1	0.325	0.103	-0.026	-0.063	-0.155	0.285	0.000	0.137	0.000

Table 5-7. Coefficients for Vertical Component

T (sec)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	σ_{1A}	σ_{1B}	σ_{2A}	σ_{2B}
PGA	0.835	0.083	-2.489	0.206	5.6	0.078	0.046	-0.126	0.005	-0.082	0.262	0.000	0.100	0.000
0.050	1.426	0.053	-2.681	0.217	4.7	0.090	0.039	-0.168	0.005	-0.070	0.301	0.000	0.115	0.000
0.055	1.330	0.077	-2.598	0.200	5.1	0.086	0.041	-0.162	-0.009	-0.067	0.296	0.000	0.112	0.000
0.060	1.333	0.090	-2.601	0.195	5.7	0.091	0.051	-0.171	-0.016	-0.069	0.295	0.000	0.111	0.000
0.065	1.261	0.106	-2.538	0.185	6.0	0.082	0.058	-0.172	-0.026	-0.078	0.292	0.000	0.109	0.000
0.070	1.231	0.107	-2.497	0.183	6.1	0.081	0.050	-0.164	-0.011	-0.083	0.290	0.000	0.106	0.000
0.075	1.119	0.119	-2.403	0.173	6.0	0.079	0.047	-0.149	-0.011	-0.077	0.290	0.000	0.106	0.000
0.080	0.947	0.143	-2.287	0.158	5.8	0.075	0.045	-0.142	-0.013	-0.075	0.293	0.000	0.108	0.000
0.085	0.794	0.169	-2.171	0.140	6.1	0.070	0.047	-0.132	0.000	-0.078	0.295	0.000	0.108	0.000
0.090	0.721	0.181	-2.123	0.132	6.5	0.078	0.054	-0.118	0.012	-0.083	0.294	0.000	0.106	0.000
0.095	0.695	0.187	-2.119	0.131	6.7	0.081	0.055	-0.116	0.007	-0.089	0.287	0.000	0.106	0.000
0.100	0.844	0.166	-2.217	0.146	7.1	0.083	0.050	-0.108	0.003	-0.091	0.287	0.000	0.106	0.000
0.110	0.990	0.145	-2.270	0.154	7.8	0.079	0.057	-0.105	-0.014	-0.100	0.285	0.000	0.104	0.000
0.120	0.830	0.168	-2.133	0.136	7.9	0.065	0.054	-0.104	-0.025	-0.091	0.281	0.000	0.105	0.000
0.130	0.655	0.189	-2.048	0.127	7.7	0.053	0.045	-0.090	-0.013	-0.087	0.278	0.000	0.104	0.000
0.140	0.600	0.179	-2.012	0.132	6.7	0.057	0.055	-0.084	-0.006	-0.084	0.282	0.000	0.103	0.000
0.150	0.824	0.130	-2.107	0.152	6.4	0.077	0.058	-0.082	0.009	-0.084	0.554	0.045	0.203	0.017
0.160	0.798	0.116	-2.093	0.160	5.6	0.079	0.050	-0.067	0.036	-0.078	0.619	0.056	0.220	0.020
0.170	0.989	0.087	-2.262	0.185	6.0	0.089	0.045	-0.054	0.051	-0.080	0.684	0.067	0.242	0.024
0.180	0.764	0.119	-2.160	0.170	5.9	0.099	0.056	-0.045	0.053	-0.077	0.607	0.055	0.216	0.020
0.190	0.798	0.112	-2.208	0.177	6.3	0.107	0.057	-0.035	0.059	-0.074	0.591	0.053	0.204	0.018
0.200	0.758	0.113	-2.182	0.174	6.3	0.111	0.056	-0.025	0.073	-0.068	0.625	0.059	0.212	0.020
0.220	0.907	0.082	-2.319	0.197	5.9	0.117	0.072	-0.029	0.088	-0.051	0.672	0.067	0.235	0.023
0.240	1.165	0.038	-2.543	0.231	6.7	0.118	0.091	-0.039	0.094	-0.056	0.613	0.057	0.213	0.020
0.260	1.238	0.016	-2.590	0.245	6.2	0.111	0.082	-0.051	0.078	-0.071	0.670	0.067	0.238	0.024
0.280	1.165	0.020	-2.594	0.249	5.9	0.112	0.083	-0.042	0.066	-0.064	0.605	0.056	0.217	0.020
0.300	0.986	0.053	-2.574	0.242	6.1	0.111	0.082	-0.047	0.070	-0.052	0.569	0.051	0.215	0.019
0.320	0.685	0.104	-2.402	0.212	6.4	0.103	0.070	-0.055	0.068	-0.056	0.572	0.051	0.216	0.019
0.340	0.398	0.144	-2.251	0.189	6.4	0.110	0.071	-0.042	0.071	-0.056	0.537	0.047	0.205	0.018
0.360	0.333	0.146	-2.247	0.191	6.3	0.120	0.072	-0.031	0.082	-0.055	0.544	0.048	0.209	0.019
0.380	0.579	0.097	-2.415	0.221	6.2	0.128	0.077	-0.023	0.098	-0.061	0.577	0.054	0.224	0.021
0.400	0.704	0.075	-2.502	0.234	6.2	0.127	0.087	-0.025	0.108	-0.069	0.551	0.049	0.215	0.019
0.420	0.318	0.135	-2.345	0.209	6.1	0.129	0.103	-0.034	0.090	-0.078	0.270	0.000	0.103	0.000
0.440	0.446	0.110	-2.466	0.230	6.5	0.130	0.101	-0.017	0.081	-0.081	0.272	0.000	0.101	0.000
0.460	0.391	0.113	-2.478	0.233	6.8	0.136	0.103	0.002	0.082	-0.070	0.272	0.000	0.102	0.000
0.480	0.253	0.132	-2.455	0.228	6.8	0.147	0.105	0.017	0.085	-0.052	0.273	0.000	0.105	0.000
0.500	0.075	0.154	-2.381	0.219	6.6	0.151	0.103	0.026	0.092	-0.047	0.275	0.000	0.108	0.000
0.550	-0.147	0.178	-2.334	0.216	6.5	0.149	0.108	0.027	0.099	-0.029	0.273	0.000	0.115	0.000
0.600	0.193	0.095	-2.521	0.258	5.5	0.167	0.099	0.037	0.125	-0.037	0.602	0.056	0.259	0.024
0.650	-0.036	0.131	-2.463	0.244	6.0	0.187	0.107	0.047	0.125	-0.024	0.569	0.050	0.239	0.021
0.700	-0.508	0.217	-2.337	0.216	6.7	0.208	0.114	0.033	0.113	-0.013	0.284	0.000	0.120	0.000
0.750	-0.429	0.187	-2.326	0.220	6.0	0.219	0.109	0.044	0.157	-0.026	0.587	0.052	0.245	0.022
0.800	-0.617	0.214	-2.339	0.223	6.4	0.251	0.140	0.018	0.130	-0.060	0.278	0.000	0.118	0.000
0.850	-0.272	0.143	-2.512	0.255	6.0	0.261	0.120	0.051	0.163	-0.056	0.598	0.055	0.248	0.023
0.900	-0.786	0.220	-2.377	0.236	5.6	0.281	0.138	0.028	0.142	-0.074	0.277	0.000	0.121	0.000
0.950	-1.112	0.272	-2.208	0.208	5.7	0.281	0.126	0.032	0.144	-0.081	0.277	0.000	0.119	0.000
1.000	-1.200	0.296	-2.185	0.196	6.7	0.269	0.117	0.050	0.145	-0.073	0.278	0.000	0.115	0.000
1.100	-1.594	0.361	-2.017	0.164	7.3	0.269	0.117	0.049	0.113	-0.070	0.286	0.000	0.113	0.000
1.200	-1.754	0.383	-2.033	0.163	7.8	0.284	0.141	0.053	0.104	-0.055	0.279	0.000	0.118	0.000
1.300	-1.838	0.391	-2.059	0.167	8.0	0.302	0.151	0.049	0.077	-0.062	0.282	0.000	0.121	0.000
1.400	-2.296	0.457	-1.787	0.123	8.9	0.313	0.174	0.100	0.067	-0.052	0.279	0.000	0.110	0.000
1.500	-2.616	0.507	-1.581	0.088	9.3	0.319	0.178	0.102	0.054	-0.078	0.285	0.000	0.108	0.000
1.600	-2.596	0.526	-1.692	0.089	11.9	0.313	0.184	0.124	0.049	-0.067	0.291	0.000	0.111	0.000
1.700	-2.512	0.518	-1.835	0.106	12.8	0.305	0.176	0.104	0.036	-0.080	0.296	0.000	0.117	0.000
1.800	-2.947	0.550	-1.661	0.099	9.1	0.313	0.154	0.076	0.053	-0.110	0.292	0.000	0.129	0.000
1.900	-3.007	0.556	-1.640	0.095	8.7	0.307	0.146	0.060	0.047	-0.128	0.294	0.000	0.129	0.000
2.000	-2.711	0.531	-1.655	0.083	11.8	0.319	0.171	0.051	0.113	-0.148	0.290	0.000	0.126	0.000
2.100	-2.765	0.531	-1.663	0.085	11.7	0.318	0.170	0.056	0.128	-0.155	0.291	0.000	0.128	0.000
2.200	-2.677	0.502	-1.781	0.111	11.1	0.306	0.145	0.058	0.140	-0.156	0.293	0.000	0.132	0.000
2.300	-3.340	0.616	-1.287	0.031	11.1	0.234	0.112	0.024	0.122	-0.111	0.297	0.000	0.131	0.000
2.400	-3.490	0.623	-1.265	0.035	10.2	0.228	0.112	0.018	0.114	-0.110	0.291	0.000	0.131	0.000
2.500	-3.731	0.633	-1.182	0.035	7.7	0.221	0.097	0.012	0.092	-0.098	0.283	0.000	0.135	0.000

5.3.4 Calibration Plots

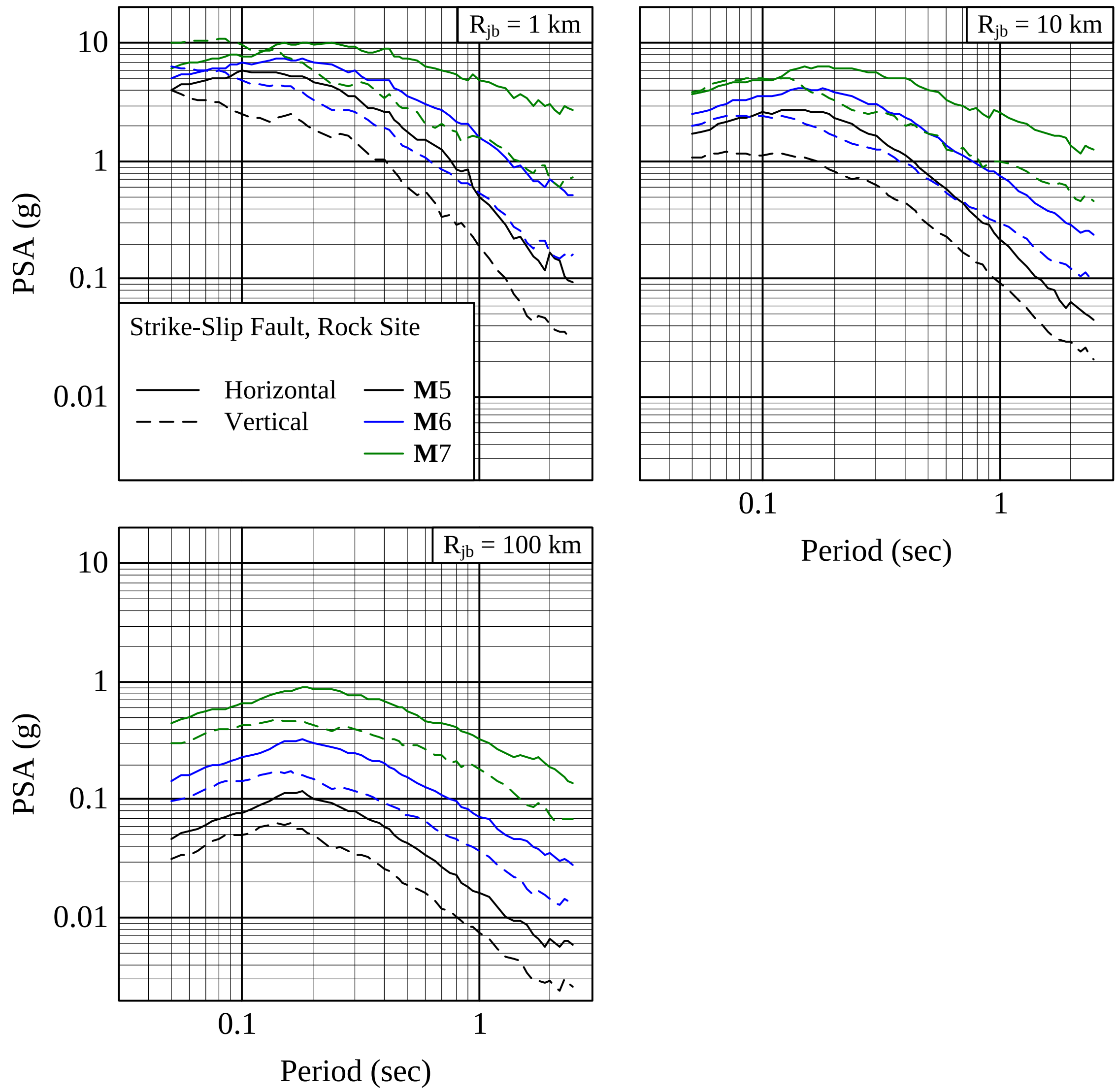


Figure 5-7. PSA as a function of period for given conditions. Note that all soil and fault type parameters equal 0.

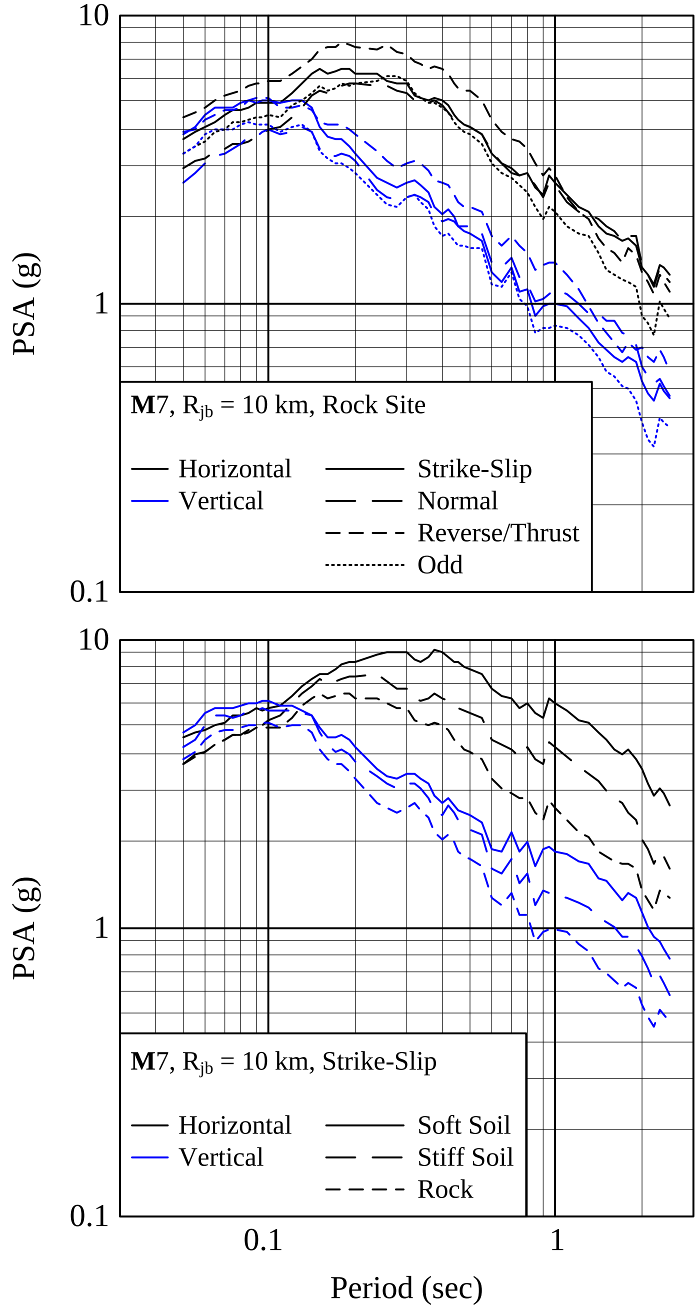


Figure 5-8. Shows variation in fault type (above) and site conditions (below).

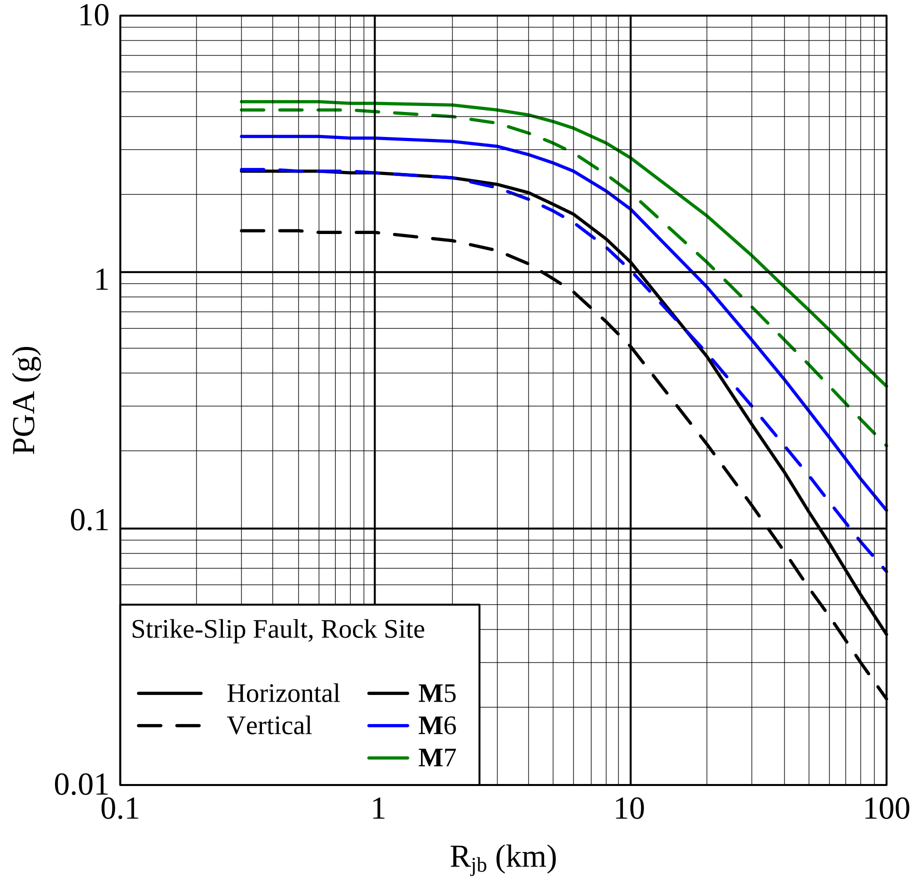


Figure 5-9. PGA as a function of distance for given conditions. Note that all soil and fault type parameters equal 0.

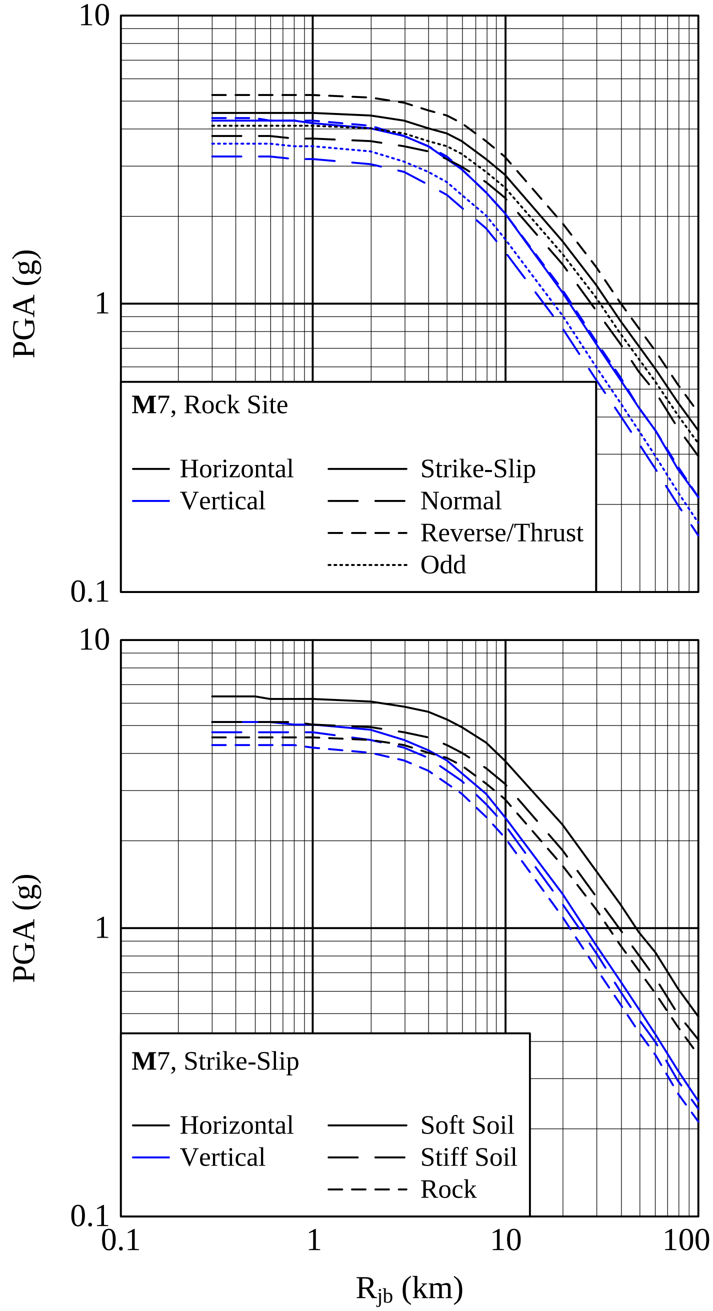


Figure 5-10. Shows variation in fault type (above) and site conditions (below).

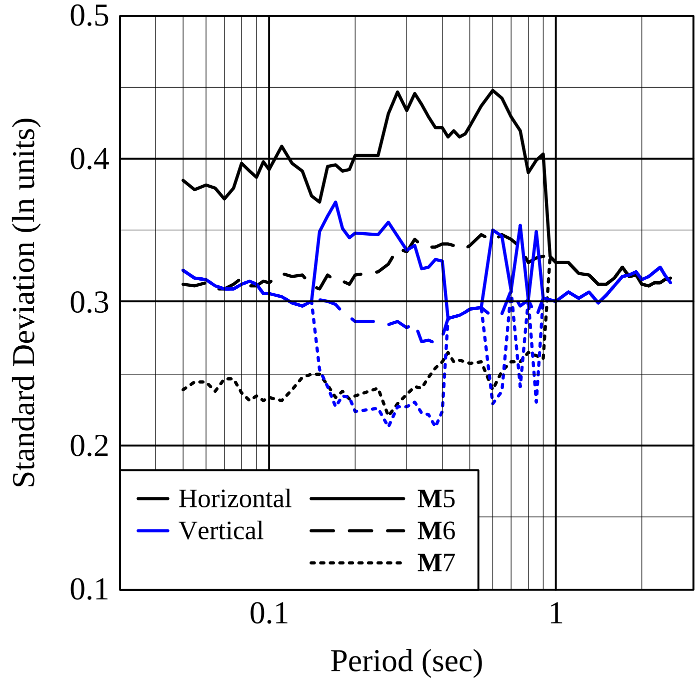


Figure 5-11. Standard deviation as a function of period for different magnitudes. Note that standard deviation is not dependant on distance, fault type or site conditions.

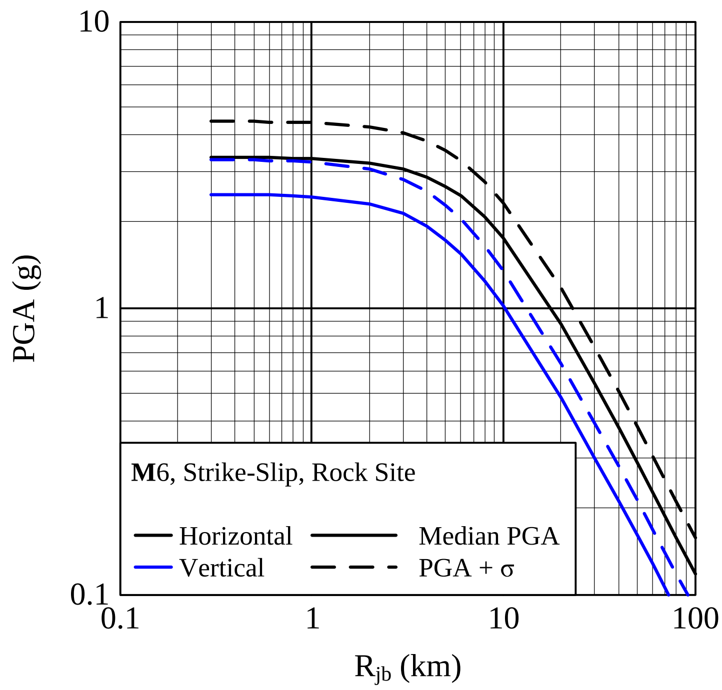


Figure 5-12. Example of application of median PSA plus one standard deviation.

5.3.5 Database

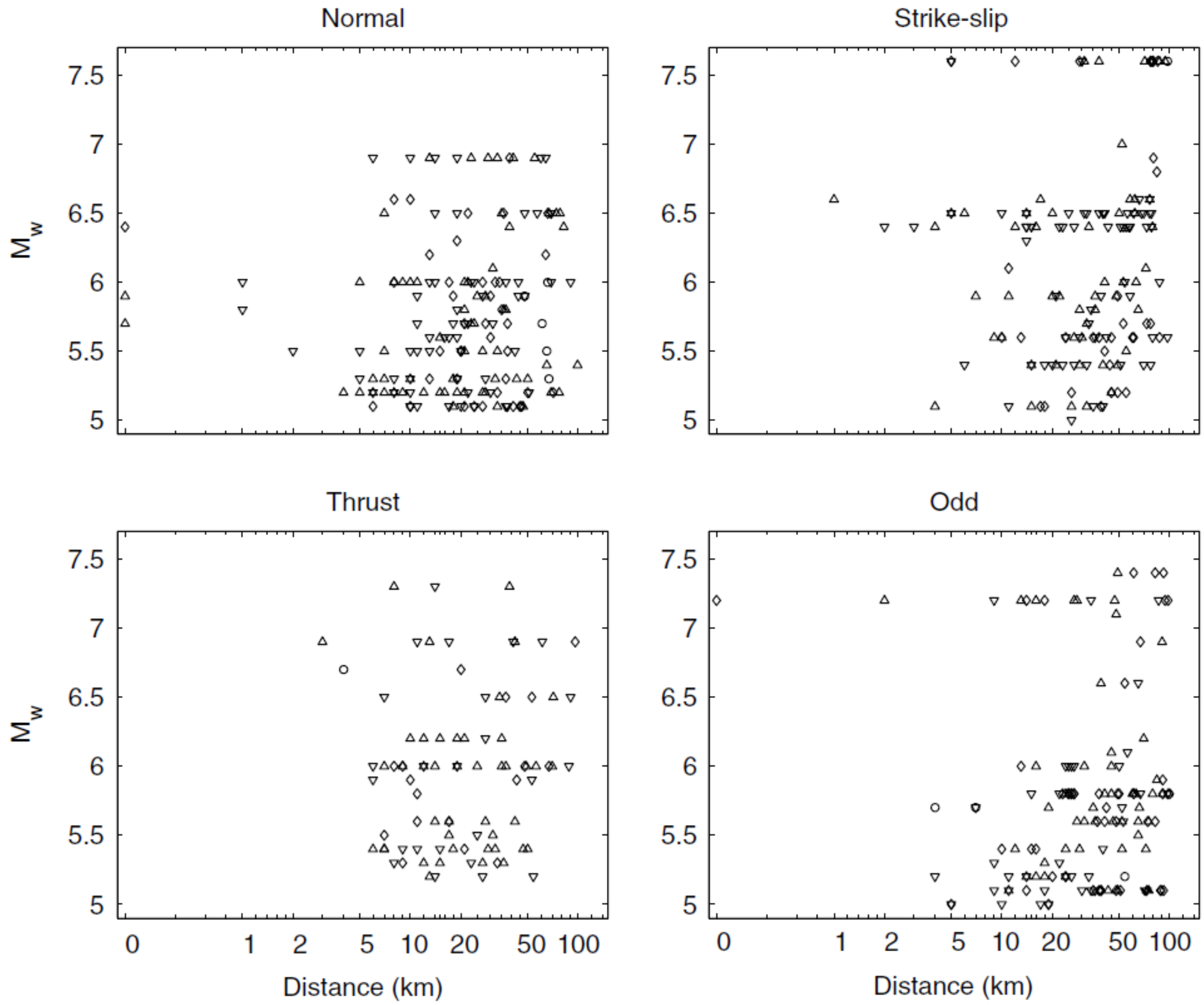


Figure 5-13. Distribution of the data used in terms of magnitude, distance, local site class and mechanism. ○ denotes record from very soft soil site, ◊ denotes record from soft soil site, △ denotes record from stiff soil site and ▽ denotes record from rock site.

5.3.6 MATLAB Code

```
% by Kathryn A. Gunberg 4/17/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Ambraseys, Douglas, Sarma and Smit attenuation equation, 2005
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T          = Period (sec), 0 for PGA
% M          = Magnitude
% C          = 1 for vertical, 0 for horizontal
% F          = Fault type: 1 for strike-slip, 2 for normal, 3 for
%              thrust/reverse, 4 for odd
% Rjb        = Joyner-Boore distance (km)
% S          = Soil type: 1 for soft soil, 2 for stiff soil, 3 for rock
% --------------------------------------------------------------------------
% Output Variables
% Sa:        Median spectral acceleration or PGA prediction (g)
% sigma:     logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = ADSS_2005(T, M, C, F, Rjb, S)
% Coefficients
period   = [0.000   0.050   0.055   0.060   0.065   0.070   0.075   0.080   0.085   0.090...
            0.095   0.100   0.110   0.120   0.130   0.140   0.150   0.160   0.170   0.180...
            0.190   0.200   0.220   0.240   0.260   0.280   0.300   0.320   0.340   0.360...
            0.380   0.400   0.420   0.440   0.460   0.480   0.500   0.550   0.600   0.650...
            0.700   0.750   0.800   0.850   0.900   0.950   1.000   1.100   1.200   1.300...
            1.400   1.500   1.600   1.700   1.800   1.900   2.000   2.100   2.200   2.300...
            2.400   2.500];
if C == 0
    a1   = [2.522   3.247   3.125   3.202   3.442   3.504   3.472   3.526   3.320   3.309...
            3.479   3.596   3.453   3.330   3.249   2.993   2.725   2.738   2.692   2.665...
            2.713   2.632   2.483   2.212   2.058   1.896   1.739   1.728   1.598   1.477...
            1.236   1.070   0.998   1.045   0.980   0.874   0.624   0.377   0.359   0.130...
            -0.014  -0.307  -0.567  -0.519  -0.485  -1.133  -1.359  -1.675  -1.982  -2.226...
            -2.419  -2.639  -2.900  -2.695  -3.209  -3.313  -3.063  -3.043  -3.068  -3.996...
            -4.108  -4.203];
    a2   = [-0.142  -0.225  -0.206  -0.212  -0.242  -0.249  -0.240  -0.248  -0.215  -0.211...
            -0.240  -0.258  -0.239  -0.214  -0.195  -0.154  -0.111  -0.120  -0.114  -0.110...
            -0.118  -0.109  -0.088  -0.051  -0.036  -0.010  0.009   0.001   0.020   0.034...
            0.071   0.091   0.096   0.085   0.093   0.103   0.139   0.174   0.158   0.182...
            0.198   0.236   0.279   0.262   0.249   0.369   0.403   0.437   0.477   0.511...
            0.533   0.550   0.587   0.564   0.630   0.647   0.586   0.578   0.575   0.740...
            0.758   0.768];
    a3   = [-3.184  -3.525  -3.418  -3.444  -3.571  -3.576  -3.521  -3.520  -3.381  -3.353...
            -3.420  -3.511  -3.398  -3.300  -3.254  -3.088  -2.909  -2.912  -2.907  -2.907...
            -2.989  -2.990  -2.941  -2.823  -2.787  -2.732  -2.667  -2.688  -2.667  -2.641...
            -2.534  -2.474  -2.469  -2.540  -2.564  -2.530  -2.410  -2.317  -2.343  -2.294...
            -2.305  -2.201  -2.083  -2.177  -2.246  -1.957  -1.848  -1.711  -1.636  -1.605...
            -1.541  -1.443  -1.351  -1.564  -1.410  -1.424  -1.372  -1.435  -1.448  -0.829...
            -0.755  -0.714];
    a4   = [0.314   0.359   0.345   0.347   0.365   0.367   0.358   0.358   0.336   0.332...
            0.345   0.360   0.345   0.329   0.321   0.297   0.270   0.274   0.275   0.276...
            0.288   0.289   0.281   0.265   0.263   0.251   0.244   0.251   0.246   0.244...
            0.227   0.219   0.220   0.231   0.234   0.231   0.212   0.196   0.206   0.202...
            0.205   0.191   0.170   0.186   0.199   0.143   0.124   0.108   0.095   0.089...
            0.080   0.074   0.060   0.086   0.069   0.067   0.070   0.080   0.083   -0.025...
            -0.038  -0.044];
    a5   = [7.6 7.4 7.1 7.4 7.7 7.9 8.0 8.1 8.0 7.9 7.8 7.9 7.9 8.0 8.2 8.2 8.3 8.2 8.2 8.1...
            8.1 8.1 7.9 7.6 7.3 7.5 7.1 7.1 7.2 6.9 6.7 6.3 5.9 6.3 6.3 6.2 6.1 6.1 5.4 5.0...
            4.8 4.7 5.2 4.9 4.5 5.5 6.0 5.5 5.4 5.5 6.0 4.9 5.2 6.5 5.4 5.9 4.2 4.3 4.2 5.1...
            5.3 5.1];
    a6   = [0.137   0.098   0.085   0.079   0.069   0.064   0.064   0.069   0.067   0.064...
            0.062   0.065   0.077   0.070   0.069   0.065   0.067   0.085   0.091   0.098...
            0.112   0.124   0.136   0.156   0.179   0.193   0.192   0.207   0.216   0.230...
            0.247   0.256   0.259   0.269   0.278   0.286   0.289   0.293   0.311   0.318...
            0.327   0.318   0.332   0.341   0.354   0.353   0.357   0.373   0.389   0.395...
```

```
        0.408   0.405   0.387   0.380   0.391   0.386   0.421   0.404   0.394   0.349...
        0.338   0.325];
    a7  = [0.050   0.005   0.004   0.002   0.001   -0.002  -0.003  -0.002  0.010   0.014...
        0.014   0.025   0.041   0.045   0.043   0.042   0.044   0.049   0.053   0.049...
        0.059   0.070   0.078   0.087   0.077   0.074   0.069   0.073   0.078   0.091...
        0.100   0.097   0.100   0.114   0.122   0.130   0.133   0.137   0.136   0.149...
        0.154   0.148   0.178   0.183   0.191   0.204   0.211   0.213   0.226   0.215...
        0.237   0.229   0.216   0.212   0.174   0.175   0.177   0.171   0.160   0.135...
        0.119   0.103];
    a8  = [-0.084  -0.096  -0.096  -0.103  -0.104  -0.114  -0.121  -0.116  -0.116  -0.119...
        -0.107  -0.095  -0.082  -0.081  -0.084  -0.074  -0.074  -0.069  -0.059  -0.057...
        -0.050  -0.033  -0.033  -0.037  -0.024  -0.023  -0.034  -0.021  -0.010  -0.013...
        -0.010  -0.013  -0.021  -0.016  -0.011  0.001   0.004   -0.004  0.008   0.005...
        -0.011  -0.001  -0.003  0.005   -0.003  -0.025  -0.013  -0.029  -0.014  -0.004...
        0.028   0.020   0.019   0.001   0.012   0.030   0.008   0.002   -0.007  -0.010...
        -0.024  -0.026];
    a9  = [0.062   0.078   0.072   0.073   0.076   0.068   0.063   0.074   0.075   0.065...
        0.073   0.076   0.072   0.065   0.056   0.053   0.067   0.090   0.087   0.087...
        0.090   0.090   0.086   0.090   0.120   0.112   0.104   0.118   0.118   0.107...
        0.106   0.115   0.116   0.114   0.108   0.118   0.126   0.118   0.118   0.107...
        0.105   0.114   0.083   0.085   0.072   0.024   0.024   -0.007  -0.017  -0.025...
        -0.040  -0.053  -0.056  -0.081  -0.035  -0.033  -0.019  -0.026  -0.034  -0.031...
        -0.050  -0.063];
    a10 = [-0.044  -0.048  -0.050  -0.047  -0.035  -0.043  -0.046  -0.040  -0.039  -0.048...
        -0.051  -0.047  -0.052  -0.046  -0.059  -0.067  -0.060  -0.061  -0.055  -0.054...
        -0.054  -0.039  -0.024  -0.020  0.010   0.027   0.012   0.008   0.005   -0.011...
        -0.018  -0.020  -0.024  -0.028  -0.029  -0.024  -0.026  -0.035  -0.028  -0.031...
        -0.032  -0.032  -0.062  -0.070  -0.082  -0.109  -0.101  -0.108  -0.095  -0.085...
        -0.091  -0.133  -0.131  -0.141  -0.154  -0.145  -0.174  -0.164  -0.169  -0.125...
        -0.147  -0.155];
    s1A = [0.665   0.708   0.672   0.687   0.693   0.647   0.674   0.756   0.750   0.727...
        0.772   0.747   0.810   0.753   0.712   0.650   0.634   0.734   0.760   0.736...
        0.752   0.784   0.778   0.770   0.917   0.947   0.890   0.917   0.896   0.846...
        0.803   0.793   0.757   0.787   0.766   0.778   0.798   0.841   0.919   0.867...
        0.803   0.774   0.661   0.694   0.714   0.309   0.305   0.306   0.297   0.296...
        0.290   0.292   0.296   0.302   0.291   0.290   0.282   0.281   0.283   0.282...
        0.284   0.285];
    s1B = [0.065   0.069   0.063   0.065   0.067   0.059   0.063   0.076   0.076   0.072...
        0.079   0.075   0.084   0.075   0.068   0.059   0.057   0.072   0.077   0.073...
        0.076   0.080   0.079   0.077   0.101   0.104   0.095   0.098   0.095   0.087...
        0.080   0.078   0.072   0.077   0.074   0.076   0.079   0.085   0.099   0.090...
        0.080   0.076   0.059   0.064   0.067   0.000   0.000   0.000   0.000   0.000...
        0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000...
        0.000   0.000];
    s2A = [0.222   0.249   0.235   0.237   0.241   0.225   0.227   0.252   0.258   0.249...
        0.262   0.249   0.256   0.240   0.236   0.218   0.223   0.251   0.257   0.251...
        0.250   0.251   0.244   0.235   0.278   0.285   0.267   0.273   0.261   0.254...
        0.250   0.244   0.233   0.241   0.238   0.240   0.246   0.268   0.308   0.301...
        0.298   0.278   0.240   0.253   0.263   0.121   0.120   0.118   0.120   0.119...
        0.115   0.111   0.114   0.117   0.128   0.133   0.134   0.134   0.136   0.137...
        0.137   0.137];
    s2B = [0.022   0.024   0.022   0.023   0.023   0.021   0.021   0.025   0.026   0.025...
        0.027   0.025   0.027   0.024   0.023   0.020   0.020   0.025   0.026   0.025...
        0.025   0.026   0.025   0.024   0.030   0.031   0.028   0.029   0.028   0.026...
        0.025   0.024   0.022   0.024   0.023   0.023   0.024   0.027   0.033   0.031...
        0.030   0.027   0.021   0.023   0.025   0.000   0.000   0.000   0.000   0.000...
        0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000...
        0.000   0.000];
else
    a1  = [0.835   1.426   1.330   1.333   1.261   1.231   1.119   0.947   0.794   0.721...
        0.695   0.844   0.990   0.830   0.655   0.600   0.824   0.798   0.989   0.764...
        0.798   0.758   0.907   1.165   1.238   1.165   0.986   0.685   0.398   0.333...
        0.579   0.704   0.318   0.446   0.391   0.253   0.075   -0.147  0.193   -0.036...
        -0.508  -0.429  -0.617  -0.272  -0.786  -1.112  -1.200  -1.594  -1.754  -1.838...
        -2.296  -2.616  -2.596  -2.512  -2.947  -3.007  -2.711  -2.765  -2.677  -3.340...
        -3.490  -3.731];
    a2  = [0.083   0.053   0.077   0.090   0.106   0.107   0.119   0.143   0.169   0.181...
        0.187   0.166   0.145   0.168   0.189   0.179   0.130   0.116   0.087   0.119...
        0.112   0.113   0.082   0.038   0.016   0.020   0.053   0.104   0.144   0.146...
        0.097   0.075   0.135   0.110   0.113   0.132   0.154   0.178   0.095   0.131...
        0.217   0.187   0.214   0.143   0.220   0.272   0.296   0.361   0.383   0.391...
```

```
         0.457   0.507   0.526   0.518   0.550   0.556   0.531   0.531   0.502   0.616...
         0.623   0.633];
a3   = [-2.489  -2.681  -2.598  -2.601  -2.538  -2.497  -2.403  -2.287  -2.171  -2.123...
        -2.119  -2.217  -2.270  -2.133  -2.048  -2.012  -2.107  -2.093  -2.262  -2.160...
        -2.208  -2.182  -2.319  -2.543  -2.590  -2.594  -2.574  -2.402  -2.251  -2.247...
        -2.415  -2.502  -2.345  -2.466  -2.478  -2.455  -2.381  -2.334  -2.521  -2.463...
        -2.337  -2.326  -2.339  -2.512  -2.377  -2.208  -2.185  -2.017  -2.033  -2.059...
        -1.787  -1.581  -1.692  -1.835  -1.661  -1.640  -1.655  -1.663  -1.781  -1.287...
        -1.265  -1.182];
a4   = [0.206   0.217   0.200   0.195   0.185   0.183   0.173   0.158   0.140   0.132...
         0.131   0.146   0.154   0.136   0.127   0.132   0.152   0.160   0.185   0.170...
         0.177   0.174   0.197   0.231   0.245   0.249   0.242   0.212   0.189   0.191...
         0.221   0.234   0.209   0.230   0.233   0.228   0.219   0.216   0.258   0.244...
         0.216   0.220   0.223   0.255   0.236   0.208   0.196   0.164   0.163   0.167...
         0.123   0.088   0.089   0.106   0.099   0.095   0.083   0.085   0.111   0.031...
         0.035   0.035];
a5   = [5.6 4.7 5.1 5.7 6.0 6.1 6.0 5.8 6.1 6.5 6.7 7.1 7.8 7.9 7.7 6.7 6.4 5.6 6.0 5.9...
         6.3 6.3 5.9 6.7 6.2 5.9 6.1 6.4 6.4 6.3 6.2 6.2 6.1 6.5 6.8 6.8 6.6 6.5 5.5 6.0...
         6.7 6.0 6.4 6.0 5.6 5.7 6.7 7.3 7.8 8.0 8.9 9.3 11.9    12.8    9.1 8.7 11.8...
         11.7    11.1    11.1    10.2    7.7];
a6   = [0.078   0.090   0.086   0.091   0.082   0.081   0.079   0.075   0.070   0.078...
         0.081   0.083   0.079   0.065   0.053   0.057   0.077   0.079   0.089   0.099...
         0.107   0.111   0.117   0.118   0.111   0.112   0.111   0.103   0.110   0.120...
         0.128   0.127   0.129   0.130   0.136   0.147   0.151   0.149   0.167   0.187...
         0.208   0.219   0.251   0.261   0.281   0.281   0.269   0.269   0.284   0.302...
         0.313   0.319   0.313   0.305   0.313   0.307   0.319   0.318   0.306   0.234...
         0.228   0.221];
a7   = [0.046   0.039   0.041   0.051   0.058   0.050   0.047   0.045   0.047   0.054...
         0.055   0.050   0.057   0.054   0.045   0.055   0.058   0.050   0.045   0.056...
         0.057   0.056   0.072   0.091   0.082   0.083   0.082   0.070   0.071   0.072...
         0.077   0.087   0.103   0.101   0.103   0.105   0.103   0.108   0.099   0.107...
         0.114   0.109   0.140   0.120   0.138   0.126   0.117   0.117   0.141   0.151...
         0.174   0.178   0.184   0.176   0.154   0.146   0.171   0.170   0.145   0.112...
         0.112   0.097];
a8   = [-0.126  -0.168  -0.162  -0.171  -0.172  -0.164  -0.149  -0.142  -0.132  -0.118...
        -0.116  -0.108  -0.105  -0.104  -0.090  -0.084  -0.082  -0.067  -0.054  -0.045...
        -0.035  -0.025  -0.029  -0.039  -0.051  -0.042  -0.047  -0.055  -0.042  -0.031...
        -0.023  -0.025  -0.034  -0.017  0.002   0.017   0.026   0.027   0.037   0.047...
         0.033   0.044   0.018   0.051   0.028   0.032   0.050   0.049   0.053   0.049...
         0.100   0.102   0.124   0.104   0.076   0.060   0.051   0.056   0.058   0.024...
         0.018   0.012];
a9   = [0.005   0.005   -0.009  -0.016  -0.026  -0.011  -0.011  -0.013  0.000   0.012...
         0.007   0.003   -0.014  -0.025  -0.013  -0.006  0.009   0.036   0.051   0.053...
         0.059   0.073   0.088   0.094   0.078   0.066   0.070   0.068   0.071   0.082...
         0.098   0.108   0.090   0.081   0.082   0.085   0.092   0.099   0.125   0.125...
         0.113   0.157   0.130   0.163   0.142   0.144   0.145   0.113   0.104   0.077...
         0.067   0.054   0.049   0.036   0.053   0.047   0.113   0.128   0.140   0.122...
         0.114   0.092];
a10  = [-0.082  -0.070  -0.067  -0.069  -0.078  -0.083  -0.077  -0.075  -0.078  -0.083...
        -0.089  -0.091  -0.100  -0.091  -0.087  -0.084  -0.084  -0.078  -0.080  -0.077...
        -0.074  -0.068  -0.051  -0.056  -0.071  -0.064  -0.052  -0.056  -0.056  -0.055...
        -0.061  -0.069  -0.078  -0.081  -0.070  -0.052  -0.047  -0.029  -0.037  -0.024...
        -0.013  -0.026  -0.060  -0.056  -0.074  -0.081  -0.073  -0.070  -0.055  -0.062...
        -0.052  -0.078  -0.067  -0.080  -0.110  -0.128  -0.148  -0.155  -0.156  -0.111...
        -0.110  -0.098];
s1A  = [0.262   0.301   0.296   0.295   0.292   0.290   0.290   0.293   0.295   0.294...
         0.287   0.287   0.285   0.281   0.278   0.282   0.554   0.619   0.684   0.607...
         0.591   0.625   0.672   0.613   0.670   0.605   0.569   0.572   0.537   0.544...
         0.577   0.551   0.270   0.272   0.272   0.273   0.275   0.273   0.602   0.569...
         0.284   0.587   0.278   0.598   0.277   0.277   0.278   0.286   0.279   0.282...
         0.279   0.285   0.291   0.296   0.292   0.294   0.290   0.291   0.293   0.297...
         0.291   0.283];
s1B  = [0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000...
         0.000   0.000   0.000   0.000   0.000   0.000   0.045   0.056   0.067   0.055...
         0.053   0.059   0.067   0.057   0.067   0.056   0.051   0.051   0.047   0.048...
         0.054   0.049   0.000   0.000   0.000   0.000   0.000   0.000   0.056   0.050...
         0.000   0.052   0.000   0.055   0.000   0.000   0.000   0.000   0.000   0.000...
         0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000...
         0.000   0.000];
s2A  = [0.100   0.115   0.112   0.111   0.109   0.106   0.106   0.108   0.108   0.106...
         0.106   0.106   0.104   0.105   0.104   0.103   0.203   0.220   0.242   0.216...
```

```
            0.204   0.212   0.235   0.213   0.238   0.217   0.215   0.216   0.205   0.209...
            0.224   0.215   0.103   0.101   0.102   0.105   0.108   0.115   0.259   0.239...
            0.120   0.245   0.118   0.248   0.121   0.119   0.115   0.113   0.118   0.121...
            0.110   0.108   0.111   0.117   0.129   0.129   0.126   0.128   0.132   0.131...
            0.131   0.135];
    s2B  = [0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000...
            0.000   0.000   0.000   0.000   0.000   0.000   0.017   0.020   0.024   0.020...
            0.018   0.020   0.023   0.020   0.024   0.020   0.019   0.019   0.018   0.019...
            0.021   0.019   0.000   0.000   0.000   0.000   0.000   0.000   0.024   0.021...
            0.000   0.022   0.000   0.023   0.000   0.000   0.000   0.000   0.000   0.000...
            0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000...
            0.000   0.000];
end
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = ADSS_2005(T_low, M, C, F, Rjb, S);
    [sa_hi,  sigma_hi]  = ADSS_2005(T_hi,  M, C, F, Rjb, S);
    x = [log10(T_low) log10(T_hi)];
    Y_sa = [log10(sa_low) log10(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = 10^(interp1(x,Y_sa,log10(T)));
    sigma = interp1(x,Y_sigma,log10(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    FN = (F == 2);
    FT = (F == 3);
    FO = (F == 4);
    SS = (S == 1);
    SA = (S == 2);
    Sa = 10^(a1(i) + a2(i)*M + (a3(i) + a4(i)*M)*log10(sqrt(Rjb^2 + a5(i)^2)) + ...
         a6(i)*SS + a7(i)*SA + a8(i)*FN + a9(i)*FT + a10(i)*FO);
    sig1 = s1A(i) - s1B(i)*M;
    sig2 = s2A(i) - s2B(i)*M;
    sigma = sqrt(sig1^2 + sig2^2);
end
```

5.4 Europe/Middle East: Akkar and Bommer – 2010

5.4.1 References

Akkar, S., and J. J. Bommer (2010). Empirical Equations for the Prediction of PGA, PGV, and Spectral Accelerations in Europe, the Mediterranean Region, and the Middle East, *Seismological Research Letters* **81**(2), 195-206.

Akkar, S., and J. J. Bommer (2007). Prediction of elastic displacement response spectra in Europe and the Middle East, *Earthquake Engineering & Structural Dynamics* **36**(10), 1275-1301.

5.4.2 Abstract

Using 532 strong ground motions records (from 131 earthquakes) from Europe and the Middle East, empirical ground-motion models for the average horizontal and vertical components were developed. The model predicts peak ground acceleration (PGA, in cm/s^2), peak ground velocity (PGV in cm/s) and 5%-damped spectral values (in cm/s^2) for periods ranging from 0.05 to 3.0 s. Based on the bounds of the earthquakes in the database, this model is most applicable for earthquakes between M5.0 and M7.6 and distances up to 100 km. Note: the MATLAB code converts all accelerations to g's.

5.4.3 Attenuation Relationship

The spectral acceleration is a function of:

T – Period (sec), use 0 for PGA
M – Moment magnitude
F – Fault Type: 0 for strike slip, 1 for normal, and 2 for reverse
R_{jb} – Joyner-Boore distance (km)
S – Soil Type: 2 for soft soil, 1 for stiff soil, 0 for rock

$$\log_{10}(Sa) = b_1 + b_2M + b_3M^2 + (b_4 + b_5M)\log_{10}\sqrt{{R_{jb}}^2 + {b_6}^2} + b_7S_S + b_8S_A + b_9F_N + b_{10}F_R$$

where:

$$S_S = \begin{cases} 1 & for\ soft\ soil\ sites \\ & (V_{S30} < 360\ m/s) \\ 0 & otherwise \end{cases} \qquad F_N = \begin{cases} 1 & for\ normal\ fault \\ 0 & otherwise \end{cases}$$

$$S_A = \begin{cases} 1 & for\ stiff\ soil\ sites \\ & (750\ m/s > V_{S30} > 360\ m/s) \\ 0 & otherwise \end{cases} \qquad F_R = \begin{cases} 1 & for\ reverse\ fault \\ 0 & otherwise \end{cases}$$

Standard Error

$$\sigma_{tot} = \sqrt{{\sigma_1}^2 + {\sigma_2}^2}$$

Coefficients

T (sec)	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	σ_{tot}
0.00	1.04159	0.91333	-0.08140	-2.92728	0.28120	7.86638	0.08753	0.01527	-0.04189	0.08015	0.279287236
0.05	2.11528	0.72571	-0.07351	-3.33201	0.33534	7.74734	0.04707	-0.02426	-0.04260	0.08649	0.295001085
0.10	2.11994	0.75179	-0.07448	-3.10538	0.30253	8.21405	0.02667	-0.00062	-0.04906	0.07910	0.296713212
0.15	1.64489	0.83683	-0.07544	-2.75848	0.25490	8.31786	0.02578	0.01703	-0.04184	0.07840	0.303212928
0.20	0.92065	0.96815	-0.07903	-2.49264	0.21790	8.21914	0.06557	0.02105	-0.02098	0.08438	0.302102665
0.25	0.13978	1.13068	-0.08761	-2.33824	0.20089	7.20688	0.09810	0.03919	-0.04853	0.08577	0.303689661
0.30	-0.84006	1.37439	-0.10349	-2.19123	0.18139	6.54299	0.12847	0.04340	-0.05554	0.09221	0.306172827
0.35	-1.32207	1.47055	-0.10873	-2.12993	0.17485	6.24751	0.16213	0.06695	-0.04722	0.09003	0.316373276
0.40	-1.70320	1.55930	-0.11388	-2.12718	0.17137	6.57173	0.21222	0.09201	-0.05145	0.09903	0.319377598
0.45	-1.97201	1.61645	-0.11742	-2.16619	0.17700	6.78082	0.24121	0.11675	-0.05202	0.09943	0.323797746
0.50	-2.76925	1.83268	-0.13202	-2.12969	0.16877	7.17423	0.25944	0.13562	-0.04283	0.08579	0.329038797
0.55	-3.51672	2.02523	-0.14495	-2.04211	0.15617	6.76170	0.26498	0.14446	-0.04259	0.06945	0.332384958
0.60	-3.92759	2.08471	-0.14648	-1.88144	0.13621	6.10103	0.27718	0.15156	-0.03853	0.05932	0.332970704
0.65	-4.49490	2.21154	-0.15522	-1.79031	0.12916	5.19135	0.28574	0.15239	-0.03423	0.05111	0.337848072
0.70	-4.62925	2.21764	-0.15491	-1.79800	0.13495	4.46323	0.30348	0.15652	-0.04146	0.04661	0.339298688
0.75	-4.95053	2.29142	-0.15983	-1.81321	0.13920	4.27945	0.31516	0.16333	-0.04050	0.04253	0.337714865
0.80	-5.32863	2.38389	-0.16571	-1.77273	0.13273	4.37011	0.32153	0.17366	-0.03946	0.03373	0.332812034
0.85	-5.75799	2.50635	-0.17479	-1.77068	0.13096	4.62192	0.33520	0.18480	-0.03786	0.02867	0.329996030
0.90	-5.82689	2.50287	-0.17367	-1.76295	0.13059	4.65393	0.34849	0.19061	-0.02884	0.02475	0.328795772
0.95	-5.90592	2.51405	-0.17417	-1.79854	0.13535	4.84540	0.35919	0.19411	-0.02209	0.02502	0.326833291
1.00	-6.17066	2.58558	-0.17938	-1.80717	0.13599	4.97596	0.36619	0.19519	-0.02269	0.02121	0.325273946
1.05	-6.60337	2.69584	-0.18646	-1.73843	0.12485	5.04489	0.37278	0.19461	-0.02613	0.01115	0.323832812
1.10	-6.90379	2.77044	-0.19171	-1.71109	0.12227	5.00975	0.37756	0.19423	-0.02655	0.00140	0.322848958
1.15	-6.96180	2.75857	-0.18890	-1.66588	0.11447	5.08902	0.38149	0.19402	-0.02088	0.00148	0.320965201
1.20	-6.99236	2.73427	-0.18491	-1.59120	0.10265	5.03274	0.38120	0.19309	-0.01623	0.00413	0.321770182
1.25	-6.74613	2.62375	-0.17392	-1.52886	0.09129	5.08347	0.38782	0.19392	-0.01826	0.00413	0.321060399
1.30	-6.51719	2.51869	-0.16330	-1.46527	0.08005	5.14423	0.38862	0.19273	-0.01902	-0.00369	0.320429243
1.35	-6.55821	2.52238	-0.16307	-1.48223	0.08173	5.29006	0.38677	0.19082	-0.01842	-0.00897	0.321906959
1.40	-6.61945	2.52611	-0.16274	-1.48257	0.08213	5.33490	0.38625	0.19285	-0.01607	-0.00876	0.322356774
1.45	-6.62737	2.49858	-0.15910	-1.43310	0.07577	5.19412	0.38285	0.19161	-0.01288	-0.00564	0.321620553
1.50	-6.71787	2.49486	-0.15689	-1.35301	0.06379	5.15750	0.37867	0.18812	-0.01208	-0.00215	0.319608276
1.55	-6.80776	2.50291	-0.15629	-1.31227	0.05697	5.27441	0.37267	0.18568	-0.00845	-0.00047	0.319319981
1.60	-6.83632	2.51009	-0.15676	-1.33260	0.05870	5.54539	0.36952	0.18149	-0.00533	-0.00006	0.319549448
1.65	-6.88684	2.54048	-0.15995	-1.40931	0.06860	5.93828	0.36531	0.17617	-0.00852	-0.00301	0.321407685
1.70	-6.94600	2.57151	-0.16294	-1.47676	0.07672	6.36599	0.35936	0.17301	-0.01204	-0.00744	0.322923660
1.75	-7.09166	2.62938	-0.16794	-1.54037	0.08428	6.82292	0.35284	0.16945	-0.01386	-0.01387	0.323928449
1.80	-7.22818	2.66824	-0.17057	-1.54273	0.08325	7.11603	0.34775	0.16743	-0.01402	-0.01492	0.324565556
1.85	-7.29772	2.67565	-0.17004	-1.50936	0.07663	7.31928	0.34561	0.16730	-0.01526	-0.01192	0.324531170
1.90	-7.35522	2.67749	-0.16934	-1.46988	0.07065	7.25988	0.34142	0.16325	-0.01563	-0.00703	0.325293667
1.95	-7.40716	2.68206	-0.16906	-1.43816	0.06525	7.25344	0.33720	0.16171	-0.01848	-0.00351	0.327358947
2.00	-7.50404	2.71004	-0.17130	-1.44395	0.06602	7.26059	0.33298	0.15839	-0.02258	-0.00486	0.328372867
2.05	-7.55598	2.72737	-0.17291	-1.45794	0.06774	7.40320	0.33010	0.15496	-0.02626	-0.00731	0.328863513
2.10	-7.53463	2.71709	-0.17221	-1.46662	0.06940	7.46168	0.32645	0.15337	-0.02920	-0.00871	0.328417311
2.15	-7.50811	2.71035	-0.17212	-1.49679	0.07429	7.51273	0.32439	0.15264	-0.03484	-0.01225	0.328143581
2.20	-8.09168	2.91159	-0.18920	-1.55644	0.08428	7.77062	0.31354	0.14430	-0.03985	-0.01927	0.326435736
2.25	-8.11057	2.92087	-0.19044	-1.59537	0.09052	7.87702	0.30997	0.14430	-0.04155	-0.02322	0.326435736
2.30	-8.16272	2.93325	-0.19155	-1.60461	0.09284	7.91753	0.30826	0.14412	-0.04238	-0.02626	0.326648588
2.35	-7.94704	2.85328	-0.18539	-1.57428	0.09077	7.61956	0.32071	0.14321	-0.04963	-0.02342	0.325386678
2.40	-7.96679	2.85363	-0.18561	-1.57833	0.09288	7.59643	0.31801	0.14301	-0.04910	-0.02570	0.326990841
2.45	-7.97878	2.84900	-0.18527	-1.57728	0.09428	7.50338	0.31401	0.14324	-0.04812	-0.02643	0.327915385
2.50	-7.88403	2.81817	-0.18320	-1.60381	0.09887	7.53947	0.31104	0.14332	-0.04710	-0.02769	0.328129319
2.55	-7.68101	2.75720	-0.17905	-1.65212	0.10680	7.61893	0.30875	0.14343	-0.04607	-0.02819	0.328488478
2.60	-7.72574	2.82043	-0.18717	-1.88782	0.14049	8.12248	0.31122	0.14255	-0.05106	-0.02966	0.332946317
2.65	-7.53288	2.74824	-0.18142	-1.89525	0.14356	7.92236	0.30935	0.14223	-0.05024	-0.02930	0.334486263
2.70	-7.41587	2.69012	-0.17632	-1.87041	0.14283	7.49999	0.30688	0.14074	-0.04887	-0.02963	0.335936006
2.75	-7.34541	2.65352	-0.17313	-1.86079	0.14340	7.26668	0.30635	0.14052	-0.04743	-0.02919	0.337196278
2.80	-7.24561	2.61028	-0.16951	-1.85612	0.14444	7.11861	0.30534	0.13923	-0.04731	-0.02751	0.338202972
2.85	-7.07107	2.56123	-0.16616	-1.90422	0.15127	7.36277	0.30508	0.13933	-0.04522	-0.02776	0.338054803
2.90	-6.99332	2.52699	-0.16303	-1.89704	0.15039	7.45038	0.30362	0.13776	-0.04203	-0.02615	0.338268119
2.95	-6.95669	2.51006	-0.16142	-1.90132	0.15081	7.60234	0.29987	0.13584	-0.03863	-0.02487	0.338045456
3.00	-6.92924	2.45899	-0.15513	-1.76801	0.13314	7.21950	0.29772	0.13198	-0.03855	-0.02469	0.338490783
PGV	-2.12833	1.21448	-0.08137	-2.46942	0.22349	6.41443	0.20354	0.08484	-0.05856	0.01305	0.278149834

5.4.4 Calibration Plots

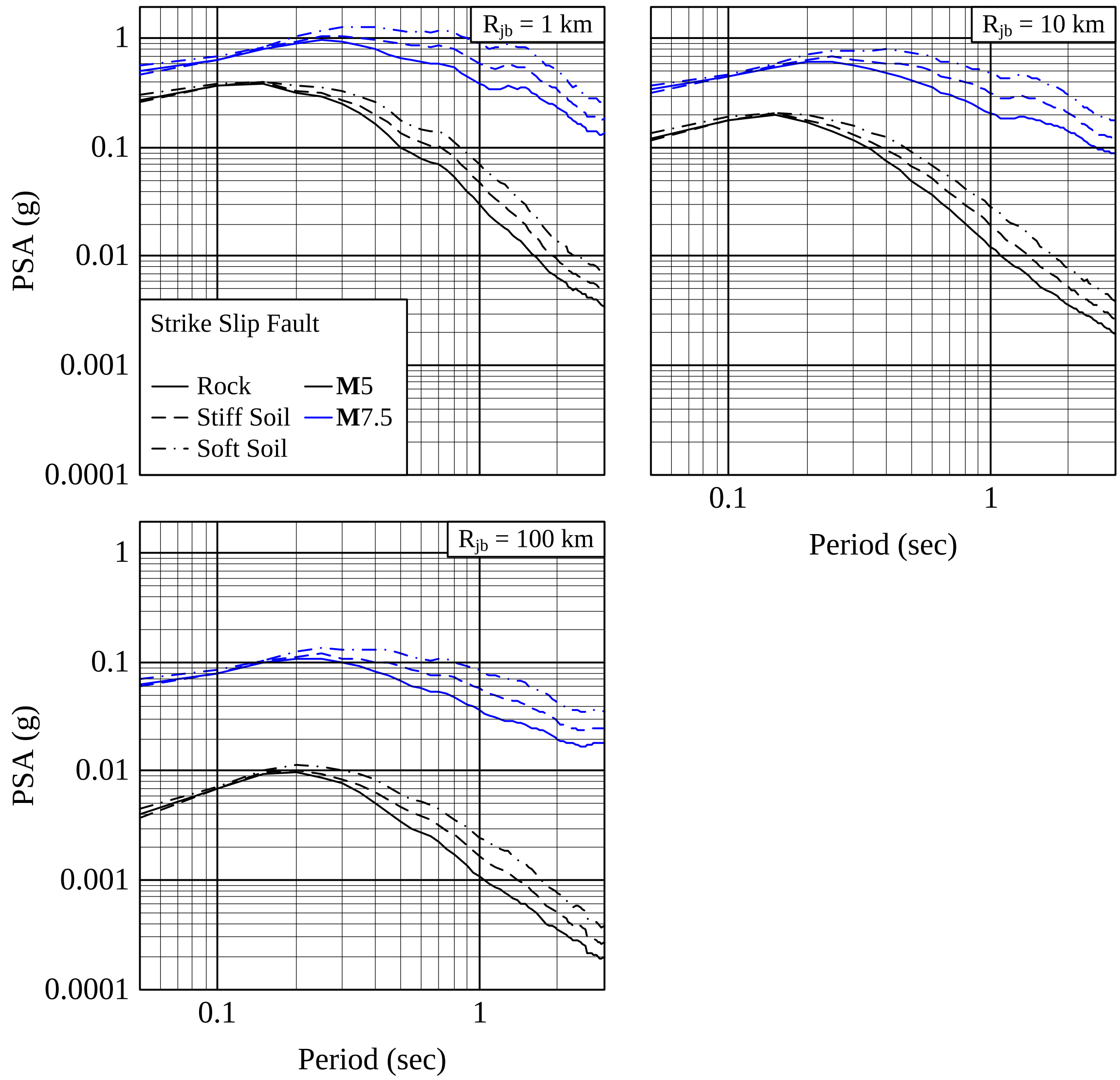


Figure 5-14. PSA for a strike-slip fault as a function of period for various soil types, magnitudes, and distances.

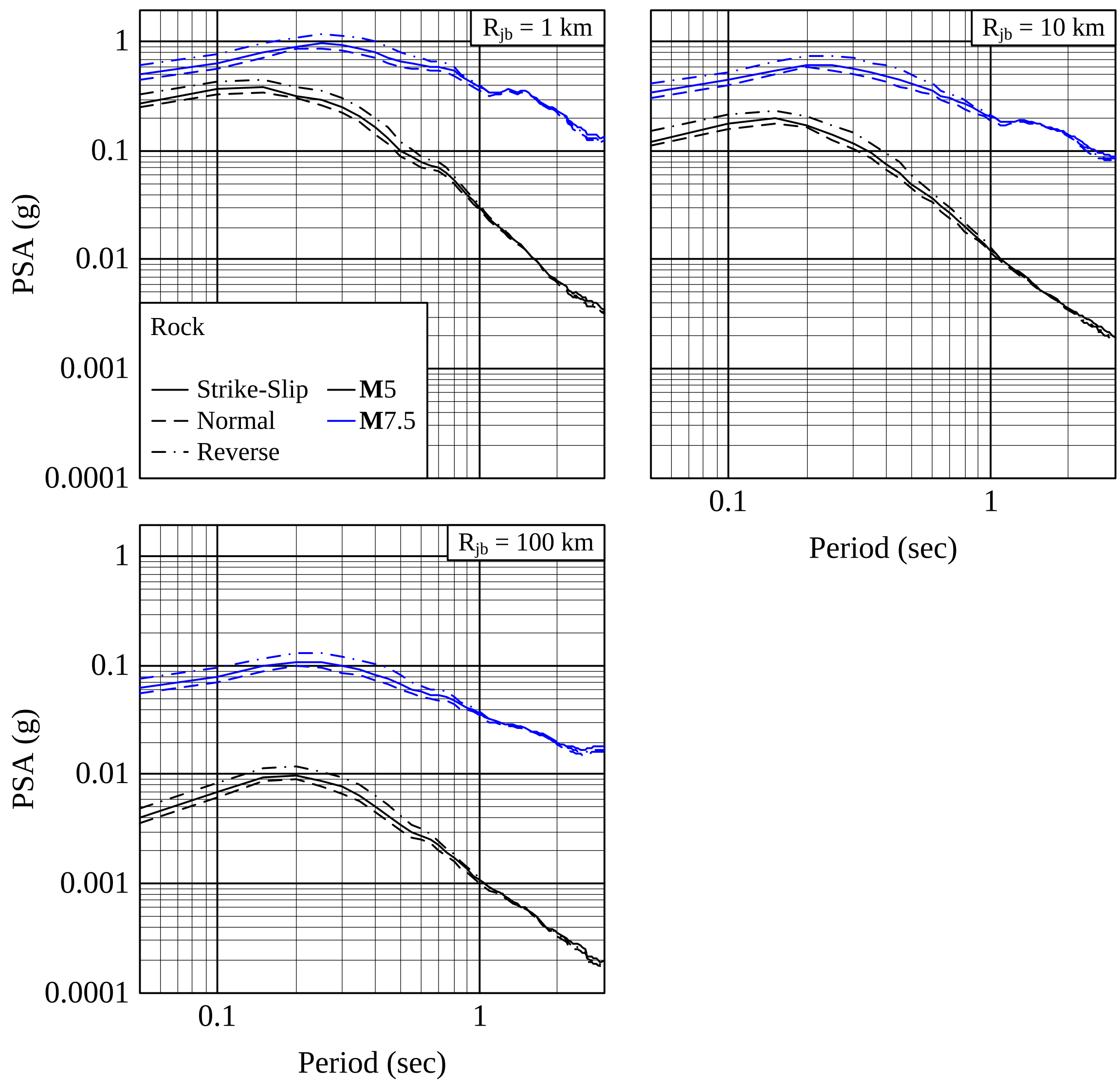


Figure 5-15. PSA for a rock site as a function of period for various fault types, magnitudes, and distances.

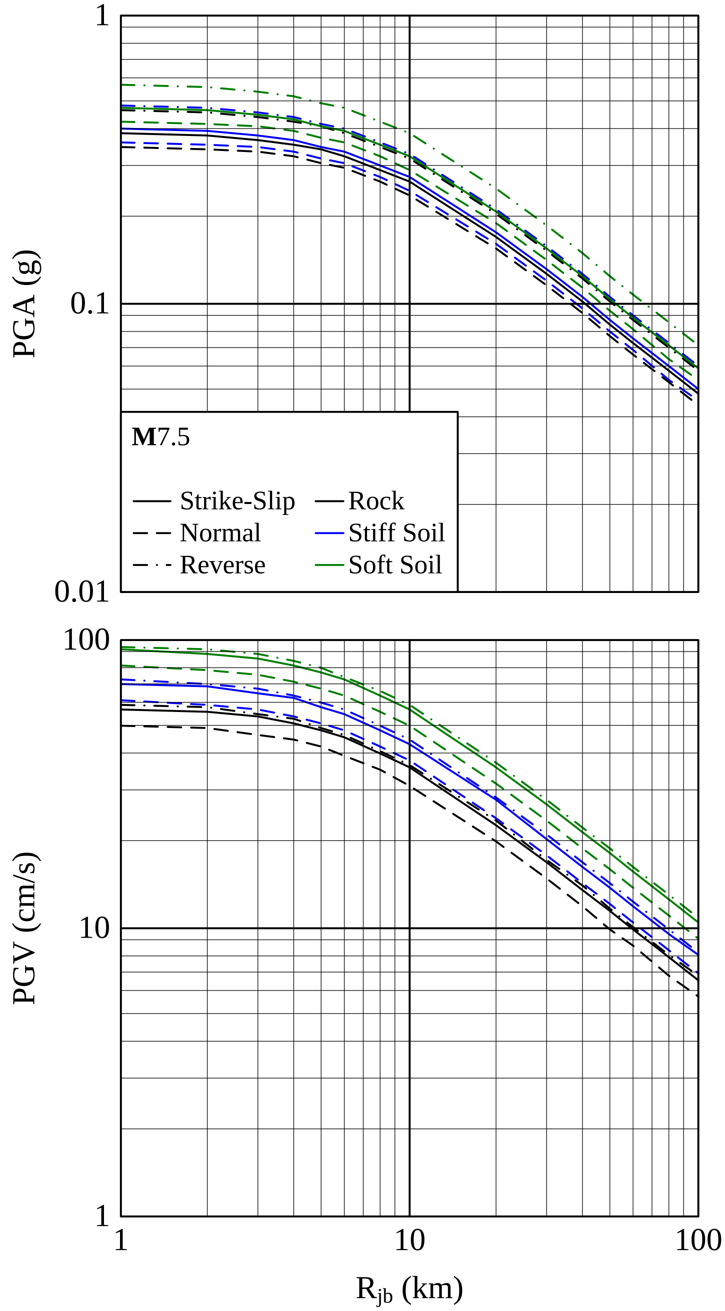


Figure 5-16. PGA and PGV for a M7.5 earthquake as a function of distance for various soil types and fault types.

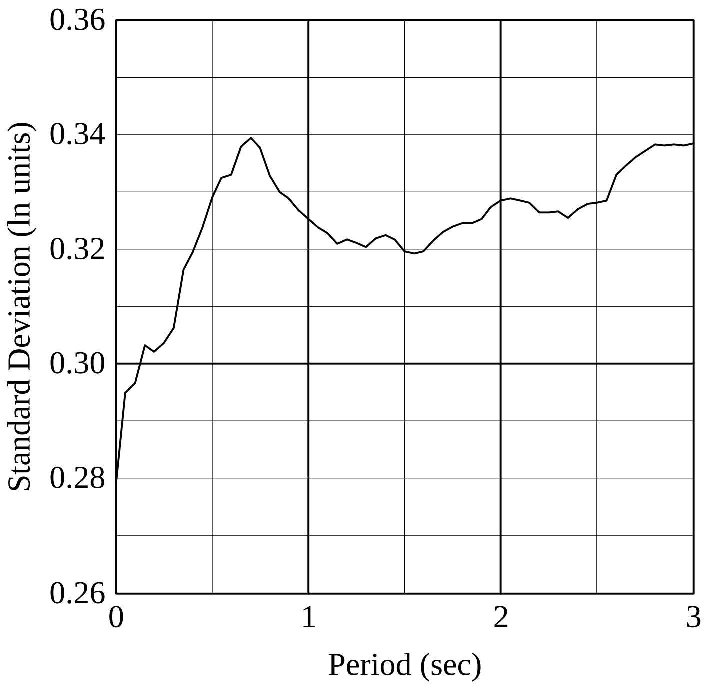


Figure 5-17. Standard deviation as a function of period. Note that standard deviation is not a function of magnitude, distance, fault type or soil type.

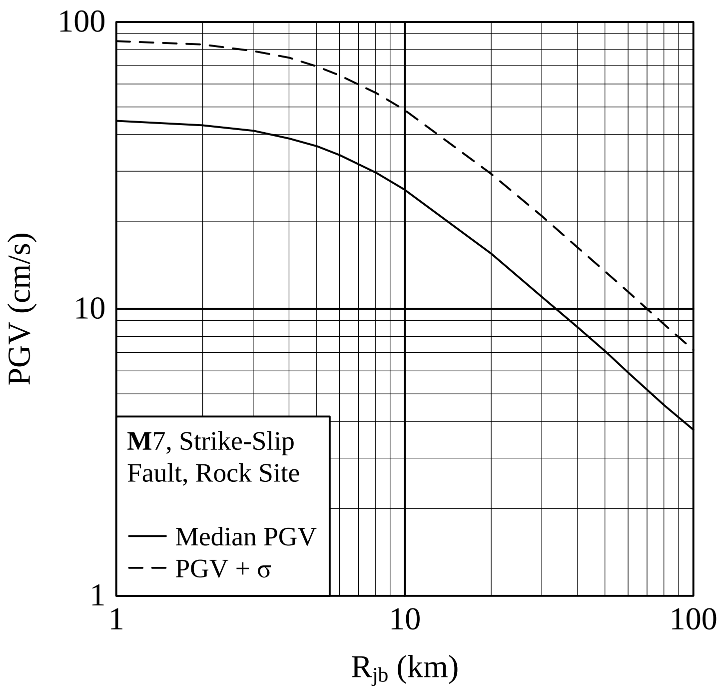


Figure 5-18. Example of application of median PGV plus one standard deviation.

5.4.5 Database

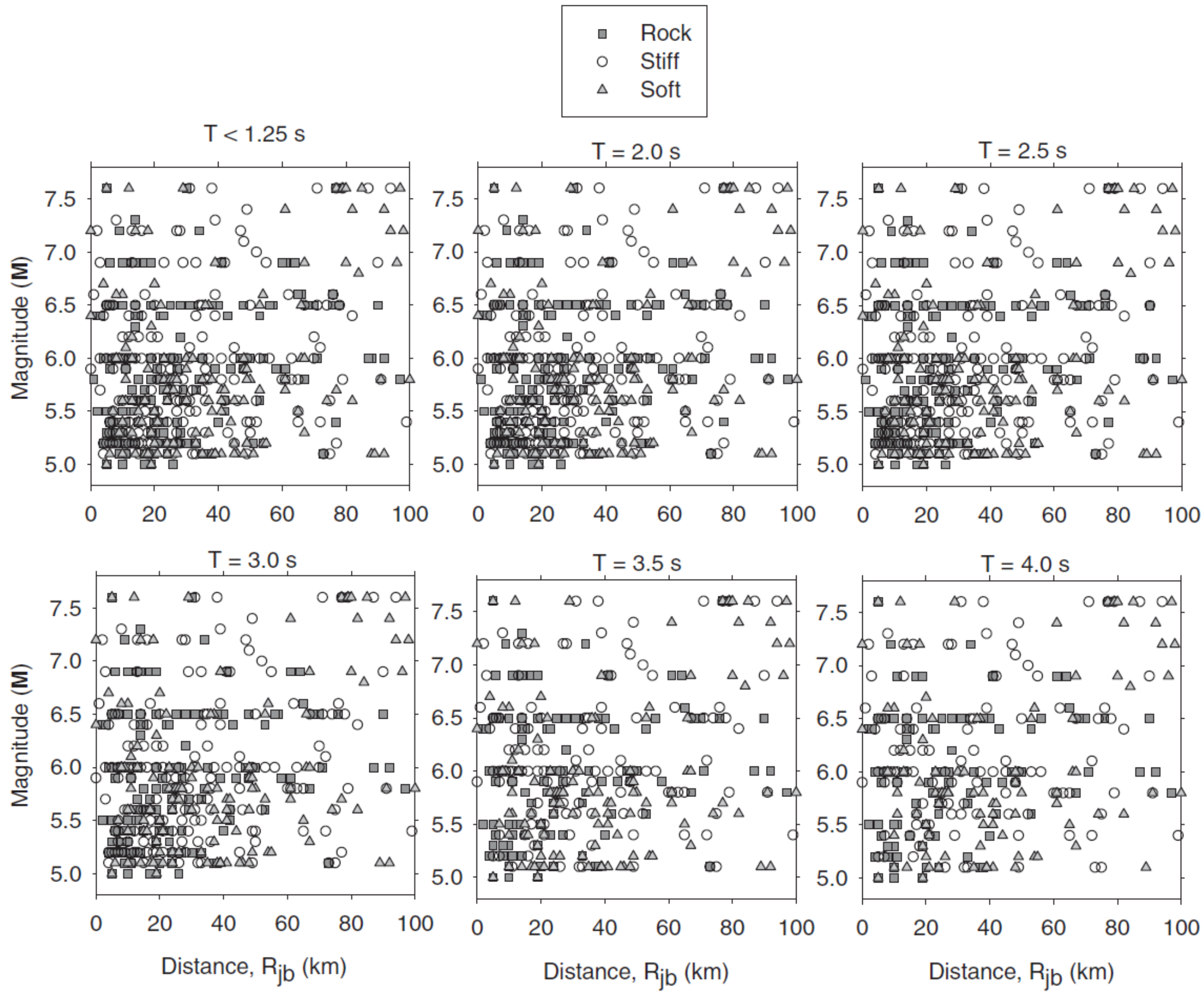


Figure 5-19. Magnitude-distance-site class distribution of database at different periods (from Akkar and Bommer 2007).

5.4.6 MATLAB Code

```
% by Kathryn A. Gunberg 3/10/2010
% Virginia Tech
% kgunberg@vt.edu
%
% Akkar and Bommer attenuation equation, 2010
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0 for PGA, -1 for PGV
% M         = Magnitude
% F         = Fault type: 0 for strike-slip, 1 for normal, 2 for reverse
% Rjb       = Joyner-Boore distance (km)
% S         = Soil type: 2 for soft soil, 1 for stiff soil, 0 for rock
% -------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration, PGA or PGV prediction (g or cm/s)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = AB_2010(T, M, F, Rjb, S)
% Coefficients
period   = [0.00    0.05    0.10    0.15    0.20    0.25    0.30    0.35    0.40    0.45...
            0.50    0.55    0.60    0.65    0.70    0.75    0.80    0.85    0.90    0.95...
            1.00    1.05    1.10    1.15    1.20    1.25    1.30    1.35    1.40    1.45...
            1.50    1.55    1.60    1.65    1.70    1.75    1.80    1.85    1.90    1.95...
            2.00    2.05    2.10    2.15    2.20    2.25    2.30    2.35    2.40    2.45...
            2.50    2.55    2.60    2.65    2.70    2.75    2.80    2.85    2.90    2.95...
            3.00    -1];
b1       = [1.04159 2.11528 2.11994 1.64489 0.92065 0.13978 -0.84006    -1.32207    -1.70320...
            -1.97201    -2.76925    -3.51672    -3.92759    -4.49490    -4.62925    -4.95053...
            -5.32863    -5.75799    -5.82689    -5.90592    -6.17066    -6.60337    -6.90379...
            -6.96180    -6.99236    -6.74613    -6.51719    -6.55821    -6.61945    -6.62737...
            -6.71787    -6.80776    -6.83632    -6.88684    -6.94600    -7.09166    -7.22818...
            -7.29772    -7.35522    -7.40716    -7.50404    -7.55598    -7.53463    -7.50811...
            -8.09168    -8.11057    -8.16272    -7.94704    -7.96679    -7.97878    -7.88403...
            -7.68101    -7.72574    -7.53288    -7.41587    -7.34541    -7.24561    -7.07107...
            -6.99332    -6.95669    -6.92924    -2.12833];
b2       = [0.91333 0.72571 0.75179 0.83683 0.96815 1.13068 1.37439 1.47055 1.55930 1.61645...
            1.83268 2.02523 2.08471 2.21154 2.21764 2.29142 2.38389 2.50635 2.50287 2.51405...
            2.58558 2.69584 2.77044 2.75857 2.73427 2.62375 2.51869 2.52238 2.52611 2.49858...
            2.49486 2.50291 2.51009 2.54048 2.57151 2.62938 2.66824 2.67565 2.67749 2.68206...
            2.71004 2.72737 2.71709 2.71035 2.91159 2.92087 2.93325 2.85328 2.85363 2.84900...
            2.81817 2.75720 2.82043 2.74824 2.69012 2.65352 2.61028 2.56123 2.52699 2.51006...
            2.45899 1.21448];
b3       = [-0.08140    -0.07351    -0.07448    -0.07544    -0.07903    -0.08761    -0.10349...
            -0.10873    -0.11388    -0.11742    -0.13202    -0.14495    -0.14648    -0.15522...
            -0.15491    -0.15983    -0.16571    -0.17479    -0.17367    -0.17417    -0.17938...
            -0.18646    -0.19171    -0.18890    -0.18491    -0.17392    -0.16330    -0.16307...
            -0.16274    -0.15910    -0.15689    -0.15629    -0.15676    -0.15995    -0.16294...
            -0.16794    -0.17057    -0.17004    -0.16934    -0.16906    -0.17130    -0.17291...
            -0.17221    -0.17212    -0.18920    -0.19044    -0.19155    -0.18539    -0.18561...
            -0.18527    -0.18320    -0.17905    -0.18717    -0.18142    -0.17632    -0.17313...
            -0.16951    -0.16616    -0.16303    -0.16142    -0.15513    -0.08137];
b4       = [-2.92728    -3.33201    -3.10538    -2.75848    -2.49264    -2.33824    -2.19123...
            -2.12993    -2.12718    -2.16619    -2.12969    -2.04211    -1.88144    -1.79031...
            -1.79800    -1.81321    -1.77273    -1.77068    -1.76295    -1.79854    -1.80717...
            -1.73843    -1.71109    -1.66588    -1.59120    -1.52886    -1.46527    -1.48223...
            -1.48257    -1.43310    -1.35301    -1.31227    -1.33260    -1.40931    -1.47676...
            -1.54037    -1.54273    -1.50936    -1.46988    -1.43816    -1.44395    -1.45794...
            -1.46662    -1.49679    -1.55644    -1.59537    -1.60461    -1.57428    -1.57833...
            -1.57728    -1.60381    -1.65212    -1.88782    -1.89525    -1.87041    -1.86079...
            -1.85612    -1.90422    -1.89704    -1.90132    -1.76801    -2.46942];
b5       = [0.28120 0.33534 0.30253 0.25490 0.21790 0.20089 0.18139 0.17485 0.17137 0.17700...
            0.16877 0.15617 0.13621 0.12916 0.13495 0.13920 0.13273 0.13096 0.13059 0.13535...
            0.13599 0.12485 0.12227 0.11447 0.10265 0.09129 0.08005 0.08173 0.08213 0.07577...
            0.06379 0.05697 0.05870 0.06860 0.07672 0.08428 0.08325 0.07663 0.07065 0.06525...
            0.06602 0.06774 0.06940 0.07429 0.08428 0.09052 0.09284 0.09077 0.09288 0.09428...
            0.09887 0.10680 0.14049 0.14356 0.14283 0.14340 0.14444 0.15127 0.15039 0.15081...
```

```
            0.13314 0.22349];
b6        = [7.86638 7.74734 8.21405 8.31786 8.21914 7.20688 6.54299 6.24751 6.57173 6.78082...
            7.17423 6.76170 6.10103 5.19135 4.46323 4.27945 4.37011 4.62192 4.65393 4.84540...
            4.97596 5.04489 5.00975 5.08902 5.03274 5.08347 5.14423 5.29006 5.33490 5.19412...
            5.15750 5.27441 5.54539 5.93828 6.36599 6.82292 7.11603 7.31928 7.25988 7.25344...
            7.26059 7.40320 7.46168 7.51273 7.77062 7.87702 7.91753 7.61956 7.59643 7.50338...
            7.53947 7.61893 8.12248 7.92236 7.49999 7.26668 7.11861 7.36277 7.45038 7.60234...
            7.21950 6.41443];
b7        = [0.08753 0.04707 0.02667 0.02578 0.06557 0.09810 0.12847 0.16213 0.21222 0.24121...
            0.25944 0.26498 0.27718 0.28574 0.30348 0.31516 0.32153 0.33520 0.34849 0.35919...
            0.36619 0.37278 0.37756 0.38149 0.38120 0.38782 0.38862 0.38677 0.38625 0.38285...
            0.37867 0.37267 0.36952 0.36531 0.35936 0.35284 0.34775 0.34561 0.34142 0.33720...
            0.33298 0.33010 0.32645 0.32439 0.31354 0.30997 0.30826 0.32071 0.31801 0.31401...
            0.31104 0.30875 0.31122 0.30935 0.30688 0.30635 0.30534 0.30508 0.30362 0.29987...
            0.29772 0.20354];
b8        = [0.01527 -0.02426    -0.00062    0.01703 0.02105 0.03919 0.04340 0.06695 0.09201...
            0.11675 0.13562 0.14446 0.15156 0.15239 0.15652 0.16333 0.17366 0.18480 0.19061...
            0.19411 0.19519 0.19461 0.19423 0.19402 0.19309 0.19392 0.19273 0.19082 0.19285...
            0.19161 0.18812 0.18568 0.18149 0.17617 0.17301 0.16945 0.16743 0.16730 0.16325...
            0.16171 0.15839 0.15496 0.15337 0.15264 0.14430 0.14430 0.14412 0.14321 0.14301...
            0.14324 0.14332 0.14343 0.14255 0.14223 0.14074 0.14052 0.13923 0.13933 0.13776...
            0.13584 0.13198 0.08484];
b9        = [-0.04189    -0.04260    -0.04906    -0.04184    -0.02098    -0.04853    -0.05554...
            -0.04722    -0.05145    -0.05202    -0.04283    -0.04259    -0.03853    -0.03423...
            -0.04146    -0.04050    -0.03946    -0.03786    -0.02884    -0.02209    -0.02269...
            -0.02613    -0.02655    -0.02088    -0.01623    -0.01826    -0.01902    -0.01842...
            -0.01607    -0.01288    -0.01208    -0.00845    -0.00533    -0.00852    -0.01204...
            -0.01386    -0.01402    -0.01526    -0.01563    -0.01848    -0.02258    -0.02626...
            -0.02920    -0.03484    -0.03985    -0.04155    -0.04238    -0.04963    -0.04910...
            -0.04812    -0.04710    -0.04607    -0.05106    -0.05024    -0.04887    -0.04743...
            -0.04731    -0.04522    -0.04203    -0.03863    -0.03855    -0.05856];
b10       = [0.08015 0.08649 0.07910 0.07840 0.08438 0.08577 0.09221 0.09003 0.09903 0.09943...
            0.08579 0.06945 0.05932 0.05111 0.04661 0.04253 0.03373 0.02867 0.02475 0.02502...
            0.02121 0.01115 0.00140 0.00148 0.00413 0.00413 -0.00369    -0.00897    -0.00876...
            -0.00564    -0.00215    -0.00047    -0.00006    -0.00301    -0.00744    -0.01387...
            -0.01492    -0.01192    -0.00703    -0.00351    -0.00486    -0.00731    -0.00871...
            -0.01225    -0.01927    -0.02322    -0.02626    -0.02342    -0.02570    -0.02643...
            -0.02769    -0.02819    -0.02966    -0.02930    -0.02963    -0.02919    -0.02751...
            -0.02776    -0.02615    -0.02487    -0.02469    0.01305];
sigtot    = [0.279287236 0.295001085 0.296713212 0.303212928 0.302102665 0.303689661...
            0.306172827 0.316373276 0.319377598 0.323797746 0.329038797 0.332384958...
            0.332970704 0.337848072 0.339298688 0.337714865 0.332812034 0.329996030...
            0.328795772 0.326833291 0.325273946 0.323832812 0.322848958 0.320965201...
            0.321770182 0.321060399 0.320429243 0.321906959 0.322356774 0.321620553...
            0.319608276 0.319319981 0.319549448 0.321407685 0.322923660 0.323928449...
            0.324565556 0.324531170 0.325293667 0.327358947 0.328372867 0.328863513...
            0.328417311 0.328143581 0.326435736 0.326435736 0.326648588 0.325386678...
            0.326990841 0.327915385 0.328129319 0.328488478 0.332946317 0.334486263...
            0.335936006 0.337196278 0.338202972 0.338054803 0.338268119 0.338045456...
            0.338490783 0.278149834];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = AB_2010(T_low, M, F, Rjb, S);
    [sa_hi,  sigma_hi]  = AB_2010(T_hi, M, F, Rjb, S);
    x = [log10(T_low) log10(T_hi)];
    Y_sa = [log10(sa_low) log10(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = 10^(interp1(x,Y_sa,log10(T)));
    sigma = interp1(x,Y_sigma,log10(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    FN = (F == 1);
    FR = (F == 2);
    SS = (S == 2);
    SA = (S == 1);
    SaSI = 10^(b1(i) + b2(i)*M + b3(i)*M^2 + (b4(i) + b5(i)*M)*log10(sqrt(Rjb^2 + b6(i)^2)) + ...
         b7(i)*SS + b8(i)*SA + b9(i)*FN + b10(i)*FR);
    if T == -1
        Sa = SaSI;
```

```
    else
        Sa = SaSI/980.665;
    end
    sigma = sigtot(i);
end
```

5.5 Greece: Danciu and Tselentis – 2007

5.5.1 Reference

Danciu, L., and G-A. Tselentis (2007). Engineering Ground-Motion Parameters Attenuation Relationships for Greece, *Bulletin of the Seismological Society of America* **97**, 162-183.

Danciu, L. (2009). Swiss Seismological Service, Zurich, Switzerland. Written communication.

5.5.2 Abstract

Using 335 strong ground motions records from 151 Greek earthquakes, empirical ground-motion models for the average horizontal and vertical components were developed. The model predicts peak ground acceleration (PGA, in cm/s^2) and 5%-damped spectral values (in cm/s^2) for periods ranging from 0.05 to 2.5 s (as well as several other parameters not presented here). Based on the bounds of the earthquakes in the database, this model is most applicable for earthquakes between M4.5 and M6.9 and for distances up to 136 km. Note: the MATLAB code converts all accelerations to g's.

5.5.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA
- **M** – Moment magnitude
- F – Fault Type: 0 for normal, 1 for strike-slip and thrust
- R_{epi} – Epicentral distance(km)
- S – Soil Type: 0 for rock (V_{S30} > 800 m/s), 1 for stiff soil (360 < V_{S30} < 665 m/s) and 2 for soft soil (200 < V_{S30} < 360 m/s)

$$\log_{10}(Sa) = a + bM + c\log_{10}\sqrt{{R_{epi}}^2 + h^2} + eS + fF$$

Standard Error

$$\sigma_T = \sqrt{\tau^2 + \sigma^2}$$

Coefficients

Table 5-8. Coefficients used in relationship.

T (sec)	a	b	c	h	e	f	τ	σ	σ_T
0	0.883	0.458	-1.278	11.515	0.038	0.116	0.109	0.270	0.291
0.10	1.544	0.410	-1.364	11.708	0.039	0.112	0.139	0.264	0.299
0.15	1.810	0.429	-1.492	15.721	0.008	0.113	0.107	0.285	0.304
0.20	1.339	0.477	-1.368	14.302	0.024	0.103	0.103	0.287	0.304
0.25	1.126	0.537	-1.443	16.446	0.020	0.109	0.104	0.304	0.321
0.30	0.688	0.582	-1.374	15.117	0.034	0.121	0.107	0.323	0.341
0.35	0.311	0.623	-1.310	14.474	0.037	0.121	0.124	0.323	0.346
0.40	-0.109	0.669	-1.247	12.733	0.033	0.136	0.151	0.322	0.355
0.45	-0.361	0.702	-1.227	11.834	0.019	0.132	0.154	0.322	0.357
0.50	-0.619	0.726	-1.174	10.945	0.021	0.117	0.163	0.318	0.357
0.55	-0.823	0.735	-1.114	9.327	0.020	0.110	0.163	0.322	0.361
0.60	-0.938	0.742	-1.087	8.732	0.011	0.098	0.167	0.321	0.362
0.65	-1.060	0.750	-1.067	8.183	0.013	0.075	0.169	0.323	0.364
0.70	-1.177	0.756	-1.051	7.597	0.020	0.072	0.151	0.329	0.362
0.75	-1.265	0.762	-1.049	7.554	0.030	0.064	0.140	0.330	0.358
0.80	-1.315	0.770	-1.067	7.986	0.024	0.069	0.140	0.331	0.359
0.85	-1.366	0.782	-1.091	8.481	0.019	0.071	0.145	0.326	0.357
0.90	-1.429	0.791	-1.101	8.566	0.016	0.063	0.145	0.325	0.356
0.95	-1.464	0.797	-1.120	8.854	0.014	0.056	0.149	0.321	0.353
1.0	-1.517	0.799	-1.113	9.128	0.016	0.050	0.156	0.314	0.351
1.1	-1.650	0.806	-1.098	9.340	0.025	0.046	0.148	0.307	0.341
1.2	-1.661	0.799	-1.099	10.185	0.023	0.053	0.142	0.303	0.335
1.3	-1.663	0.790	-1.093	10.890	0.015	0.054	0.149	0.299	0.334
1.4	-1.745	0.779	-1.029	10.359	0.013	0.051	0.147	0.296	0.330
1.5	-1.786	0.764	-0.980	9.889	0.011	0.058	0.151	0.291	0.327
1.8	-1.747	0.729	-0.937	10.061	0.008	0.057	0.159	0.278	0.320
2.0	-1.764	0.687	-0.825	9.191	0.009	0.061	0.172	0.267	0.318
2.3	-1.697	0.644	-0.762	8.936	0.010	0.057	0.174	0.271	0.322
2.8	-1.617	0.585	-0.681	8.057	0.008	0.058	0.195	0.270	0.333
3.0	-1.612	0.562	-0.632	6.711	-0.002	0.057	0.205	0.263	0.333
3.5	-1.669	0.534	-0.565	5.347	-0.010	0.064	0.205	0.259	0.330
4.0	-1.834	0.540	-0.573	5.160	-0.007	0.070	0.194	0.258	0.322

5.5.4 Calibration Plots

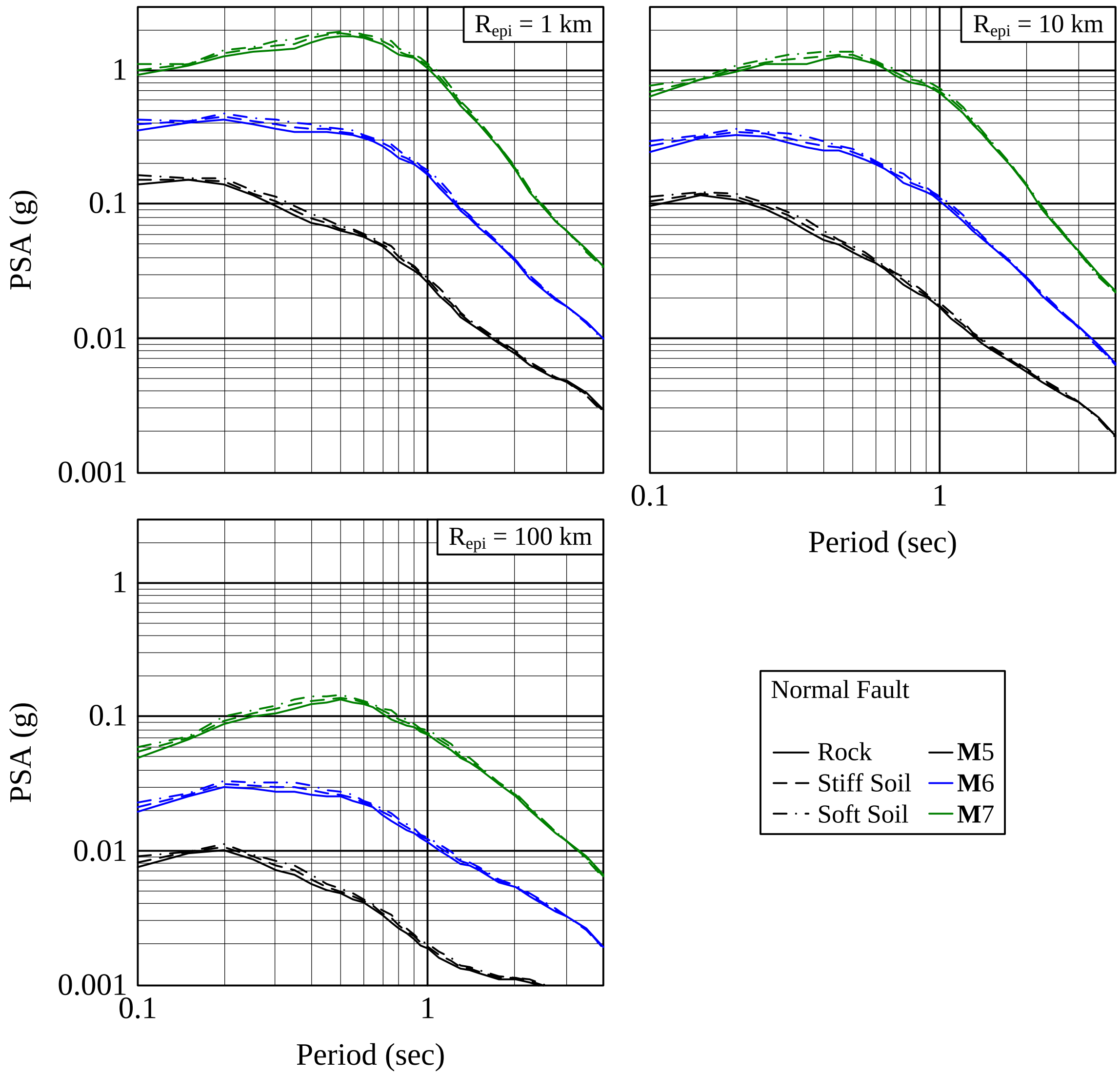


Figure 5-20. PSA as a function of period for given conditions.

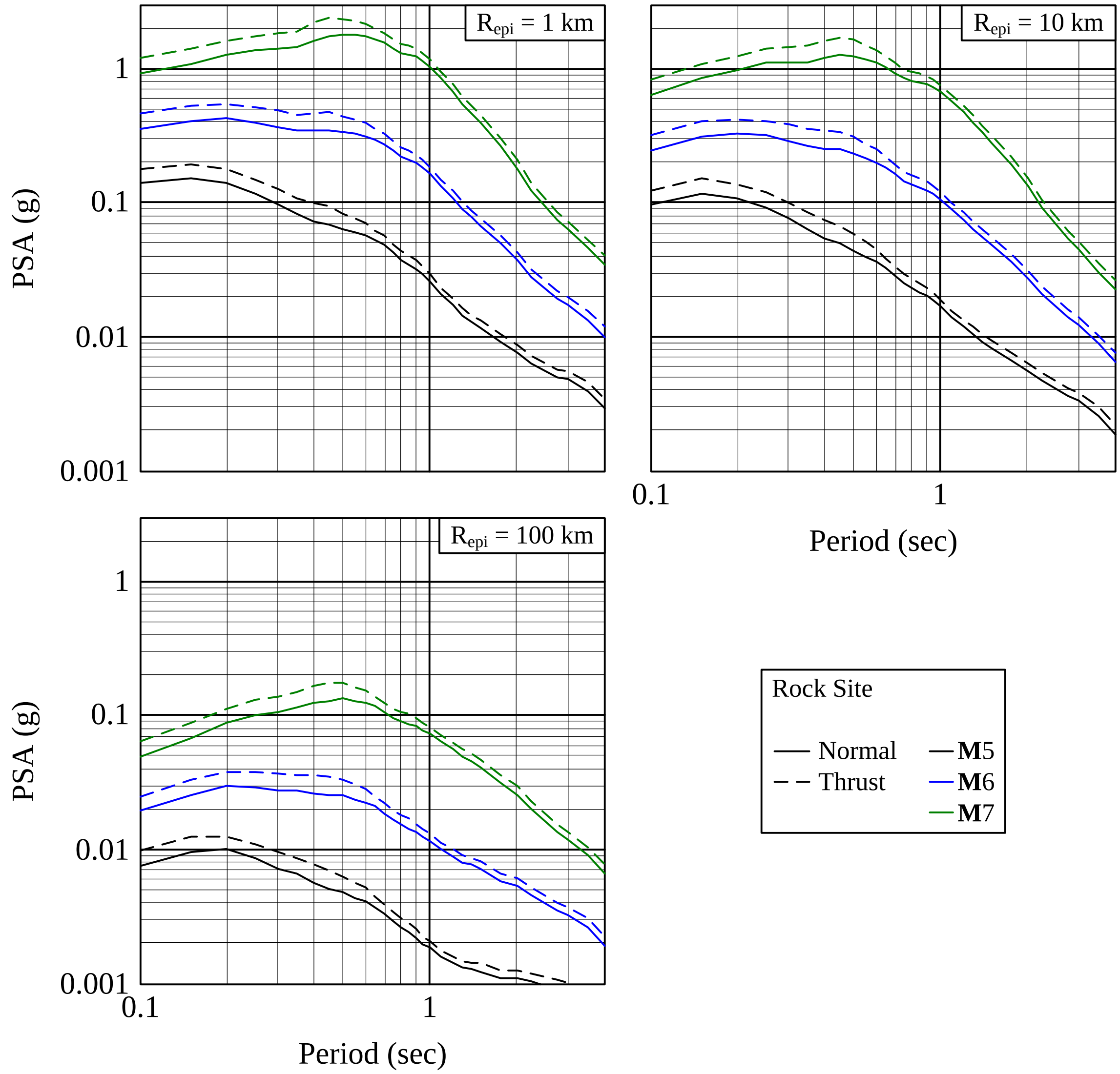


Figure 5-21. PSA as a function of period for given conditions.

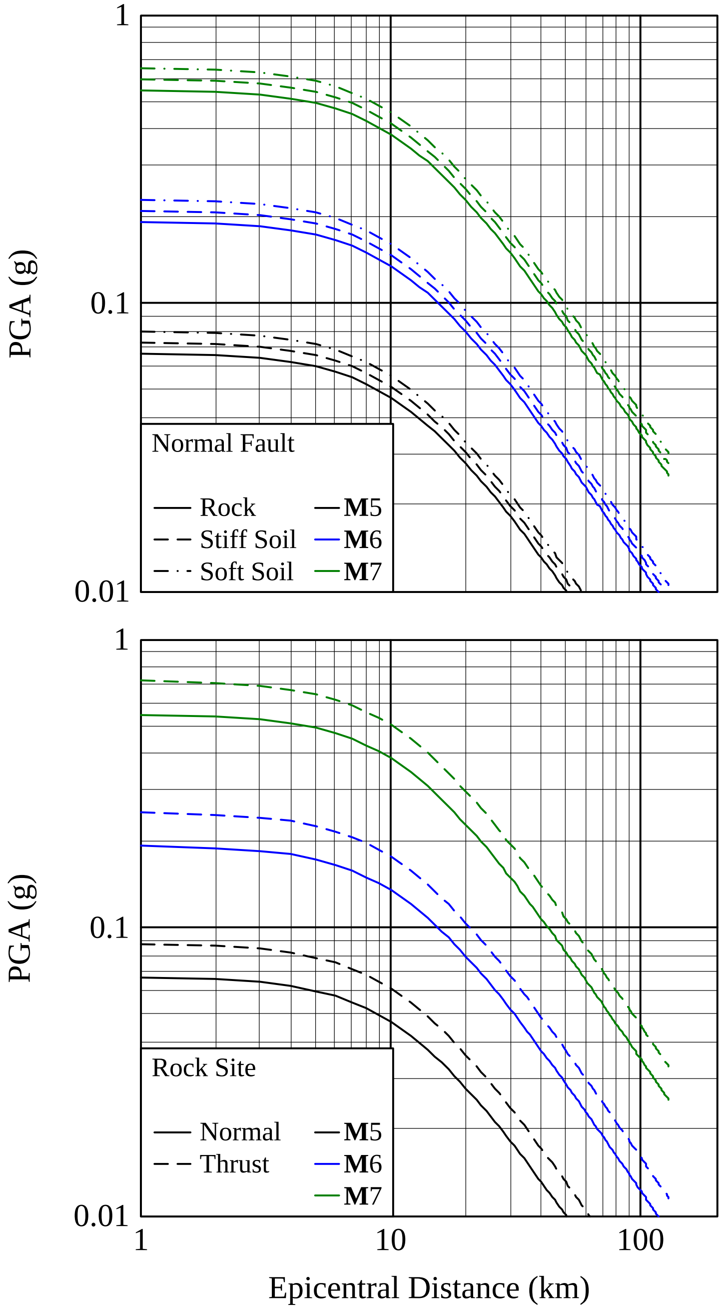


Figure 5-22. PGA as a function of epicentral distance for given conditions.

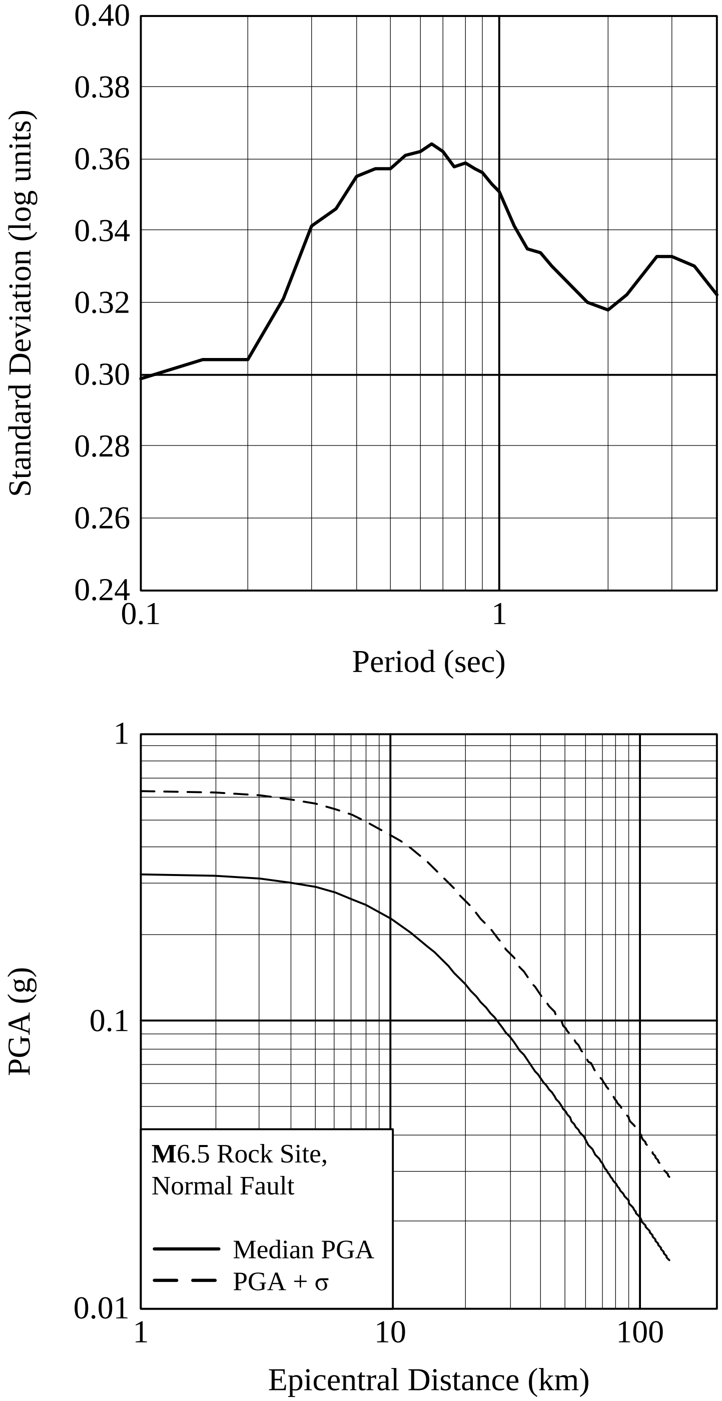


Figure 5-23. Above: standard deviation as a function of period. Below: example of application of median PGA plus one standard deviation.

5.5.5 Database

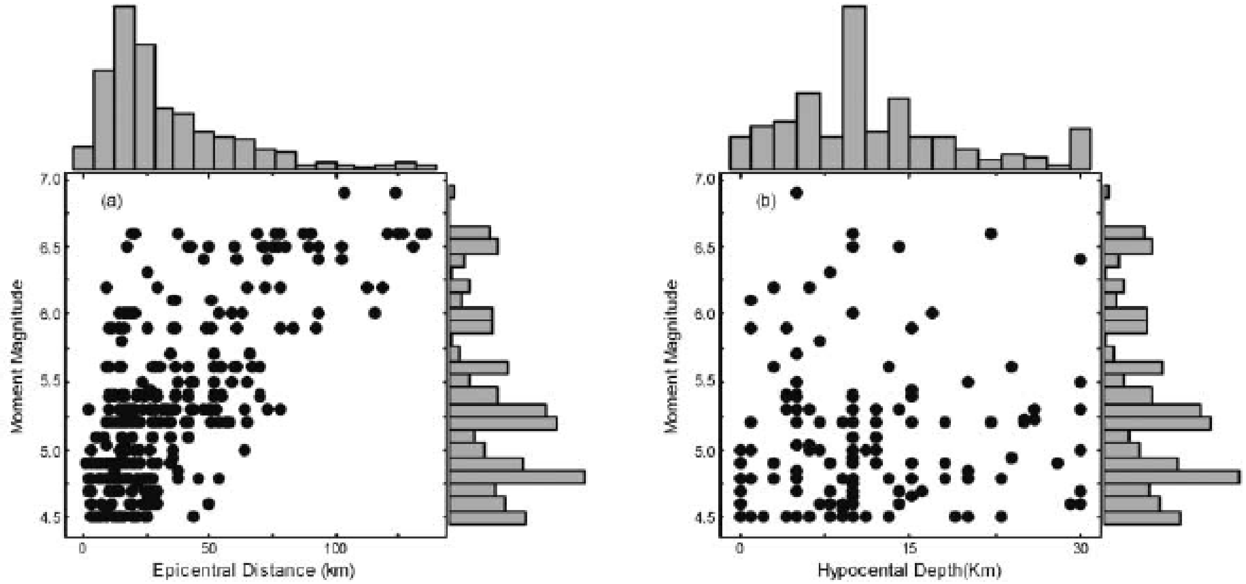


Figure 5-24. Distribution of the selected datasets in magnitude and epicentral distance (a) and magnitude and focal depth (b).

5.5.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/8/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Danciu and Tselentis attenuation equation, 2007
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0 for PGA
% M         = Moment magnitude
% F         = Fault type: 0 for normal faults, 1 for strike-slip or thrust
% Repi      = epicentral distance (km)
% S         = Soil type: 0 for rock (NERHP B), 1 for stiff soil (C),
%               2 for soft soil (D)
% --------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration or PGA prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = DT_2007(T, M, F, Repi, S)
period   = [0.000   0.100   0.150   0.200   0.250   0.300   0.350   0.400   0.450   0.500...
            0.550   0.600   0.650   0.700   0.750   0.800   0.850   0.900   0.950   1.000...
            1.100   1.200   1.300   1.400   1.500   1.750   2.000   2.250   2.750   3.000...
            3.500   4.000];
a    = [0.883   1.544   1.810   1.339   1.126   0.688   0.311   -0.109  -0.361  -0.619  -0.823...
        -0.938  -1.060  -1.177  -1.265  -1.315  -1.366  -1.429  -1.464  -1.517  -1.650  -1.661...
        -1.663  -1.745  -1.786  -1.747  -1.764  -1.697  -1.617  -1.612  -1.669  -1.834];
b    = [0.458   0.410   0.429   0.477   0.537   0.582   0.623   0.669   0.702   0.726   0.735...
        0.742   0.750   0.756   0.762   0.770   0.782   0.791   0.797   0.799   0.806   0.799...
        0.790   0.779   0.764   0.729   0.687   0.644   0.585   0.562   0.534   0.540];
c    = [-1.278  -1.364  -1.492  -1.368  -1.443  -1.374  -1.310  -1.247  -1.227  -1.174  -1.114...
        -1.087  -1.067  -1.051  -1.049  -1.067  -1.091  -1.101  -1.120  -1.113  -1.098  -1.099...
        -1.093  -1.029  -0.980  -0.937  -0.825  -0.762  -0.681  -0.632  -0.565  -0.573];
h    = [11.515  11.708  15.721  14.302  16.446  15.117  14.474  12.733  11.834  10.945  9.327...
        8.732   8.183   7.597   7.554   7.986   8.481   8.566   8.854   9.128   9.340   10.185...
        10.890  10.359  9.889   10.061  9.191   8.936   8.057   6.711   5.347   5.160];
e    = [0.038   0.039   0.008   0.024   0.020   0.034   0.037   0.033   0.019   0.021   0.020...
        0.011   0.013   0.020   0.030   0.024   0.019   0.016   0.014   0.016   0.025   0.023...
        0.015   0.013   0.011   0.008   0.009   0.010   0.008   -0.002  -0.010  -0.007];
f    = [0.116   0.112   0.113   0.103   0.109   0.121   0.121   0.136   0.132   0.117   0.110...
        0.098   0.075   0.072   0.064   0.069   0.071   0.063   0.056   0.050   0.046   0.053...
        0.054   0.051   0.058   0.057   0.061   0.057   0.058   0.057   0.064   0.070];
tau  = [0.109   0.139   0.107   0.103   0.104   0.107   0.124   0.151   0.154   0.163   0.163...
        0.167   0.169   0.151   0.140   0.140   0.145   0.145   0.149   0.156   0.148   0.142...
        0.149   0.147   0.151   0.159   0.172   0.174   0.195   0.205   0.205   0.194];
sig  = [0.270   0.264   0.285   0.287   0.304   0.323   0.323   0.322   0.322   0.318   0.322...
        0.321   0.323   0.329   0.330   0.331   0.326   0.325   0.321   0.314   0.307   0.303...
        0.299   0.296   0.291   0.278   0.267   0.271   0.270   0.263   0.259   0.258];
sigt = [0.291   0.299   0.304   0.304   0.321   0.341   0.346   0.355   0.357   0.357   0.361...
        0.362   0.364   0.362   0.358   0.359   0.357   0.356   0.353   0.351   0.341   0.335...
        0.334   0.330   0.327   0.320   0.318   0.322   0.333   0.333   0.330   0.322];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi  = min(period(find(period>T)));
    [sa_low, sigma_low] = DT_2007(T_low, M, F, Repi, S);
    [sa_hi,  sigma_hi]  = DT_2007(T_hi,  M, F, Repi, S);
    x = [log10(T_low) log10(T_hi)];
    Y_sa = [log10(sa_low) log10(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = 10^(interp1(x,Y_sa,log10(T)));
    sigma = interp1(x,Y_sigma,log10(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    Sa = 10^(a(i) + b(i)*M + c(i)*log10(sqrt(Repi^2 + h(i)^2)) + e(i)*S + f(i)*F)/980.665;
    sigma = sigt(i);
end
```

5.6 India: Sharma – 1998

5.6.1 Reference

Sharma, M. L. (1998). Attenuation Relationship for Estimation of Peak Ground Horizontal Acceleratino Using Data from Strong-Motion Arrays in India, *Bulletin of the Seismological Society of America* **88**, 1063-1069.

5.6.2 Abstract

Using 66 strong ground motions records from 5 Indian earthquakes in the Himalayan region, empirical ground-motion models for the average horizontal and vertical components were developed. The model predicts peak ground acceleration (PGA, in g). Based on the bounds of the earthquakes in the database, this model is most applicable for earthquakes between M5.5 and M6.6 and for distances up to 321 km.

5.6.3 Attenuation Relationship

The spectral acceleration is a function of:

- **M** – Moment magnitude
- R_{hypo} – Hypocentral distance(km)

$$\log_{10}(PGA) = -1.072 + 0.3903M - 1.21\log_{10}\left(R_{hypo} + e^{0.5873M}\right)$$

Standard Error

$$\sigma_T = 0.14$$

5.6.4 *Calibration Plots*

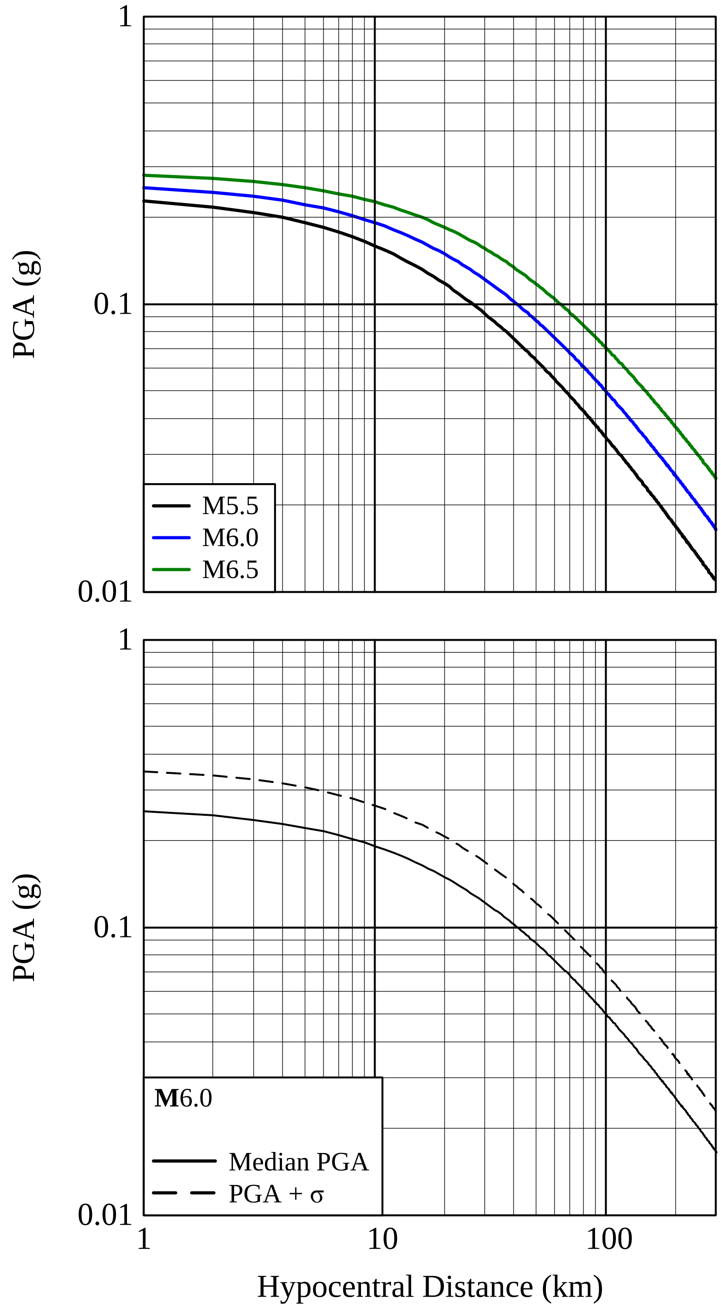


Figure 5-25. Above: PGA as a function of hypocentral distance. Below: example of application of median PGA plus one standard deviation.

5.6.5 Database

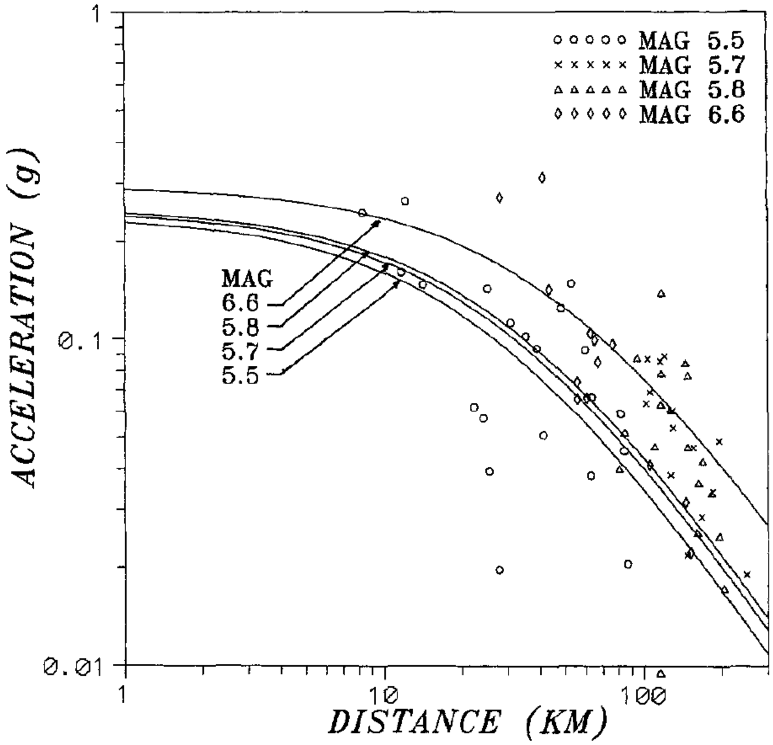


Figure 5-26. Proposed attenuation relationship plotted along with the data set used for the study.

5.6.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/19/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Sharma attenuation equation, 1998
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% M         = Moment magnitude
% Rhyp      = Hypocentral distance (km)
% --------------------------------------------------------------------------
% Output Variables
% Sa:       Median peak ground acceleration prediction
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = S_1998(M, Rhyp)
    Sa = 10^(-1.072 + 0.3903*M - 1.21*log10(Rhyp + exp(0.5873*M)));
    sigma = 0.14;
```

5.7 Japan: Kanno, Narita, Morikawa, Fujiwara and Fukushima – 2006

5.7.1 Reference

Kanno, T., A. Narita, N. Morikawa, H. Fujiwara, and Y. Fukushima (2006). A New Attenuation Relation for Strong Ground Motion in Japan Based on Recorded Data, *Bulletin of the Seismological Society of America* **96**, 879-897.

5.7.2 Abstract

Using the number of records shown in Table 5-10, empirical ground-motion models for the average horizontal component were developed. The model predicts peak ground acceleration (PGA, in cm/s^2), peak ground velocity (PGV in cm/s) and 5%-damped spectral values (in cm/s^2) for periods ranging from 0.05 to 5.0 s. Based on the bounds of the earthquakes in the database, this model is most applicable for earthquakes between M5.5 and M8.2, and for distances up to 300 km for M5.5 events and up to 500 km for > M8 events. Note: the MATLAB code converts all accelerations to g's.

5.7.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA, -1 for PGV
- **M** – Moment magnitude
- H – Focal depth (km)
- R_{rup} – Closest distance to rupture plane (km)
- R_{tr} – Distance to trench axis (km), enter 0 for unapplicable events
- V_{S30} – Shear wave velocity in upper 30 m (m/s)

$$\log_{10}(Sa) = \log_{10}\left(Sa_{pre}\right) + G + A$$

where:

$$\log_{10}\left(Sa_{pre}\right) = a\boldsymbol{M} + bR_{rup} + c - \log_{10}\left(R_{rup} + d10^{0.5\boldsymbol{M}}\right)$$

$$G = p\log_{10} V_{S30} + q$$

$$A = (\alpha R_{tr} + \beta)(H - 30)$$

Notes on *G*: this is a correction term for site effects. If it is desired to determine PSA, PGA or PGV without site effects, enter *0* for V_{S30} in the MATLAB code.

Notes on *A*: this value is only added for events that take place within the Pacific Plate and east of 137°E longitude, events deeper than 30 m, and sites with estimated V_{S30}.

Coefficients

Table 5-9. Coefficients for model. Note that for *H* > 30, *d* = 0 for all cases.

T (sec)	Shallow (H ≤ 30 km)					Deep (H > 30 km)				p	q	α	β
	a	b	c	d	σ	a	b	c	σ				
PGA	0.56	-0.0031	0.26	0.0055	0.37	0.41	-0.0039	1.56	0.40	-0.55	1.35	-6.73E-05	2.09E-02
PGV	0.70	-0.0009	-1.93	0.0022	0.32	0.55	-0.0032	-0.57	0.36	-0.71	1.77	-1.94E-05	7.24E-03
0.05	0.54	-0.0035	0.48	0.0061	0.37	0.39	-0.0040	1.76	0.42	-0.32	0.80	-7.78E-05	2.37E-02
0.06	0.54	-0.0037	0.57	0.0065	0.38	0.39	-0.0041	1.86	0.43	-0.26	0.65	-8.02E-05	2.42E-02
0.07	0.53	-0.0039	0.67	0.0066	0.38	0.38	-0.0042	1.96	0.45	-0.24	0.60	-8.15E-05	2.47E-02
0.08	0.52	-0.0040	0.75	0.0069	0.39	0.38	-0.0042	2.03	0.45	-0.26	0.64	-8.22E-05	2.50E-02
0.09	0.52	-0.0041	0.80	0.0071	0.40	0.38	-0.0043	2.08	0.46	-0.29	0.72	-8.26E-05	2.55E-02
0.10	0.52	-0.0041	0.85	0.0073	0.40	0.38	-0.0043	2.12	0.46	-0.32	0.78	-8.23E-05	2.54E-02
0.11	0.50	-0.0040	0.96	0.0061	0.40	0.38	-0.0044	2.14	0.46	-0.35	0.84	-8.18E-05	2.56E-02
0.12	0.51	-0.0040	0.93	0.0062	0.40	0.38	-0.0044	2.14	0.46	-0.39	0.94	-8.08E-05	2.53E-02
0.13	0.51	-0.0039	0.91	0.0062	0.40	0.38	-0.0044	2.13	0.46	-0.43	1.04	-7.99E-05	2.51E-02
0.15	0.52	-0.0038	0.89	0.0060	0.41	0.39	-0.0044	2.12	0.46	-0.53	1.28	-7.99E-05	2.51E-02
0.17	0.53	-0.0037	0.84	0.0056	0.41	0.40	-0.0043	2.08	0.45	-0.61	1.47	-7.53E-05	2.38E-02
0.20	0.54	-0.0034	0.76	0.0053	0.40	0.40	-0.0042	2.02	0.44	-0.68	1.65	-6.99E-05	2.23E-02
0.22	0.54	-0.0032	0.73	0.0048	0.40	0.40	-0.0041	1.99	0.43	-0.72	1.74	-6.54E-05	2.09E-02
0.25	0.54	-0.0029	0.66	0.0044	0.40	0.41	-0.0040	1.88	0.42	-0.75	1.82	-6.07E-05	1.96E-02
0.30	0.56	-0.0026	0.51	0.0039	0.39	0.43	-0.0038	1.75	0.42	-0.80	1.96	-5.47E-05	1.78E-02
0.35	0.56	-0.0024	0.42	0.0036	0.40	0.43	-0.0036	1.62	0.41	-0.85	2.09	-5.06E-05	1.67E-02
0.40	0.58	-0.0021	0.26	0.0033	0.40	0.45	-0.0034	1.49	0.41	-0.87	2.13	-4.62E-05	1.54E-02
0.45	0.59	-0.0019	0.13	0.0030	0.41	0.46	-0.0032	1.33	0.41	-0.89	2.18	-4.62E-05	1.51E-02
0.50	0.59	-0.0016	0.04	0.0022	0.41	0.47	-0.0030	1.19	0.40	-0.91	2.25	-4.41E-05	1.44E-02
0.60	0.62	-0.0014	-0.22	0.0025	0.41	0.49	-0.0028	0.95	0.40	-0.92	2.30	-3.60E-05	1.19E-02
0.70	0.63	-0.0012	-0.37	0.0022	0.41	0.51	-0.0026	0.72	0.40	-0.96	2.41	-2.88E-05	9.48E-03
0.80	0.65	-0.0011	-0.54	0.0020	0.41	0.53	-0.0025	0.49	0.40	-0.98	2.46	-2.50E-05	8.19E-03
0.90	0.68	-0.0009	-0.80	0.0019	0.41	0.56	-0.0023	0.27	0.40	-0.97	2.44	-2.16E-05	7.35E-03
1.00	0.71	-0.0009	-1.04	0.0021	0.41	0.57	-0.0022	0.08	0.41	-0.93	2.32	-2.18E-05	7.61E-03
1.10	0.72	-0.0007	-1.19	0.0018	0.41	0.59	-0.0022	-0.08	0.41	-0.92	2.30	-1.95E-05	7.08E-03
1.20	0.73	-0.0006	-1.32	0.0014	0.41	0.60	-0.0021	-0.24	0.41	-0.91	2.26	-1.63E-05	6.52E-03
1.30	0.74	-0.0006	-1.44	0.0014	0.41	0.62	-0.0020	-0.40	0.41	-0.88	2.20	-1.38E-05	5.85E-03
1.50	0.77	-0.0005	-1.70	0.0017	0.40	0.64	-0.0020	-0.63	0.41	-0.85	2.12	-1.18E-05	5.52E-03
1.70	0.79	-0.0005	-1.89	0.0019	0.39	0.66	-0.0018	-0.83	0.40	-0.83	2.06	-8.53E-06	4.80E-03
2.00	0.80	-0.0004	-2.08	0.0020	0.39	0.68	-0.0017	-1.12	0.40	-0.78	1.92	-4.53E-06	4.05E-03
2.20	0.82	-0.0004	-2.24	0.0022	0.38	0.69	-0.0017	-1.27	0.40	-0.76	1.88	-1.18E-06	3.11E-03
2.50	0.84	-0.0003	-2.46	0.0023	0.38	0.71	-0.0017	-1.48	0.39	-0.72	1.80	2.60E-06	2.15E-03
3.00	0.86	-0.0002	-2.72	0.0021	0.38	0.73	-0.0017	-1.72	0.39	-0.68	1.70	3.01E-06	2.01E-03
3.50	0.90	-0.0003	-2.99	0.0032	0.37	0.75	-0.0017	-1.97	0.38	-0.66	1.64	2.49E-06	2.06E-03
4.00	0.92	-0.0005	-3.21	0.0045	0.38	0.77	-0.0016	-2.22	0.37	-0.62	1.54	9.28E-06	2.27E-03
4.50	0.94	-0.0007	-3.39	0.0064	0.38	0.79	-0.0016	-2.45	0.36	-0.60	1.50	-2.13E-06	2.95E-03
5.00	0.92	-0.0004	-3.35	0.0030	0.38	0.82	-0.0017	-2.70	0.35	-0.59	1.46	-4.61E-06	3.44E-03

5.7.4 Calibration Plots

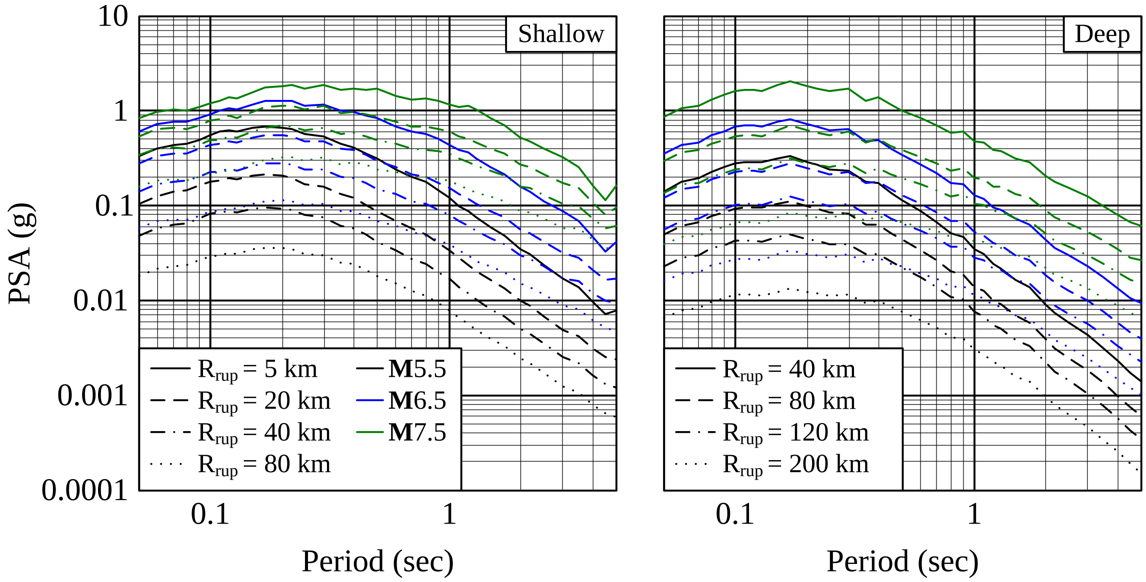


Figure 5-27. PSA as a function of period for given conditions. Note: *A* and *G* are equal to zero in this case (correction terms are not included).

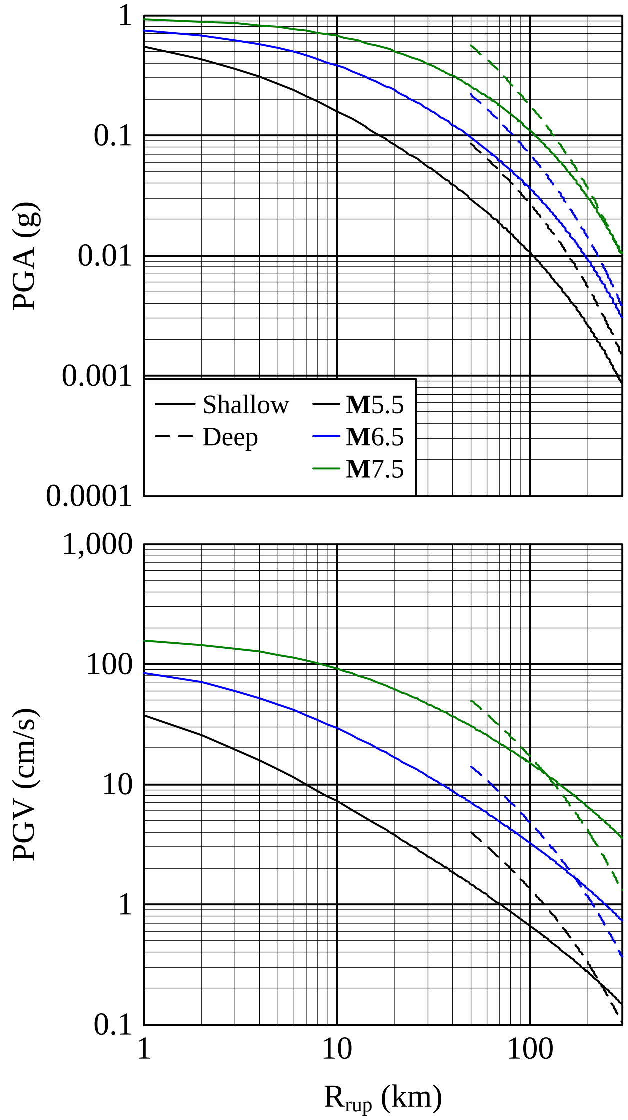


Figure 5-28. PGA and PGV as a function of distance for given conditions. Note: A and G are equal to zero in this case (correction terms are not included).

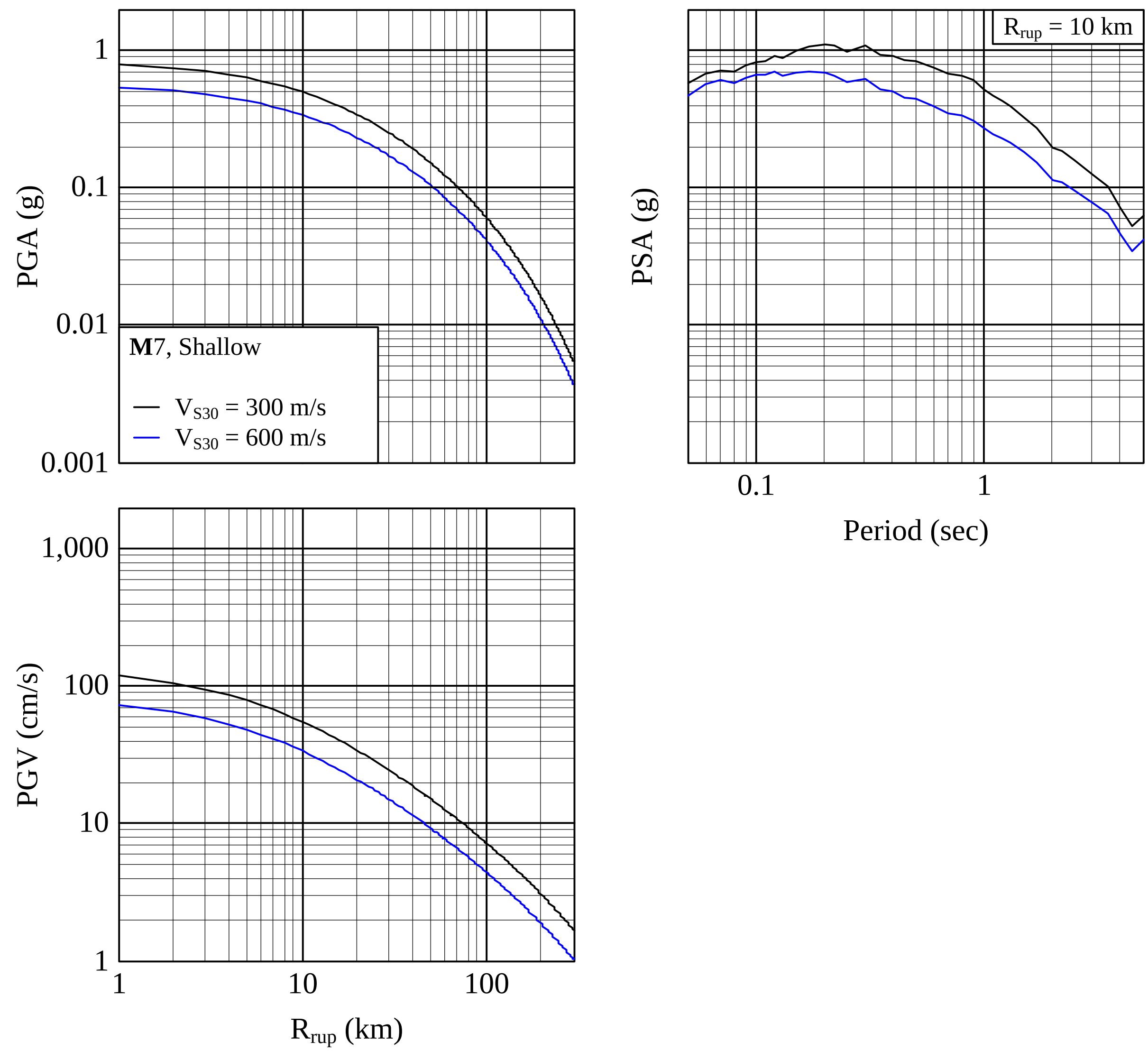


Figure 5-29. PGA and PGV as a function of distance, and PSA as a function of period for given conditions. Note: A is equal to zero in this case.

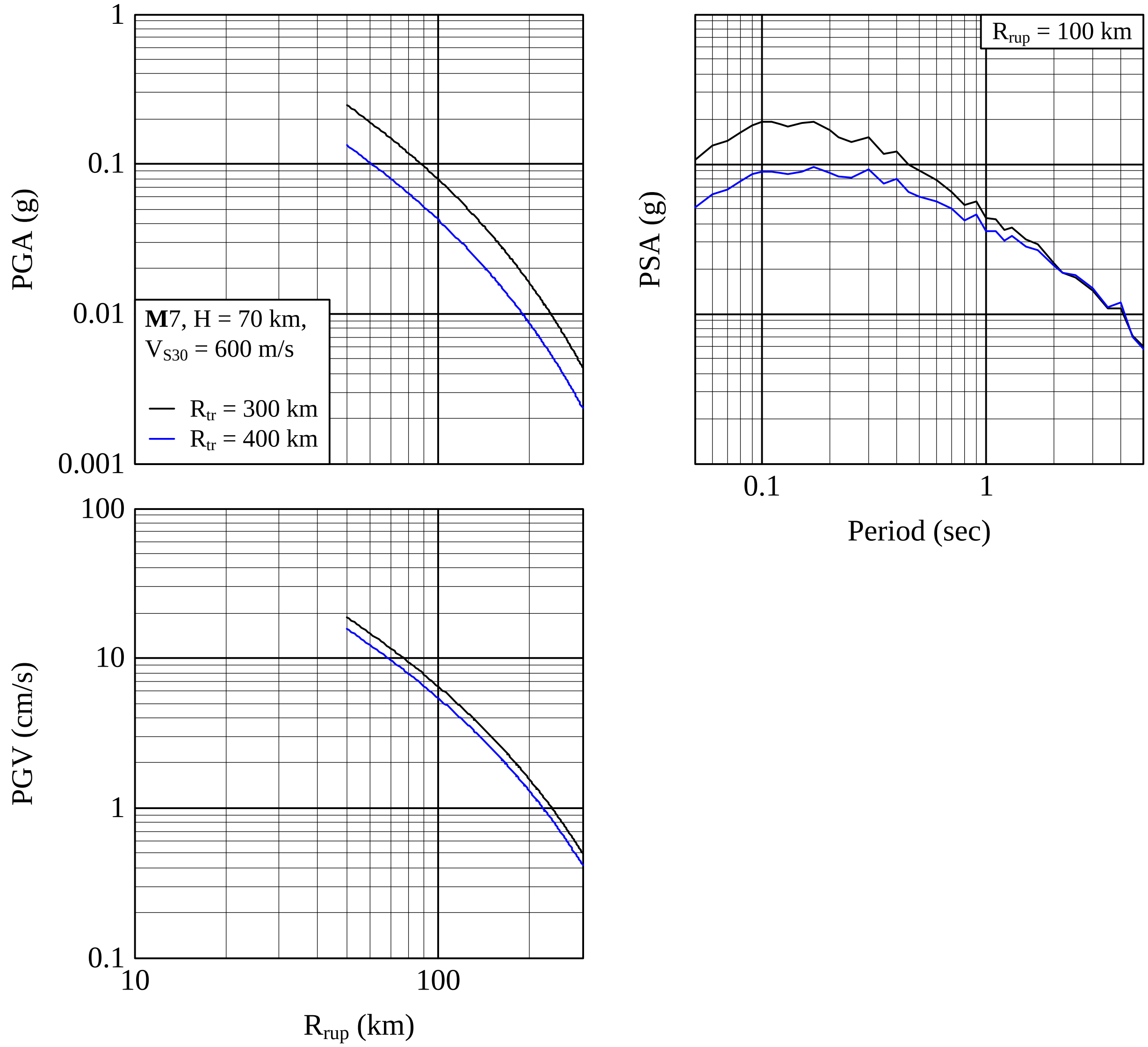


Figure 5-30. PGA and PGV as a function of distance, and PSA as a function of period for given conditions.

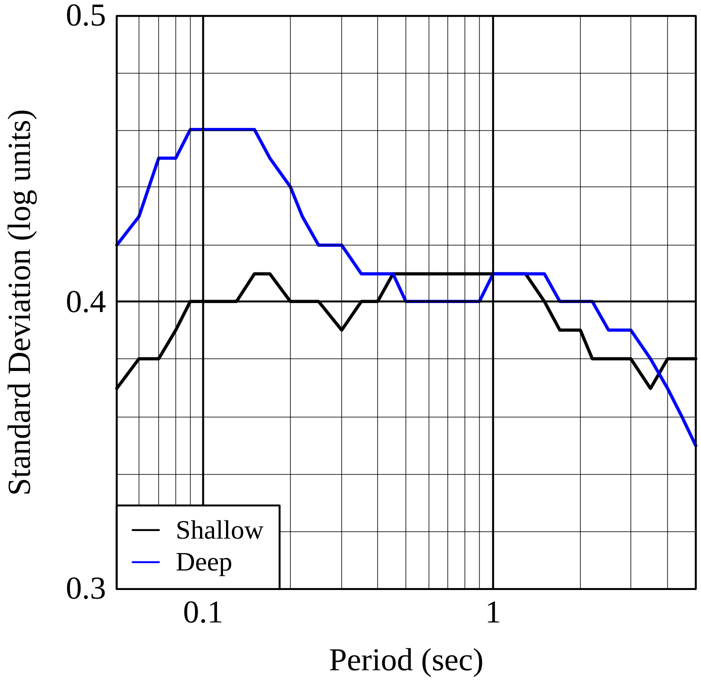


Figure 5-31. Standard deviations as a function of period.

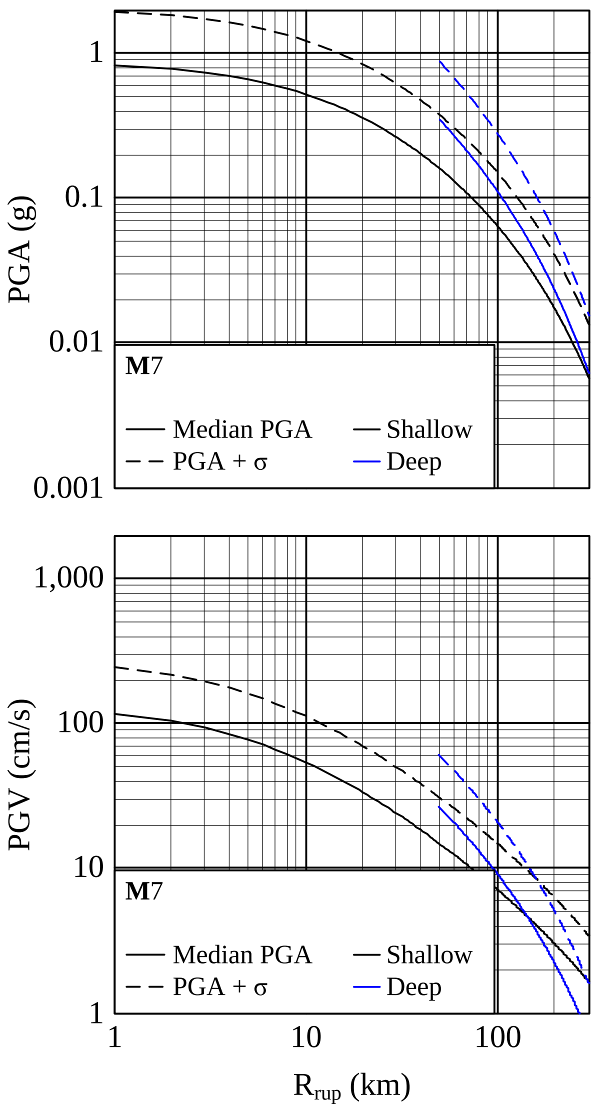


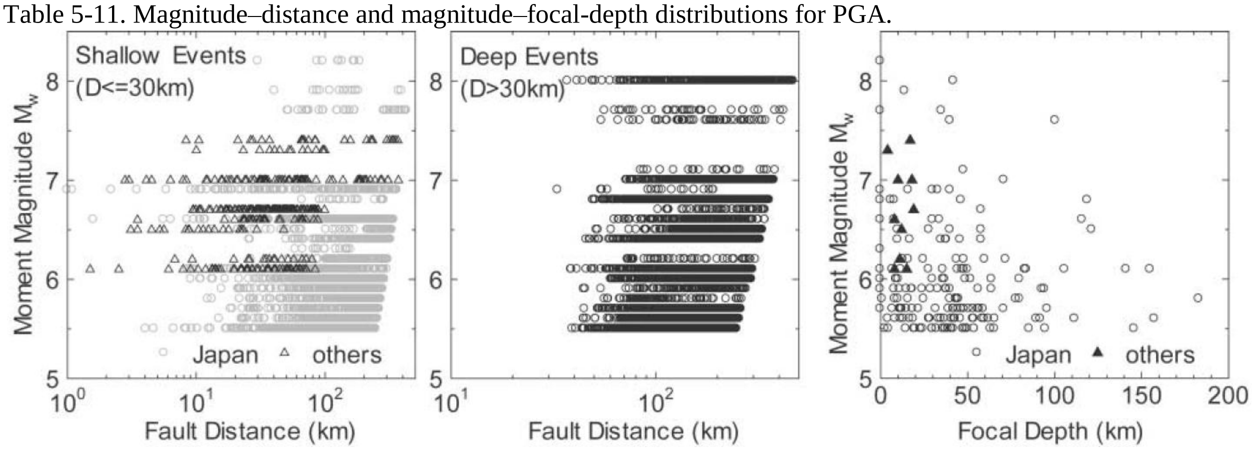
Figure 5-32. Example of applications of median PGA and median PGV plus one standard deviation. Note: A and G are equal to zero in this case.

5.7.5 Database

Table 5-10. Number of data used for regression analysis. Note: Others refers to 8 earthquakes Califonia, USA and 2 in Turkey. All periods with the exception of PGA, refer to 5%-damped acceleration spectra (sec).

Period	Shallow Events				Deep Events	
	Japan		Others		Japan	
	Data	Earthquake	Data	Earthquake	Data	Earthquake
PGA	3392	73	377	10	8150	111
0.05~1.00	3392	73	377	10	8150	111
1.10~1.20	3391	73	377	10	8145	111
1.30	3391	73	377	10	8144	111
1.50	3391	73	377	10	8140	111
1.70~2.00	3391	73	377	10	8137	111
2.20	3380	73	375	10	8100	111
2.50~3.00	3360	73	375	10	8039	110
3.50~4.00	3312	73	371	10	7963	110
4.50	3311	73	371	10	7963	110
5.00	3205	70	331	10	7721	101
PGV	2057	61	352	10	6490	110

Table 5-11. Magnitude–distance and magnitude–focal-depth distributions for PGA.



5.7.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/19/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Kanno et al. attenuation equation, 2007
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0 for PGA, -1 for PGV
% M         = Magnitude
% H         = Focal depth (km)
% Rrup      = Closest distance to rupture plane (km)
% Rtr       = Distance to trench axis (km), enter 0 if not Pacific Plate
%             event or not east of 137E longitude
% Vs30      = Shear wave velocity in upper 30 m (m/s), 0 if don't want to
%             inlude effect
% ---------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration, PGA or PGV prediction (g, cm/s)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = KNMFF_2006(T, M, H, Rrup, Rtr, Vs30)
% Coefficients
period   = [0       -1      0.05    0.06    0.07    0.08    0.09    0.10    0.11    0.12...
            0.13    0.15    0.17    0.20    0.22    0.25    0.30    0.35    0.40    0.45...
            0.50    0.60    0.70    0.80    0.90    1.00    1.10    1.20    1.30    1.50...
            1.70    2.00    2.20    2.50    3.00    3.50    4.00    4.50    5.00];
if H <= 30
    a    = [0.56    0.70    0.54    0.54    0.53    0.52    0.52    0.52    0.50    0.51...
            0.51    0.52    0.53    0.54    0.54    0.54    0.56    0.56    0.58    0.59...
            0.59    0.62    0.63    0.65    0.68    0.71    0.72    0.73    0.74    0.77...
            0.79    0.80    0.82    0.84    0.86    0.90    0.92    0.94    0.92];
    b    = [-0.0031 -0.0009 -0.0035 -0.0037 -0.0039 -0.0040 -0.0041 -0.0041 -0.0040 -0.0040...
            -0.0039 -0.0038 -0.0037 -0.0034 -0.0032 -0.0029 -0.0026 -0.0024 -0.0021 -0.0019...
            -0.0016 -0.0014 -0.0012 -0.0011 -0.0009 -0.0009 -0.0007 -0.0006 -0.0006 -0.0005...
            -0.0005 -0.0004 -0.0004 -0.0003 -0.0002 -0.0003 -0.0005 -0.0007 -0.0004];
    c    = [0.26    -1.93   0.48    0.57    0.67    0.75    0.80    0.85    0.96    0.93...
            0.91    0.89    0.84    0.76    0.73    0.66    0.51    0.42    0.26    0.13...
            0.04    -0.22   -0.37   -0.54   -0.80   -1.04   -1.19   -1.32   -1.44   -1.70...
            -1.89   -2.08   -2.24   -2.46   -2.72   -2.99   -3.21   -3.39   -3.35];
    d    = [0.0055  0.0022  0.0061  0.0065  0.0066  0.0069  0.0071  0.0073  0.0061  0.0062...
            0.0062  0.0060  0.0056  0.0053  0.0048  0.0044  0.0039  0.0036  0.0033  0.0030...
            0.0022  0.0025  0.0022  0.0020  0.0019  0.0021  0.0018  0.0014  0.0014  0.0017...
            0.0019  0.0020  0.0022  0.0023  0.0021  0.0032  0.0045  0.0064  0.0030];
    sigt = [0.37    0.32    0.37    0.38    0.38    0.39    0.40    0.40    0.40    0.40...
            0.40    0.41    0.41    0.40    0.40    0.40    0.39    0.40    0.40    0.41...
            0.41    0.41    0.41    0.41    0.41    0.41    0.41    0.41    0.41    0.40...
            0.39    0.39    0.38    0.38    0.38    0.37    0.38    0.38    0.38];
else
    a    = [0.41    0.55    0.39    0.39    0.38    0.38    0.38    0.38    0.38    0.38...
            0.38    0.39    0.40    0.40    0.40    0.41    0.43    0.43    0.45    0.46...
            0.47    0.49    0.51    0.53    0.56    0.57    0.59    0.60    0.62    0.64...
            0.66    0.68    0.69    0.71    0.73    0.75    0.77    0.79    0.82];
    b    = [-0.0039 -0.0032 -0.0040 -0.0041 -0.0042 -0.0042 -0.0043 -0.0043 -0.0044 -0.0044...
            -0.0044 -0.0044 -0.0043 -0.0042 -0.0041 -0.0040 -0.0038 -0.0036 -0.0034 -0.0032...
            -0.0030 -0.0028 -0.0026 -0.0025 -0.0023 -0.0022 -0.0022 -0.0021 -0.0020 -0.0020...
            -0.0018 -0.0017 -0.0017 -0.0017 -0.0017 -0.0017 -0.0016 -0.0016 -0.0017];
    c    = [1.56    -0.57   1.76    1.86    1.96    2.03    2.08    2.12    2.14    2.14...
            2.13    2.12    2.08    2.02    1.99    1.88    1.75    1.62    1.49    1.33...
            1.19    0.95    0.72    0.49    0.27    0.08    -0.08   -0.24   -0.40   -0.63...
            -0.83   -1.12   -1.27   -1.48   -1.72   -1.97   -2.22   -2.45   -2.70];
    d    = [0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0 ...
            0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0];
    sigt = [0.40    0.36    0.42    0.43    0.45    0.45    0.46    0.46    0.46    0.46...
            0.46    0.46    0.45    0.44    0.43    0.42    0.42    0.41    0.41    0.41...
            0.40    0.40    0.40    0.40    0.40    0.41    0.41    0.41    0.41    0.41...
            0.40    0.40    0.40    0.39    0.39    0.38    0.37    0.36    0.35];
```

```
end
p       = [-0.55   -0.71   -0.32   -0.26   -0.24   -0.26   -0.29   -0.32   -0.35   -0.39...
            -0.43   -0.53   -0.61   -0.68   -0.72   -0.75   -0.80   -0.85   -0.87   -0.89...
            -0.91   -0.92   -0.96   -0.98   -0.97   -0.93   -0.92   -0.91   -0.88   -0.85...
            -0.83   -0.78   -0.76   -0.72   -0.68   -0.66   -0.62   -0.60   -0.59];
q       = [1.35    1.77    0.80    0.65    0.60    0.64    0.72    0.78    0.84    0.94...
            1.04    1.28    1.47    1.65    1.74    1.82    1.96    2.09    2.13    2.18...
            2.25    2.30    2.41    2.46    2.44    2.32    2.30    2.26    2.20    2.12...
            2.06    1.92    1.88    1.80    1.70    1.64    1.54    1.50    1.46];
alpha   = [-6.73E-05   -1.94E-05   -7.78E-05   -8.02E-05   -8.15E-05   -8.22E-05   -8.26E-05...
            -8.23E-05   -8.18E-05   -8.08E-05   -7.99E-05   -7.99E-05   -7.53E-05   -6.99E-05...
            -6.54E-05   -6.07E-05   -5.47E-05   -5.06E-05   -4.62E-05   -4.62E-05   -4.41E-05...
            -3.60E-05   -2.88E-05   -2.50E-05   -2.16E-05   -2.18E-05   -1.95E-05   -1.63E-05...
            -1.38E-05   -1.18E-05   -8.53E-06   -4.53E-06   -1.18E-06   2.60E-06    3.01E-06...
            2.49E-06    9.28E-06    -2.13E-06   -4.61E-06];
beta    = [2.09E-02    7.24E-03    2.37E-02    2.42E-02    2.47E-02    2.50E-02    2.55E-02...
            2.54E-02    2.56E-02    2.53E-02    2.51E-02    2.51E-02    2.38E-02    2.23E-02...
            2.09E-02    1.96E-02    1.78E-02    1.67E-02    1.54E-02    1.51E-02    1.44E-02...
            1.19E-02    9.48E-03    8.19E-03    7.35E-03    7.61E-03    7.08E-03    6.52E-03...
            5.85E-03    5.52E-03    4.80E-03    4.05E-03    3.11E-03    2.15E-03    2.01E-03...
            2.06E-03    2.27E-03    2.95E-03    3.44E-03];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi  = min(period(find(period>T)));
    [sa_low, sigma_low] = KNMFF_2006(T_low, M, H, Rrup, Rtr, Vs30);
    [sa_hi,  sigma_hi]  = KNMFF_2006(T_hi,  M, H, Rrup, Rtr, Vs30);
    x = [log10(T_low) log10(T_hi)];
    Y_sa = [log10(sa_low) log10(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = 10^(interp1(x,Y_sa,log10(T)));
    sigma = interp1(x,Y_sigma,log10(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    logSa_pre = a(i)*M + b(i)*Rrup + c(i) - log10(Rrup + d(i)*10^(0.5*M));
    if Vs30 == 0
        G = 0;
    else
        G = p(i)*log10(Vs30) + q(i);
    end
    if Rtr == 0 || H < 30 || Vs30 == 0
        A = 0;
    else
        A = (alpha(i)*Rtr + beta(i))*(H - 30);
    end
    if T == -1
        Sa = 10^(logSa_pre + G + A);
    else
        Sa = 10^(logSa_pre + G + A)/980.665;
    end
    sigma = sigt(i);
end
```

5.8 Japan: Zhao, Zhang, Asano, Ohno, Oouchi, Takahashi, Ogawa, Irikura, Thio, Somerville, Fukushima and Fukushima – 2006

5.8.1 Reference

Zhao, J. X., J. Zhang, A. Asano, Y. Ohno, T. Oouchi, T. Takahashi, H. Ogawa, K. Irikura, H. K. Thio, P. G. Somerville, Y. Fukushima and Y. Fukushima (2006). Attenuation Relations of Strong Ground Motin in Japan Using Site Classification Based on Predominant Period, *Bulletin of the Seismological Society of America* **96**, 898-913.

5.8.2 Abstract

Using 4726 records from 269 earthquakes, empirical ground-motion models for the average horizontal component were developed. The model predicts peak ground acceleration (PGA, in cm/s^2), and 5%-damped spectral values (in cm/s^2) for periods ranging from 0.05 to 5.0 s. This model is most applicable for earthquakes between M5.0 and M8.3, and for distances up to 300 km. Note: the MATLAB code converts all accelerations to g's.

5.8.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA
- **M** – Moment magnitude
- H – Focal Depth (km)
- F – Fault type: 1 for crustal events with reverse faulting mechanism, 2 for interface events, 3 for in-slab events and 0 otherwise (e.g. 0 for normal or strike-slip faulting crustal events)
- R_{rup} – Closest distance to rupture plane (km)
- S – Soil type: 0 for hard rock, 1 for rock, 2 for hard soil, 3 for medium soil and 4 for soft soil (see Table 5-12 for definitions)

$$\ln(Sa) = a\boldsymbol{M} + bR_{rup} - \ln\left(R_{rup} + c\exp(d\boldsymbol{M})\right) + e(H-15)\delta_h + S_R + S_I + S_S + S_{SL}\ln\left(R_{rup}\right) + C_k$$

where:

$$S_R = \begin{cases} S_R & for\ F = 1 \\ 0 & otherwise \end{cases} \qquad S_{SL} = \begin{cases} S_{SL} & for\ F = 3 \\ 0 & otherwise \end{cases}$$

$$S_I = \begin{cases} S_I & for\ F = 2 \\ 0 & otherwise \end{cases}$$

$$S_S = \begin{cases} S_S & for\ F = 3 \\ 0 & otherwise \end{cases}$$

$$C_k = \begin{cases} C_{h.\ rock} & for\ S = 0 \\ C_{rock} & for\ S = 1 \\ C_{h.\ soil} & for\ S = 2 \\ C_{m.\ soil} & for\ S = 3 \\ C_{s.\ soil} & for\ S = 4 \end{cases}$$

δ_h = 1 if H > 15 km and 0 if H < 15 km (maximum H = 125 km)

Table 5-12. Site class definitions used and the approximately corresponding NEHRP site classes.

Site Class	Description	Natural Period	V_{30} Calculated from Site Period	NEHRP Site Classes
Hard Rock			$V_{30} > 1100$	A
SC I	Rock	$T < 0.2$ sec	$V_{30} > 600$	A + B
SC II	Hard Soil	$0.2 = T < 0.4$ sec	$300 < V_{30} = 600$	C
SC III	Medium Soil	$0.4 = T < 0.6$ sec	$200 < V_{30} = 300$	D
SC IV	Soft Soil	$T = 0.6$ sec	$V_{30} = 200$	E + F

Standard Error

$$\sigma_T = \sqrt{\tau^2 + \sigma^2}$$

Coefficients

Table 5-13. Coefficients used in regression model.

T (sec)	a	b	c	d	e	F_R	S_I	S_S	S_{SL}
PGA	1.101	-0.00564	0.0055	1.080	0.01412	0.251	0.000	2.607	-0.528
0.05	1.076	-0.00671	0.0075	1.060	0.01463	0.251	0.000	2.764	-0.551
0.10	1.118	-0.00787	0.0090	1.083	0.01423	0.240	0.000	2.156	-0.420
0.15	1.134	-0.00722	0.0100	1.053	0.01509	0.251	0.000	2.161	-0.431
0.20	1.147	-0.00659	0.0120	1.014	0.01462	0.260	0.000	1.901	-0.372
0.25	1.149	-0.00590	0.0140	0.966	0.01459	0.269	0.000	1.814	-0.360
0.30	1.163	-0.00520	0.0150	0.934	0.01458	0.259	0.000	2.181	-0.450
0.40	1.200	-0.00422	0.0100	0.959	0.01257	0.248	-0.041	2.432	-0.506
0.50	1.250	-0.00338	0.0060	1.008	0.01114	0.247	-0.053	2.629	-0.554
0.60	1.293	-0.00282	0.0030	1.088	0.01019	0.233	-0.103	2.702	-0.575
0.70	1.336	-0.00258	0.0025	1.084	0.00979	0.220	-0.146	2.654	-0.572
0.80	1.386	-0.00242	0.0022	1.088	0.00944	0.232	-0.164	2.480	-0.540
0.90	1.433	-0.00232	0.0020	1.109	0.00972	0.220	-0.206	2.332	-0.522
1.00	1.479	-0.00220	0.0020	1.115	0.01005	0.211	-0.239	2.233	-0.509
1.25	1.551	-0.00207	0.0020	1.083	0.01003	0.251	-0.256	2.029	-0.469
1.50	1.621	-0.00224	0.0020	1.091	0.00928	0.248	-0.306	1.589	-0.379
2.00	1.694	-0.00201	0.0025	1.055	0.00833	0.263	-0.321	0.966	-0.248
2.50	1.748	-0.00187	0.0028	1.052	0.00776	0.262	-0.337	0.789	-0.221
3.00	1.759	-0.00147	0.0032	1.025	0.00644	0.307	-0.331	1.037	-0.263
4.00	1.826	-0.00195	0.0040	1.044	0.00590	0.353	-0.390	0.561	-0.169
5.00	1.825	-0.00237	0.0050	1.065	0.00510	0.248	-0.498	0.225	-0.120

T (sec)	$C_{h.rock}$	C_{rock}	$C_{h.soil}$	$C_{m.soil}$	$C_{s.soil}$	σ	τ	σ_T
PGA	0.293	1.111	1.344	1.355	1.420	0.604	0.398	0.723
0.05	0.939	1.684	1.793	1.747	1.814	0.640	0.444	0.779
0.10	1.499	2.061	2.135	2.031	2.082	0.694	0.490	0.849
0.15	1.462	1.916	2.168	2.052	2.113	0.702	0.460	0.839
0.20	1.280	1.669	2.085	2.001	2.030	0.692	0.423	0.811
0.25	1.121	1.468	1.942	1.941	1.937	0.682	0.391	0.786
0.30	0.852	1.172	1.683	1.808	1.770	0.670	0.379	0.770
0.40	0.365	0.655	1.127	1.482	1.397	0.659	0.390	0.766
0.50	-0.207	0.071	0.515	0.934	0.955	0.653	0.389	0.760
0.60	-0.705	-0.429	-0.003	0.394	0.559	0.653	0.401	0.766
0.70	-1.144	-0.866	-0.449	-0.111	0.188	0.652	0.408	0.769
0.80	-1.609	-1.325	-0.928	-0.620	-0.246	0.647	0.418	0.770
0.90	-2.023	-1.732	-1.349	-1.066	-0.643	0.653	0.411	0.771
1.00	-2.451	-2.152	-1.776	-1.523	-1.084	0.657	0.410	0.775
1.25	-3.243	-2.923	-2.542	-2.327	-1.936	0.660	0.402	0.773
1.50	-3.888	-3.548	-3.169	-2.979	-2.661	0.664	0.408	0.779
2.00	-4.783	-4.410	-4.039	-3.871	-3.640	0.669	0.414	0.787
2.50	-5.444	-5.049	-4.698	-4.496	-4.341	0.671	0.411	0.786
3.00	-5.839	-5.431	-5.089	-4.893	-4.758	0.667	0.396	0.776
4.00	-6.598	-6.181	-5.882	-5.698	-5.588	0.647	0.382	0.751
5.00	-6.752	-6.347	-6.051	-5.873	-5.798	0.643	0.377	0.745

5.8.4 Calibration Plots

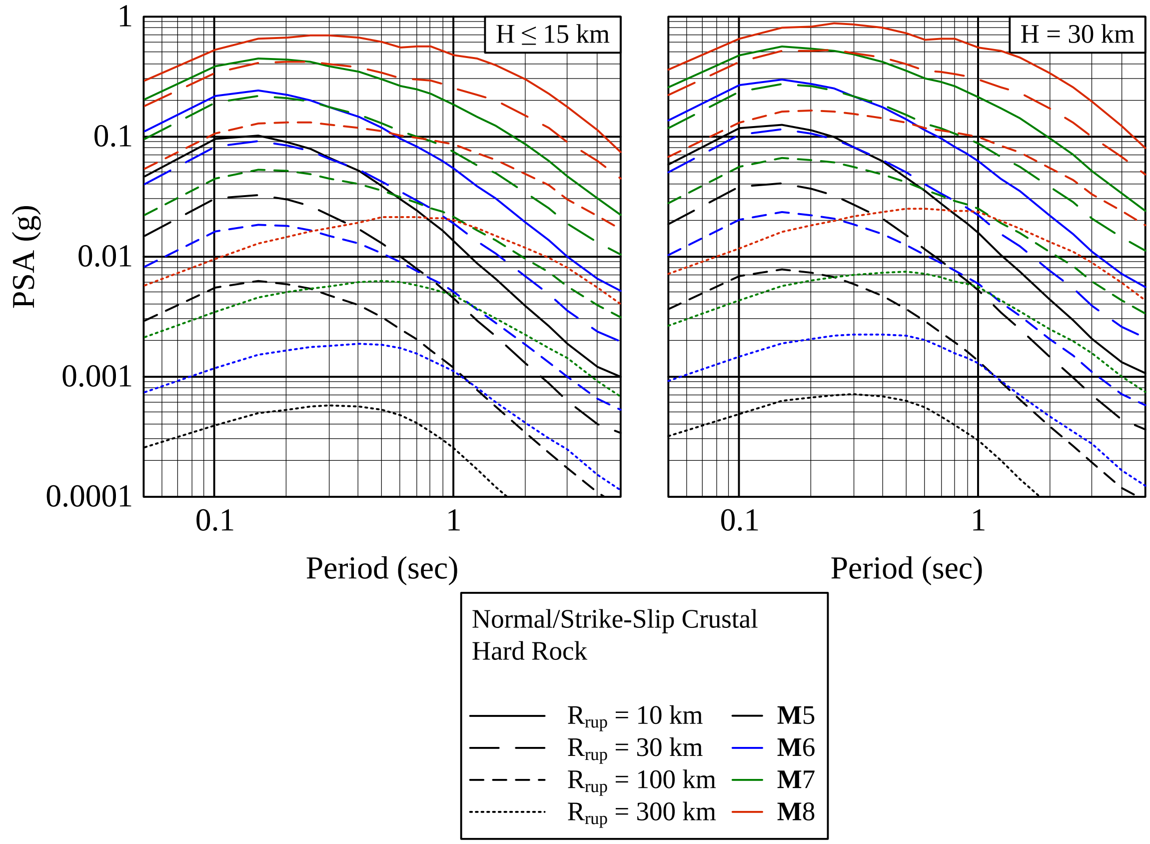


Figure 5-33. PSA as a function of period for various magnitudes and distances.

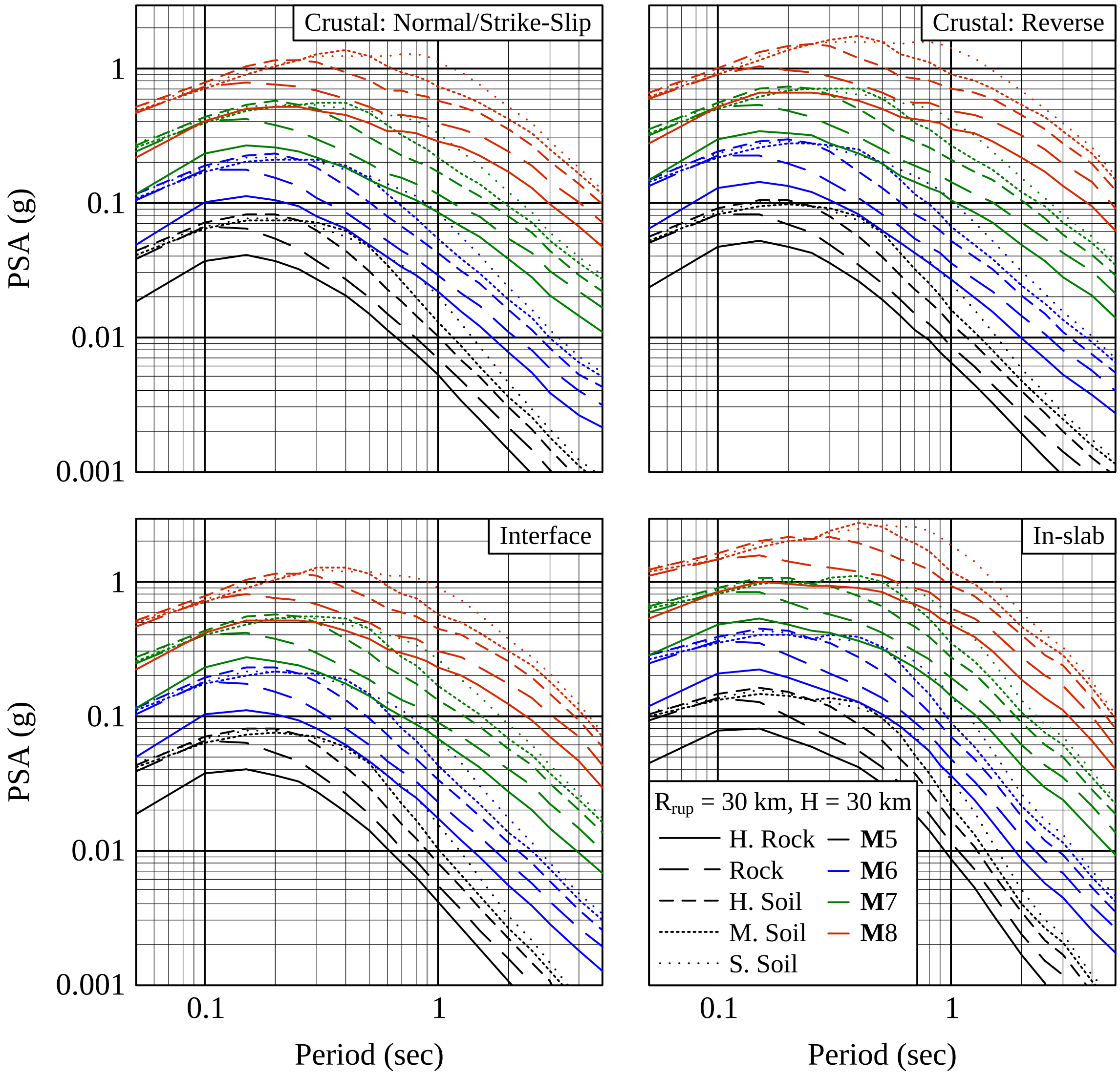


Figure 5-34. PSA as a function of period for various magnitudes, soil types and fault types.

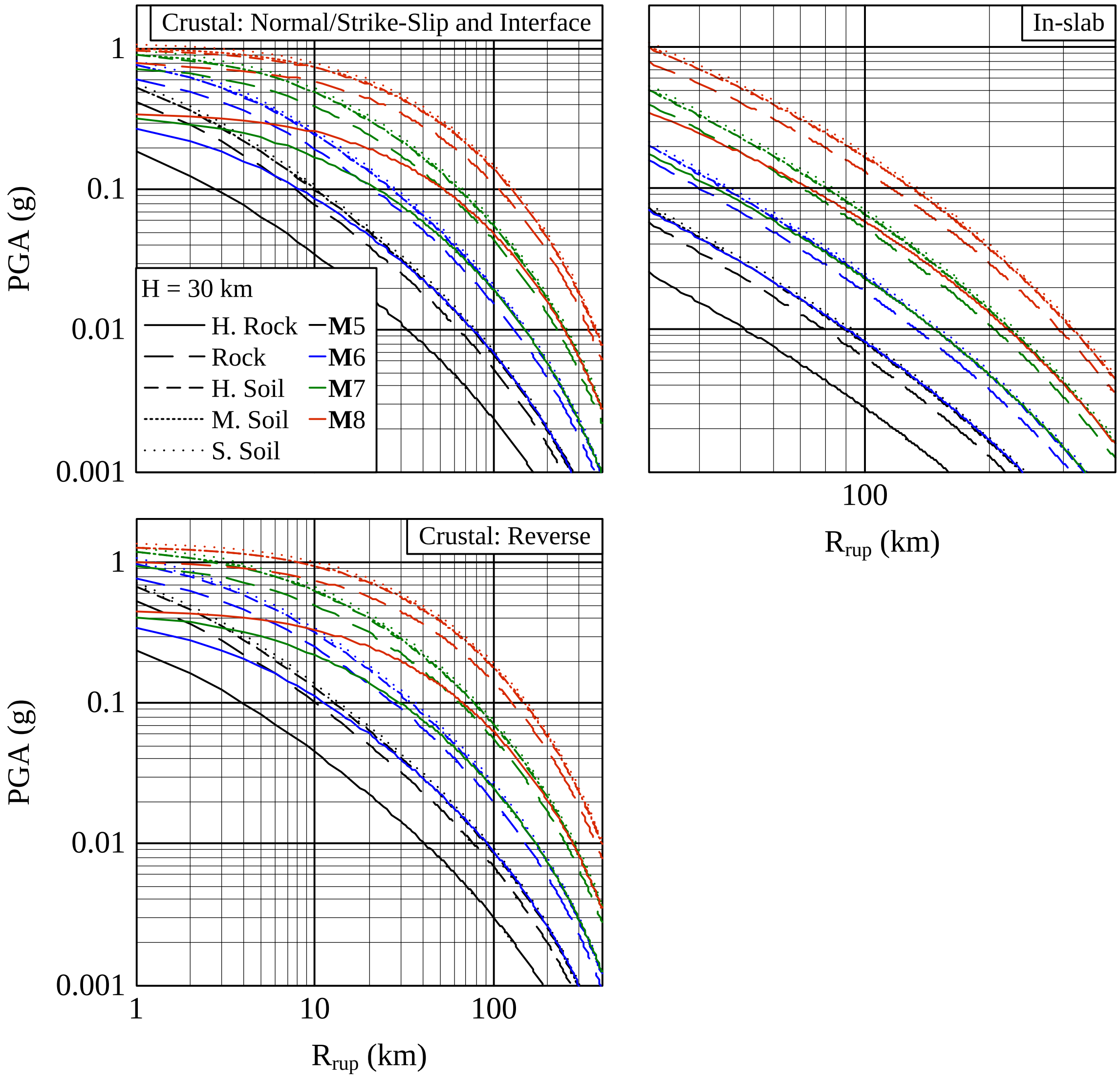


Figure 5-35. PGA as a function of distance for various magnitudes, soil types and fault types.

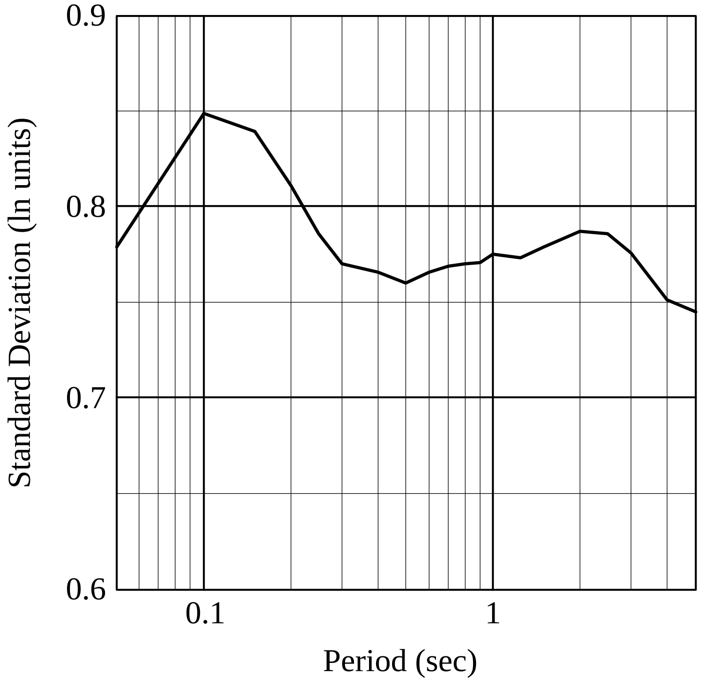


Figure 5-36. Standard deviation as a function of period.

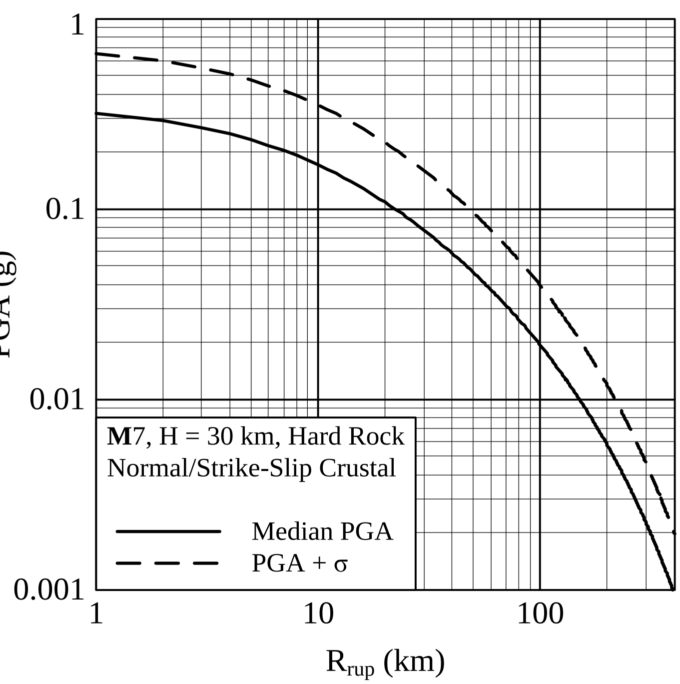


Figure 5-37. Example of application of median PGA plus one standard deviation.

5.8.5 Database

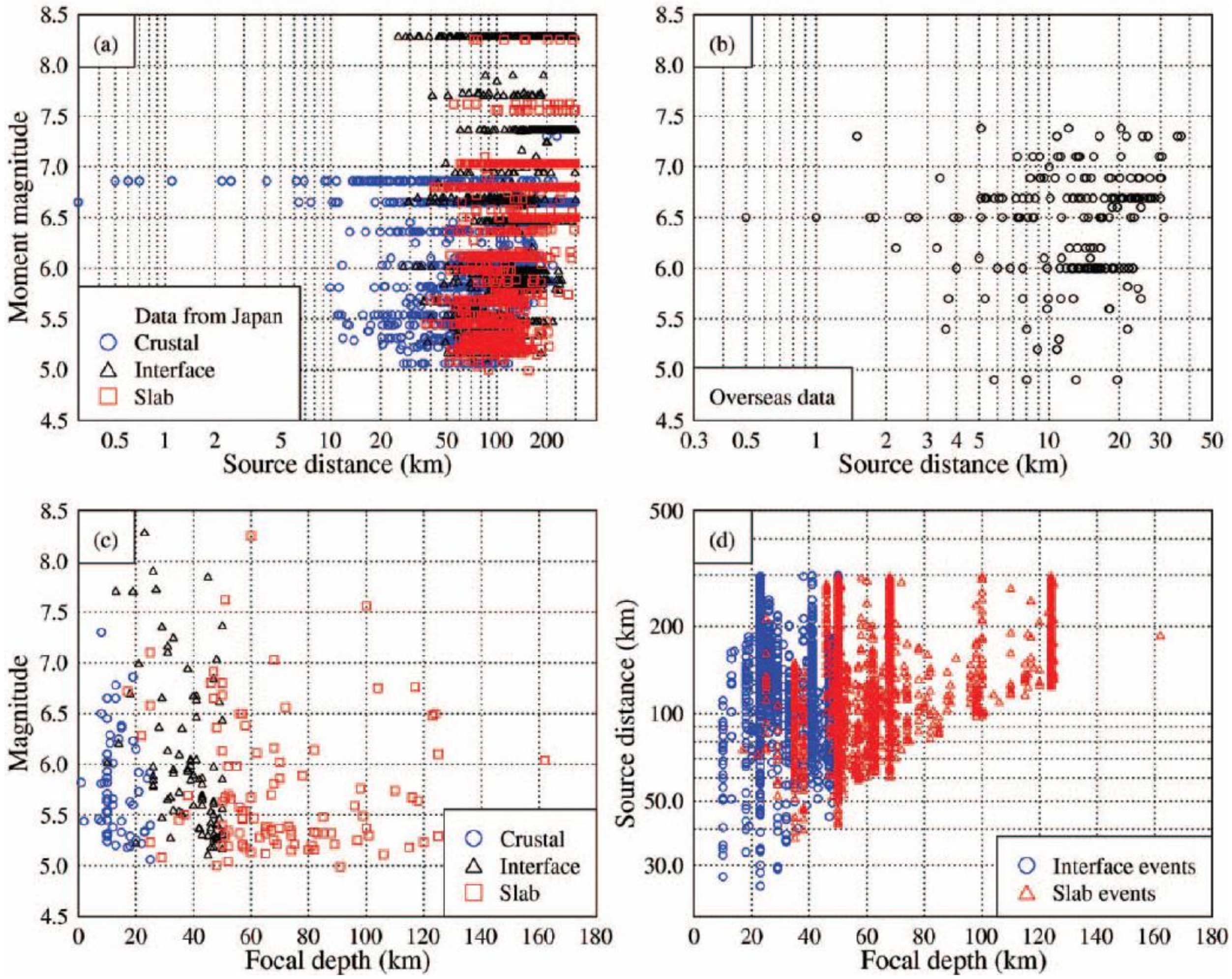


Figure 5-38. Distributions of data in database.

Focal Mechanism	Crustal	Interface	Slab	Total
Japan				
Reverse	250	1492	408	2150
Strike-slip	1011	13	574	1598
Normal	24	3	735	762
Unknown			8	8
Total	1285	1508	1725	4518
Iran and Western USA				
Reverse	123	12		135
Strike-slip	73			73
Total	196	12		208
Total from all regions				Grand Total
	1481	1520	1725	4726

Figure 5-39. Numbers of records by source type, faulting mechanism and region.

Source Type	Unknown	SC I	SC II	SC III	SC IV	Total
Japan						
Crustal	32	427	401	137	288	1285
Interface	9	373	540	186	400	1508
Slab	22	668	530	210	295	1725
Total	63	1468	1471	533	983	4518
Iran and Western USA						
Reverse		24	73	93	6	196
Strike-slip		2	7	3		12
Total		26	80	96	6	208
Total from all regions						Grand Total
	63	1494	1551	629	989	4726

Figure 5-40. Numbers of records by site class, source type and region.

5.8.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/22/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Zhao et al. attenuation equation, 2006
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T     = Period (sec), 0 for PGA
% M     = Moment magnitude
% H     = Focal depth (km)
% F     = Source location: 1 for reverse faulting crustal events, 2 for
%         interface, 3 for in-slab, and 0 otherwise
% Rrup  = Closest distance to rupture plane (km)
% S     = Site Class: 0 for hard rock, 1 for rock, 2 for hard soil, 3 for
%         medium soil and 4 for soft soil
% ---------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration or PGA prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = Zea_2006(T, M, H, F, Rrup, S)
% Coefficients
period   = [0.00    0.05    0.10    0.15    0.20    0.25    0.30    0.40    0.50    0.60...
    0.70    0.80    0.90    1.00    1.25    1.50    2.00    2.50    3.00    4.00    5.00];
a        = [1.101   1.076   1.118   1.134   1.147   1.149   1.163   1.200   1.250   1.293...
    1.336   1.386   1.433   1.479   1.551   1.621   1.694   1.748   1.759   1.826   1.825];
b        = [-0.00564    -0.00671    -0.00787    -0.00722    -0.00659    -0.00590    -0.00520...
            -0.00422    -0.00338    -0.00282    -0.00258    -0.00242    -0.00232    -0.00220...
            -0.00207    -0.00224    -0.00201    -0.00187    -0.00147    -0.00195    -0.00237];
c        = [0.0055  0.0075  0.0090  0.0100  0.0120  0.0140  0.0150  0.0100  0.0060  0.0030...
    0.0025  0.0022  0.0020  0.0020  0.0020  0.0020  0.0025  0.0028  0.0032  0.0040  0.0050];
d        = [1.080   1.060   1.083   1.053   1.014   0.966   0.934   0.959   1.008   1.088...
    1.084   1.088   1.109   1.115   1.083   1.091   1.055   1.052   1.025   1.044   1.065];
e        = [0.01412 0.01463 0.01423 0.01509 0.01462 0.01459 0.01458 0.01257 0.01114 0.01019...
    0.00979 0.00944 0.00972 0.01005 0.01003 0.00928 0.00833 0.00776 0.00644 0.00590 0.00510];
SR       = [0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0];
SI       = [0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0];
SS       = [0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0];
SSL      = [0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0];
if F == 1
    SR   = [0.251   0.251   0.240   0.251   0.260   0.269   0.259   0.248   0.247   0.233...
    0.220   0.232   0.220   0.211   0.251   0.248   0.263   0.262   0.307   0.353   0.248];
elseif F == 2
    SI   = [0.000   0.000   0.000   0.000   0.000   0.000   0.000   -0.041  -0.053  -0.103...
    -0.146  -0.164  -0.206  -0.239  -0.256  -0.306  -0.321  -0.337  -0.331  -0.390  -0.498];
elseif F == 3
    SS   = [2.607   2.764   2.156   2.161   1.901   1.814   2.181   2.432   2.629   2.702...
    2.654   2.480   2.332   2.233   2.029   1.589   0.966   0.789   1.037   0.561   0.225];
    SSL     = [-0.528   -0.551  -0.420  -0.431  -0.372  -0.360  -0.450  -0.506  -0.554  -0.575...
    -0.572  -0.540  -0.522  -0.509  -0.469  -0.379  -0.248  -0.221  -0.263  -0.169  -0.120];
end
if S == 0
    C    = [0.293   0.939   1.499   1.462   1.280   1.121   0.852   0.365   -0.207  -0.705...
    -1.144  -1.609  -2.023  -2.451  -3.243  -3.888  -4.783  -5.444  -5.839  -6.598  -6.752];
elseif S == 1
    C    = [1.111   1.684   2.061   1.916   1.669   1.468   1.172   0.655   0.071   -0.429...
    -0.866  -1.325  -1.732  -2.152  -2.923  -3.548  -4.410  -5.049  -5.431  -6.181  -6.347];
elseif S == 2
    C    = [1.344   1.793   2.135   2.168   2.085   1.942   1.683   1.127   0.515   -0.003...
    -0.449  -0.928  -1.349  -1.776  -2.542  -3.169  -4.039  -4.698  -5.089  -5.882  -6.051];
elseif S == 3
    C    = [1.355   1.747   2.031   2.052   2.001   1.941   1.808   1.482   0.934   0.394...
    -0.111  -0.620  -1.066  -1.523  -2.327  -2.979  -3.871  -4.496  -4.893  -5.698  -5.873];
elseif S == 4
    C    = [1.420   1.814   2.082   2.113   2.030   1.937   1.770   1.397   0.955   0.559...
    0.188   -0.246  -0.643  -1.084  -1.936  -2.661  -3.640  -4.341  -4.758  -5.588  -5.798];
```

```
end
sig      = [0.604   0.640   0.694   0.702   0.692   0.682   0.670   0.659   0.653   0.653...
    0.652   0.647   0.653   0.657   0.660   0.664   0.669   0.671   0.667   0.647   0.643];
tau      = [0.398   0.444   0.490   0.460   0.423   0.391   0.379   0.390   0.389   0.401...
    0.408   0.418   0.411   0.410   0.402   0.408   0.414   0.411   0.396   0.382   0.377];
sigT     = [0.723   0.779   0.849   0.839   0.811   0.786   0.770   0.766   0.760   0.766...
    0.769   0.770   0.771   0.775   0.773   0.779   0.787   0.786   0.776   0.751   0.745];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi  = min(period(find(period>T)));
    [sa_low, sigma_low] = Zea_2006(T_low, M, H, F, Rrup, S);
    [sa_hi,  sigma_hi]  = Zea_2006(T_hi,  M, H, F, Rrup, S);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    Sa = exp(a(i)*M + b(i)*Rrup - log(Rrup+c(i)*exp(d(i)*M)) + e(i)*(min(max(H,15),125)-15) + ...
        SR(i) + SI(i) + SS(i) + SSL(i)*log(Rrup) + C(i))/980.665;
    sigma = sigT(i);
end
```

5.9 New Zealand (crustal): McVerry, Zhao, Abrahamson and Somerville – 2006

5.9.1 Reference

McVerry, G. H., J. X. Zhao, N. A. Abrahamson, and P. G. Sommerville (2006). New Zeeland Acceleration Response Spectrum Attenuation Relations for Crustal and Subduction Zone Earthquakes, *Bulletin of the New Zealand Society for Earthquake Engineering* **39**(1), 1-58.

McVerry, G. H. (2011). Inst of Geol & Nuclear Sciences, Lower Hutt, New Zealand. Written communication.

5.9.2 Abstract

Using strong ground motions from 24 New Zealand earthquakes and 17 overseas earthquakes, empirical ground-motion models for the geometric mean of the horizontal and maximum horizontal components were developed. The model predicts peak ground acceleration (PGA) and 5%-damped spectral values (in g) for periods ranging from 0.075 to 3 s. This model is most applicable for earthquakes between M5.25 and M7.5 and distances up to 400 km. Please note that not all plots in the publication were able to be reproduced.

5.9.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0.01 or 0 for PGA
- **M** – Moment magnitude
- C_H – Horizontal component: 1 for geometric mean, 0 for maximum
- F – Fault type: 2 for normal, 1 for reverse, 0.5 for reverse/oblique, 0 otherwise
- R_{rup} – Closest distance to rupture plane (km)
- R_{VOL} – Length of the part of the source-to-site path in the volcanic zone (km) (see Figure 5-41)
- S – Soil type: 0 NEHRP site clas A/B, 1 for C, 2 for D

$$SA_{A/B,C,D} = SA_{A/B,C,D}{'}\left(\frac{PGA_{A/B,C,D}}{PGA_{A/B,C,D}{'}}\right)$$

where:

$$\ln\left(Sa_{A/B}{'}\right) = \mathrm{c_1}' + c_4(M-6) + c_3(8.5-M)^2 + \mathrm{c_5}'\mathrm{R_{rup}}$$
$$+ \left(\mathrm{c_8}' + \mathrm{c_6}(M-6)\right)\ln\sqrt{{R_{rup}}^2 + {c_{10}}^2} + \mathrm{c_{46}}'R_{VOL} + c_{32}CN + c_{33}CR$$

where:

$$CN = \begin{cases} -1 & for\ F = 2 \\ 0 & otherwise \end{cases}$$

$$CR = \begin{cases} 1 & for\ F = 1 \\ 0.5 & for\ F = 0.5 \\ 0 & otherwise \end{cases}$$

$$\ln\left(Sa_{C,D}{}'\right) = \ln\left(Sa_{A/B}{}'\right) + c_{29}{}'\delta_C + \left(c_{30}\ln\left(Sa_{A/B}{}' + 0.03\right) + c_{43}{}'\right)\delta_D$$

where:

$$\delta_C = \begin{cases} 1 & for\ S = 1 \\ 0 & otherwise \end{cases}$$

$$\delta_D = \begin{cases} 1 & for\ S = 2 \\ 0 & otherwise \end{cases}$$

$$PGA_{A/B}{}' = SA_{A/B}{}'(T = 0)$$

Note: The expressions for $PGA_{A/B,C,D}$ take the same form as those for $PGA_{A/B,C,D}$' but are differentiated by using unprimed versions of the coefficients.

Standard Error

$$\sigma_{tot} = \sqrt{\sigma^2 + \tau^2}$$

where:

$$\sigma = \sigma_{M6} + \sigma_{slope}(M - 6)$$

Note: For M > 7 use M = 7 and for M < 5, use M = 5.

Coefficients

Table 5-14. Coefficients for the maximum horizontal component.

T	c_1	c_3	c_4	c_5	c_6	c_8	c_{10}	c_{29}
0.075	1.36561	0.0300	-0.144	-0.00889	0.17	-0.94568	5.58	0.31139
0.10	1.77717	0.0280	-0.144	-0.00837	0.17	-1.01852	5.50	0.34059
0.20	1.39535	-0.0138	-0.144	-0.00940	0.17	-0.78199	5.10	0.37235
0.30	0.44591	-0.0360	-0.144	-0.00987	0.17	-0.56098	4.80	0.56648
0.40	0.01645	-0.0518	-0.144	-0.00923	0.17	-0.51281	4.52	0.69911
0.50	0.14826	-0.0635	-0.144	-0.00823	0.17	-0.56716	4.30	0.63188
0.75	-0.21246	-0.0862	-0.144	-0.00738	0.17	-0.55384	3.90	0.51577
1.0	-0.10451	-0.1020	-0.144	-0.00588	0.17	-0.65892	3.70	0.34048
1.5	-0.48665	-0.1200	-0.144	-0.00630	0.17	-0.58222	3.55	0.12468
2.0	-0.77433	-0.1200	-0.144	-0.00630	0.17	-0.58222	3.55	0.12468
3.0	-1.30916	-0.1726	-0.144	-0.00553	0.17	-0.57009	3.50	0.14593
PGA	0.28815	0	-0.144	-0.00967	0.17	-0.70494	5.60	0.30206
PGA'	0.18130	0	-0.144	-0.00846	0.17	-0.75519	5.60	0.44307

T	c_{30}	c_{32}	c_{33}	c_{43}	c_{46}	σ_{M6}	σ_{slope}	τ
0.075	-0.280	0.2	0.260	-0.48366	-0.03452	0.5281	-0.0970	0.3217
0.10	-0.280	0.2	0.260	-0.43854	-0.03595	0.5398	-0.0673	0.3088
0.20	-0.245	0.2	0.260	-0.29906	-0.03853	0.5703	-0.0243	0.2726
0.30	-0.195	0.2	0.198	-0.05184	-0.03604	0.5505	-0.0861	0.2112
0.40	-0.160	0.2	0.154	0.20301	-0.03364	0.5627	-0.1405	0.2005
0.50	-0.121	0.2	0.119	0.37026	-0.03260	0.5680	-0.1444	0.1476
0.75	-0.050	0.2	0.057	0.73517	-0.02877	0.5562	-0.0932	0.1794
1.0	0.000	0.2	0.013	0.87764	-0.02561	0.5629	-0.0749	0.2053
1.5	0.040	0.2	-0.049	0.75438	-0.02034	0.5394	-0.0056	0.2411
2.0	0.040	0.2	-0.049	0.75438	-0.02034	0.5394	-0.0056	0.2411
3.0	0.040	0.2	-0.156	0.61545	-0.01673	0.5701	0.0934	0.2406
PGA	-0.230	0.2	0.260	-0.31769	-0.03279	0.4865	-0.1261	0.2687
PGA'	-0.230	0.2	0.260	-0.29648	-0.03301	0.5035	-0.0635	0.2598

Table 5-15. Coefficients for the geometric mean of the response spectra.

T	c_1	c_3	c_4	c_5	c_6	c_8	c_{10}	c_{29}
0.075	1.22050	0.0300	-0.144	-0.00914	0.17	-0.93059	5.58	0.27879
0.10	1.53365	0.0280	-0.144	-0.00903	0.17	-0.96506	5.50	0.28619
0.20	1.22565	-0.0138	-0.144	-0.00975	0.17	-0.75855	5.10	0.34064
0.30	0.21124	-0.0360	-0.144	-0.01032	0.17	-0.52400	4.80	0.53213
0.40	-0.10541	-0.0518	-0.144	-0.00941	0.17	-0.50802	4.52	0.63272
0.50	-0.14260	-0.0635	-0.144	-0.00878	0.17	-0.52214	4.30	0.58809
0.75	-0.65968	-0.0862	-0.144	-0.00802	0.17	-0.47264	3.90	0.50708
1.0	-0.51404	-0.1020	-0.144	-0.00647	0.17	-0.58672	3.70	0.33002
1.5	-0.95399	-0.1200	-0.144	-0.00713	0.17	-0.49268	3.55	0.07445
2.0	-1.24167	-0.1200	-0.144	-0.00713	0.17	-0.49268	3.55	0.07445
3.0	-1.56570	-0.1726	-0.144	-0.00623	0.17	-0.52257	3.50	0.09869
PGA	0.14274	0	-0.144	-0.00989	0.17	-0.68744	5.60	0.27315
PGA'	0.07713	0	-0.144	-0.00898	0.17	-0.73728	5.60	0.38730

T	c_{30}	c_{32}	c_{33}	c_{43}	c_{46}	σ_{M6}	σ_{slope}	τ
0.075	-0.280	0.2	0.260	-0.49068	-0.03441	0.5297	-0.0703	0.3139
0.10	-0.280	0.2	0.260	-0.46604	-0.03594	0.5401	-0.0292	0.3017
0.20	-0.245	0.2	0.260	-0.31282	-0.03823	0.5599	0.0172	0.2583
0.30	-0.195	0.2	0.198	-0.07565	-0.03535	0.5456	-0.0566	0.1967
0.40	-0.160	0.2	0.154	0.17615	-0.03354	0.5556	-0.1064	0.1802
0.50	-0.121	0.2	0.119	0.34775	-0.03211	0.5658	-0.1123	0.1440
0.75	-0.050	0.2	0.057	0.72380	-0.02857	0.5611	-0.0836	0.1871
1.0	0.000	0.2	0.013	0.89239	-0.02500	0.5573	-0.0620	0.2073
1.5	0.040	0.2	-0.049	0.77743	-0.02008	0.5419	0.0385	0.2405
2.0	0.040	0.2	-0.049	0.77743	-0.02008	0.5419	0.0385	0.2405
3.0	0.040	0.2	-0.156	0.60938	-0.01587	0.5809	0.1403	0.2053
PGA	-0.230	0.2	0.260	-0.33716	-0.03255	0.4871	-0.1011	0.2677
PGA'	-0.230	0.2	0.260	-0.31036	-0.03250	0.5099	-0.0259	0.2469

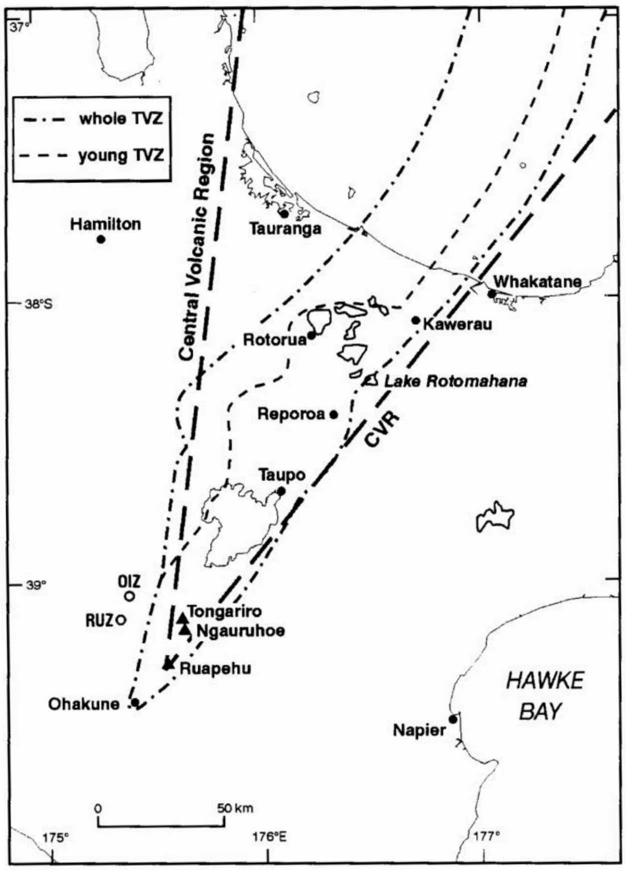


Figure 5-41. The Central Volcanic Region (CVR), whole Taupo Volcanic Zone (TVZ), and young TVZ. This model uses the whole volcanic zone in calculations of R_{VOL}.

5.9.4 *Calibration Plots*

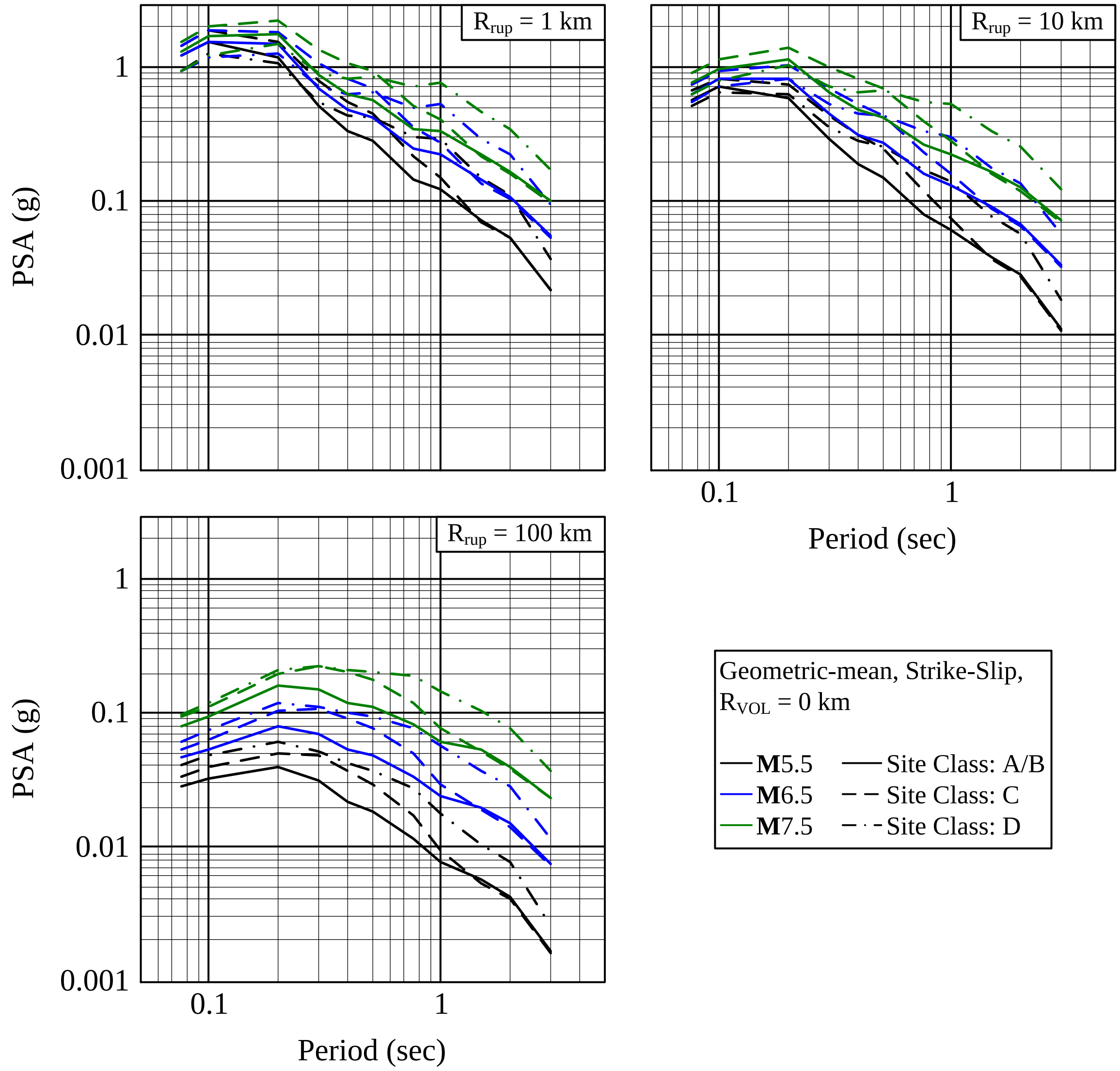


Figure 5-42. PSA as a function of period for various magnitudes, soil types and distances.

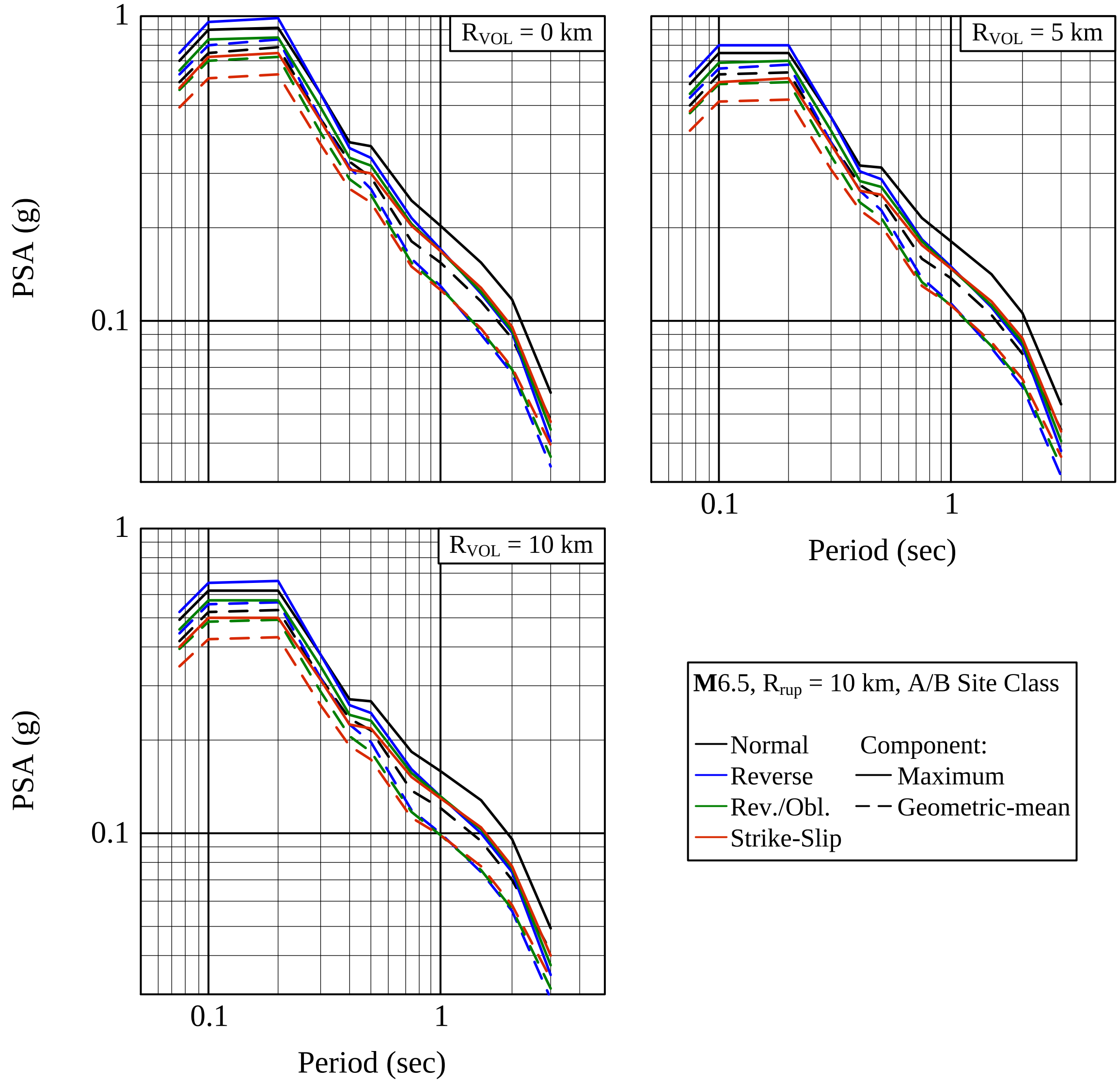


Figure 5-43. PSA as a function of period for various fault types, horizontal components and volcanic zone influence.

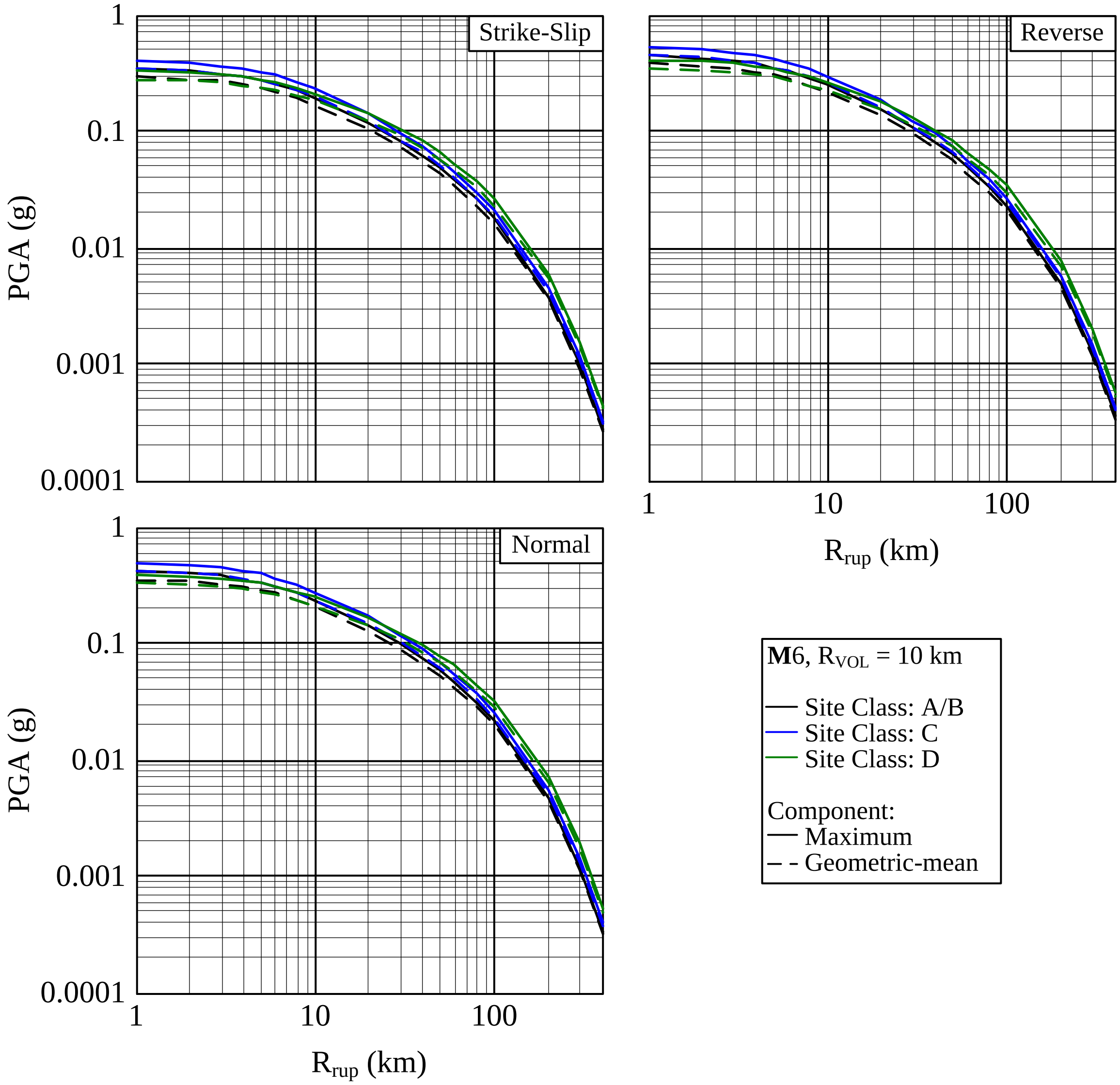


Figure 5-44. PGA as a function of period for various conditions.

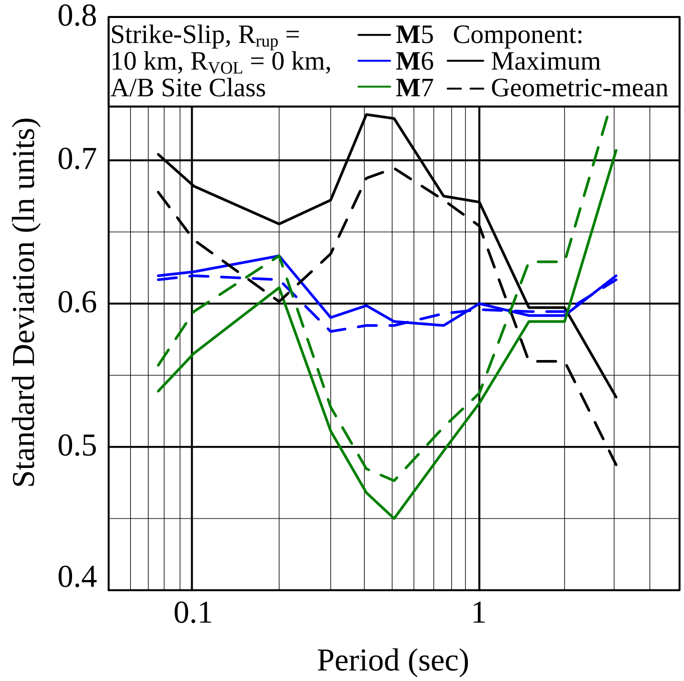


Figure 5-45. Standard deviation as a function of period.

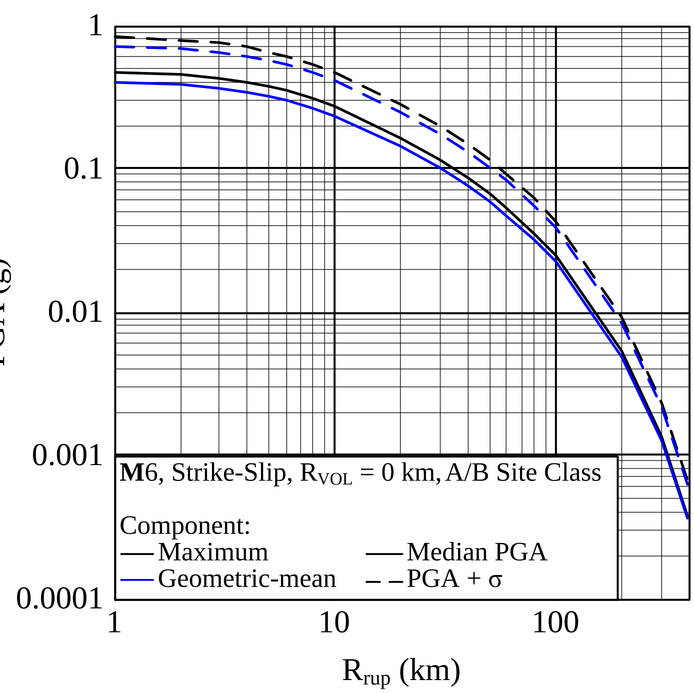


Figure 5-46. Example application of median PGA plus one standard deviation.

5.9.5 Database

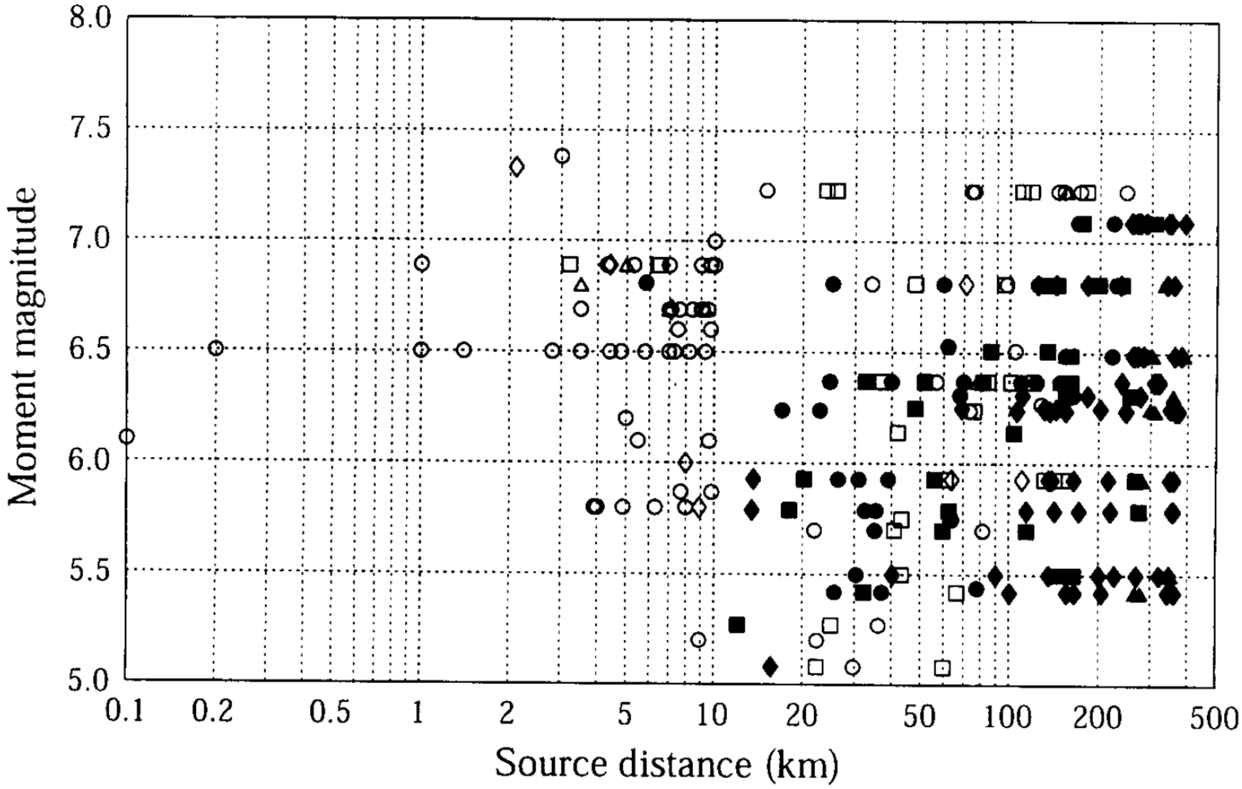


Figure 5-47. Distribution of data for the four site classes by magnitude and distance for crustal earthquakes. Triangles are weak rock, diamonds are for meadium/strong rock, circles are for AL/B soil, squares are for C soil. Open symbols are for records for which only peak ground accelerations were used, while solid symbols represent response spectrum data.

5.9.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/1/2011
% Virginia Tech
% kgunberg@vt.edu
%
% McVerry, Zhao, Abrahamson and Somerville (crustal) attenuation equation,
% 2006
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0 for PGA
% M         = Magnitude
% Ch        = Horizontal Component: 1 for geometric mean, 0 for maximum
% F         = Fault Type: 2 for normal, 1 for reverse, 0.5 for
%             reverse/oblique, 0 otherwise
% Rrup      = Closest distance to rupture plane (km)
% Rvol      = Length of the part of the source to site path in the volcanic
%             zone (km)
% S         = Soil Type: 0 for NEHRP site class A/B, 1 for C, 2 for D
% -------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = MZAS_2006_c(T,M,Ch,F,Rrup,Rvol,S)
% Coefficients
if Ch == 0
    period   = [0.075   0.10    0.20    0.30    0.40    0.50    0.75    1.0 1.5 2.0 3.0 0   -1];
    c1       = [1.36561 1.77717 1.39535 0.44591 0.01645 0.14826 -0.21246    -0.10451...
                -0.48665    -0.77433    -1.30916    0.28815 0.18130];
    c3       = [0.0300  0.0280  -0.0138 -0.0360 -0.0518 -0.0635 -0.0862 -0.1020 -0.1200...
                -0.1200 -0.1726 0   0];
    c4       = [-0.144  -0.144  -0.144  -0.144  -0.144  -0.144  -0.144  -0.144  -0.144...
                -0.144  -0.144  -0.144  -0.144];
    c5       = [-0.00889    -0.00837    -0.00940    -0.00987    -0.00923    -0.00823...
                -0.00738    -0.00588    -0.00630    -0.00630    -0.00553    -0.00967...
                -0.00846];
    c6       = [0.17    0.17    0.17    0.17    0.17    0.17    0.17    0.17    0.17...
                0.17    0.17    0.17    0.17];
    c8       = [-0.94568    -1.01852    -0.78199    -0.56098    -0.51281    -0.56716...
                -0.55384    -0.65892    -0.58222    -0.58222    -0.57009    -0.70494...
                -0.75519];
    c10      = [5.58    5.50    5.10    4.80    4.52    4.30    3.90    3.70    3.55    3.55...
                3.50    5.60    5.60];
    c29      = [0.31139 0.34059 0.37235 0.56648 0.69911 0.63188 0.51577 0.34048 0.12468...
                0.12468 0.14593 0.30206 0.44307];
    c30      = [-0.280  -0.280  -0.245  -0.195  -0.160  -0.121  -0.050  0.000   0.040   0.040...
                0.040   -0.230  -0.230];
    c32      = [0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2];
    c33      = [0.260   0.260   0.260   0.198   0.154   0.119   0.057   0.013   -0.049...
                -0.049  -0.156  0.260   0.260];
    c43      = [-0.48366    -0.43854    -0.29906    -0.05184    0.20301 0.37026 0.73517...
                0.87764 0.75438 0.75438 0.61545 -0.31769    -0.29648];
    c46      = [-0.03452    -0.03595    -0.03853    -0.03604    -0.03364    -0.03260...
                -0.02877    -0.02561    -0.02034    -0.02034    -0.01673    -0.03279...
                -0.03301];
    sig_M6   = [0.5281  0.5398  0.5703  0.5505  0.5627  0.5680  0.5562  0.5629  0.5394...
                0.5394  0.5701  0.4865  0.5035];
    sig_slope= [-0.0970 -0.0673 -0.0243 -0.0861 -0.1405 -0.1444 -0.0932 -0.0749 -0.0056...
                -0.0056 0.0934  -0.1261 -0.0635];
    tau      = [0.3217  0.3088  0.2726  0.2112  0.2005  0.1476  0.1794  0.2053  0.2411...
                0.2411  0.2406  0.2687  0.2598];
else
    period   = [0.075   0.10    0.20    0.30    0.40    0.50    0.75    1.0 1.5 2.0 3.0 0   -1];
    c1       = [1.22050 1.53365 1.22565 0.21124 -0.10541    -0.14260    -0.65968    -0.51404...
                -0.95399    -1.24167    -1.56570    0.14274 0.07713];
    c3       = [0.0300  0.0280  -0.0138 -0.0360 -0.0518 -0.0635 -0.0862 -0.1020 -0.1200...
                -0.1200 -0.1726 0   0];
```

```
    c4       = [-0.144  -0.144  -0.144  -0.144  -0.144  -0.144  -0.144  -0.144  -0.144...
                -0.144  -0.144  -0.144  -0.144];
    c5       = [-0.00914    -0.00903    -0.00975    -0.01032    -0.00941    -0.00878...
                -0.00802    -0.00647    -0.00713    -0.00713    -0.00623    -0.00989...
                -0.00898];
    c6       = [0.17    0.17    0.17    0.17    0.17    0.17    0.17    0.17    0.17...
                0.17    0.17    0.17    0.17];
    c8       = [-0.93059    -0.96506    -0.75855    -0.52400    -0.50802    -0.52214...
                -0.47264    -0.58672    -0.49268    -0.49268    -0.52257    -0.68744...
                -0.73728];
    c10      = [5.58    5.50    5.10    4.80    4.52    4.30    3.90    3.70    3.55...
                3.55    3.50    5.60    5.60];
    c29      = [0.27879 0.28619 0.34064 0.53213 0.63272 0.58809 0.50708 0.33002 0.07445...
                0.07445 0.09869 0.27315 0.38730];
    c30      = [-0.280  -0.280  -0.245  -0.195  -0.160  -0.121  -0.050  0.000   0.040...
                0.040   0.040   -0.230  -0.230];
    c32      = [0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2];
    c33      = [0.260   0.260   0.260   0.198   0.154   0.119   0.057   0.013   -0.049...
                -0.049  -0.156  0.260   0.260];
    c43      = [-0.49068    -0.46604    -0.31282    -0.07565    0.17615 0.34775 0.72380...
                0.89239 0.77743 0.77743 0.60938 -0.33716    -0.31036];
    c46      = [-0.03441    -0.03594    -0.03823    -0.03535    -0.03354    -0.03211...
                -0.02857    -0.02500    -0.02008    -0.02008    -0.01587    -0.03255...
                -0.03250];
    sig_M6   = [0.5297  0.5401  0.5599  0.5456  0.5556  0.5658  0.5611  0.5573  0.5419...
                0.5419  0.5809  0.4871  0.5099];
    sig_slope= [-0.0703 -0.0292 0.0172  -0.0566 -0.1064 -0.1123 -0.0836 -0.0620 0.0385...
                0.0385  0.1403  -0.1011 -0.0259];
    tau      = [0.3139  0.3017  0.2583  0.1967  0.1802  0.1440  0.1871  0.2073  0.2405...
                0.2405  0.2053  0.2677  0.2469];
end
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low,sig_low]=MZAS_2006_c(T_low,M,Ch,F,Rrup,Rvol,S);
    [sa_hi, sig_hi] =MZAS_2006_c(T_hi ,M,Ch,F,Rrup,Rvol,S);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sig_T = [sig_low sig_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sig_T,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    CN = F == 2; % CN: 1 for normal fault, 0 otherwise
    if or(F == 1, F == 0.5)
        CR = F;
    else
        CR = 0;
    end

    deltaC = S == 1; %deltaC: 1 for NEHRP C soil, 0 otherwise
    deltaD = S == 2; %deltaD: 1 for NEHRP D soil, 0 otherwise

    PGA_ABp = exp(c1(13) + c4(13)*(M-6) + c3(13)*(8.5-M)^2 + c5(13)*Rrup + (c8(13) +...
        c6(13)*(M-6))*log(sqrt(Rrup^2+c10(13)^2)) + c46(13)*Rvol + c32(13)*CN + c33(13)*CR);
    PGA_AB  = exp(c1(12) + c4(12)*(M-6) + c3(12)*(8.5-M)^2 + c5(12)*Rrup + (c8(12) +...
        c6(12)*(M-6))*log(sqrt(Rrup^2+c10(12)^2)) + c46(12)*Rvol + c32(12)*CN + c33(12)*CR);
    SA_ABp  = exp(c1(i) + c4(i)*(M-6) + c3(i)*(8.5-M)^2 + c5(i)*Rrup + (c8(i) +...
        c6(i)*(M-6))*log(sqrt(Rrup^2+c10(i)^2)) + c46(i)*Rvol + c32(i)*CN + c33(i)*CR);

    PGA_ABCDp = exp(log(PGA_ABp) + c29(13)*deltaC + (c30(13)*log(PGA_ABp+0.03)+c43(13))*deltaD);
    PGA_ABCD  = exp(log(PGA_AB) + c29(12)*deltaC + (c30(12)*log(PGA_ABp+0.03)+c43(12))*deltaD);
    SA_ABCDp  = exp(log(SA_ABp) + c29(i)*deltaC + (c30(i)*log(PGA_ABp+0.03)+c43(i))*deltaD);

    Sa = SA_ABCDp*(PGA_ABCD/PGA_ABCDp);
    sigma = sqrt((sig_M6(i)+sig_slope(i)*(min(7,max(5,M))-6))^2 + tau(i)^2);
end
```

5.10 New Zealand (subduction): McVerry, Zhao, Abrahamson and Somerville – 2006

5.10.1 Reference

McVerry, G. H., J. X. Zhao, N. A. Abrahamson, and P. G. Sommerville (2006). New Zeeland Acceleration Response Spectrum Attenuation Relations for Crustal and Subduction Zone Earthquakes, *Bulletin of the New Zealand Society for Earthquake Engineering* **39**(1), 1-58.

McVerry, G. H. (2011). Inst of Geol & Nuclear Sciences, Lower Hutt, New Zealand. Written communication.

5.10.2 Abstract

Using strong ground motions from 25 New Zealand earthquakes, empirical ground-motion models for the geometric-mean of the horizontal and maximum horizontal components were developed. The model predicts peak ground acceleration (PGA) and 5%-damped spectral values (in g) for periods ranging from 0.075 to 3 s. This model is most applicable for earthquakes between M5.25 and M7.5 and distances up to 400 km and focal depths less than 150 km. Please note that not all plots in the publication were able to be reproduced.

5.10.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0.01 or 0 for PGA
- **M** – Moment magnitude
- C_H – Horizontal component: 1 for geometric mean, 0 for maximum
- H – Focal depth (km)
- F – Fault type: 2 for deep slab, 1 for subduction interface, 0 otherwise
- R_{rup} – Closest distance to rupture plane (km)
- R_{VOL} – Length of the part of the source-to-site path in the volcanic zone (km) (see Figure 5-41)
- S – Soil type: 0 NEHRP site clas A/B, 1 for C, 2 for D

$$SA_{A/B,C,D} = SA_{A/B,C,D}{}' \left(\frac{PGA_{A/B,C,D}}{PGA_{A/B,C,D}{}'}\right)$$

where:

$$\begin{aligned}\ln\left(Sa_{A/B}{}'\right) = {} & \mathrm{c}_{11}{}' + (c_{12} + (c_{15}{}' - c_{17}{}')c_{19})(M-6) + c_{13}(10-M)^3 \\ & + \mathrm{c}_{17}{}' \ln\left(R_{rup} + c_{18}e^{c_{19}M}\right) + c_{20}{}'H + c_{24}{}'SI + c_{46}{}'R_{VOL}(1-DS)\end{aligned}$$

where:

$$SI = \begin{cases} 1 & for\ F = 1 \\ 0 & otherwise \end{cases}$$

$$DS = \begin{cases} 1 & for\ F = 2 \\ 0 & otherwise \end{cases}$$

$$\ln\left(Sa_{C,D}{}'\right) = \ln\left(Sa_{A/B}{}'\right) + \mathrm{c}_{29}{}'\delta_C + \left(c_{30}\ln\left(PGA_{A/B}{}' + 0.03\right) + \mathrm{c}_{43}{}'\right)\delta_D$$

where:

$$\delta_C = \begin{cases} 1 & for\ S = 1 \\ 0 & otherwise \end{cases}$$

$$\delta_D = \begin{cases} 1 & for\ S = 2 \\ 0 & otherwise \end{cases}$$

$$PGA_{A/B}{}' = SA_{A/B}{}'(T = 0)$$

Note: The expressions for $PGA_{A/B,C,D}$ take the same form as those for $PGA_{A/B,C,D}$' but are differentiated by using unprimed versions of the coefficients.

Standard Error

$$\sigma_{tot} = \sqrt{\sigma^2 + \tau^2}$$

where:

$$\sigma = \sigma_{\mathrm{M6}} + \sigma_{\mathrm{slope}}(M - 6)$$

Note: For M > 7 use M = 7 and for M < 5, use M = 5.

Coefficients

Table 5-16. Coefficients for the maximum horizontal component.

T	c_{11}	c_{12}	c_{13}	c_{15}	c_{17}	c_{18}	c_{19}	c_{20}
0.075	8.68782	1.414	0	-2.707	-2.54215	1.7818	0.554	0.01850
0.10	9.37929	1.414	-0.001	-2.655	-2.60945	1.7818	0.554	0.01740
0.20	10.6148	1.414	-0.003	-2.528	-2.70851	1.7818	0.554	0.01542
0.30	9.40776	1.414	-0.004	-2.454	-2.47668	1.7818	0.554	0.01278
0.40	8.50343	1.414	-0.004	-2.401	-2.36895	1.7818	0.554	0.01426
0.50	8.46463	1.414	-0.005	-2.360	-2.40630	1.7818	0.554	0.01287
0.75	7.30176	1.414	-0.006	-2.286	-2.26512	1.7818	0.554	0.01080
1.0	7.08727	1.414	-0.006	-2.234	-2.27668	1.7818	0.554	0.00946
1.5	6.93264	1.414	-0.007	-2.160	-2.28347	1.7818	0.554	0.00788
2.0	6.64496	1.414	-0.007	-2.160	-2.28347	1.7818	0.554	0.00788
3.0	5.05488	1.414	-0.009	-2.033	-2.03050	1.7818	0.554	-0.00265
PGA	8.68354	1.414	0	-2.552	-2.56727	1.7818	0.554	0.01550
PGA'	8.10697	1.414	0	-2.552	-2.48795	1.7818	0.554	0.01622

T	c_{24}	c_{29}	c_{30}	c_{43}	c_{46}	σ_{M6}	σ_{slope}	τ
0.075	-0.48652	0.31139	-0.280	-0.4837	-0.03452	0.5281	-0.0970	0.3217
0.10	-0.61973	0.34059	-0.280	-0.4385	-0.03595	0.5398	-0.0673	0.3088
0.20	-0.67672	0.37235	-0.245	-0.2991	-0.03853	0.5703	-0.0243	0.2726
0.30	-0.59339	0.56648	-0.195	-0.0518	-0.03604	0.5505	-0.0861	0.2112
0.40	-0.30579	0.69911	-0.160	0.20301	-0.03364	0.5627	-0.1405	0.2005
0.50	-0.24839	0.63188	-0.121	0.37026	-0.03260	0.5680	-0.1444	0.1476
0.75	-0.01298	0.51577	-0.050	0.73517	-0.02877	0.5562	-0.0932	0.1794
1.0	0.06672	0.34048	0.000	0.87764	-0.02561	0.5629	-0.0749	0.2053
1.5	-0.02289	0.12468	0.040	0.75438	-0.02034	0.5394	-0.0056	0.2411
2.0	-0.02289	0.12468	0.040	0.75438	-0.02034	0.5394	-0.0056	0.2411
3.0	-0.20537	0.14593	0.040	0.61545	-0.01673	0.5701	0.0934	0.2406
PGA	-0.50962	0.30206	-0.230	-0.3177	-0.03279	0.4865	-0.1261	0.2687
PGA'	-0.41369	0.44307	-0.230	-0.2965	-0.03301	0.5035	-0.0635	0.2598

Table 5-17. Coefficients for the geometric mean of the response spectra.

T	c_{11}	c_{12}	c_{13}	c_{15}	c_{17}	c_{18}	c_{19}	c_{20}
0.075	8.69303	1.414	0	-2.707	-2.55903	1.7818	0.554	0.01821
0.10	9.30400	1.414	-0.0011	-2.655	-2.61372	1.7818	0.554	0.01737
0.20	10.41628	1.414	-0.0027	-2.528	-2.70038	1.7818	0.554	0.01531
0.30	9.21783	1.414	-0.0036	-2.454	-2.47356	1.7818	0.554	0.01304
0.40	8.01150	1.414	-0.0043	-2.401	-2.30457	1.7818	0.554	0.01426
0.50	7.87495	1.414	-0.0048	-2.360	-2.31991	1.7818	0.554	0.01277
0.75	7.26785	1.414	-0.0057	-2.286	-2.28460	1.7818	0.554	0.01055
1.0	6.98741	1.414	-0.0064	-2.234	-2.28256	1.7818	0.554	0.00927
1.5	6.77543	1.414	-0.0073	-2.160	-2.27895	1.7818	0.554	0.00748
2.0	6.48775	1.414	-0.0073	-2.160	-2.27895	1.7818	0.554	0.00748
3.0	5.05424	1.414	-0.0089	-2.033	-2.05560	1.7818	0.554	-0.00273
PGA	8.57343	1.414	0	-2.552	-2.56592	1.7818	0.554	0.01545
PGA'	8.08611	1.414	0	-2.552	-2.49894	1.7818	0.554	0.01590

T	c_{24}	c_{29}	c_{30}	c_{43}	c_{46}	σ_{M6}	σ_{slope}	τ
0.075	-0.52504	0.27879	-0.280	-0.49068	-0.03441	0.5297	-0.0703	0.3139
0.10	-0.61452	0.28619	-0.280	-0.46604	-0.03594	0.5401	-0.0292	0.3017
0.20	-0.65966	0.34064	-0.245	-0.31282	-0.03823	0.5599	0.0172	0.2583
0.30	-0.56604	0.53213	-0.195	-0.07565	-0.03535	0.5456	-0.0566	0.1967
0.40	-0.33169	0.63272	-0.160	0.17615	-0.03354	0.5556	-0.1064	0.1802
0.50	-0.24374	0.58809	-0.121	0.34775	-0.03211	0.5658	-0.1123	0.1440
0.75	-0.01583	0.50708	-0.050	0.72380	-0.02857	0.5611	-0.0836	0.1871
1.0	0.02009	0.33002	0.000	0.89239	-0.02500	0.5573	-0.0620	0.2073
1.5	-0.07051	0.07445	0.040	0.77743	-0.02008	0.5419	0.0385	0.2405
2.0	-0.07051	0.07445	0.040	0.77743	-0.02008	0.5419	0.0385	0.2405
3.0	-0.23967	0.09869	0.040	0.60938	-0.01587	0.5809	0.1403	0.2053
PGA	-0.49963	0.27315	-0.230	-0.33716	-0.03255	0.4871	-0.1011	0.2677
PGA'	-0.43223	0.38730	-0.230	-0.31036	-0.03250	0.5099	-0.0259	0.2469

5.10.4 Calibration Plots

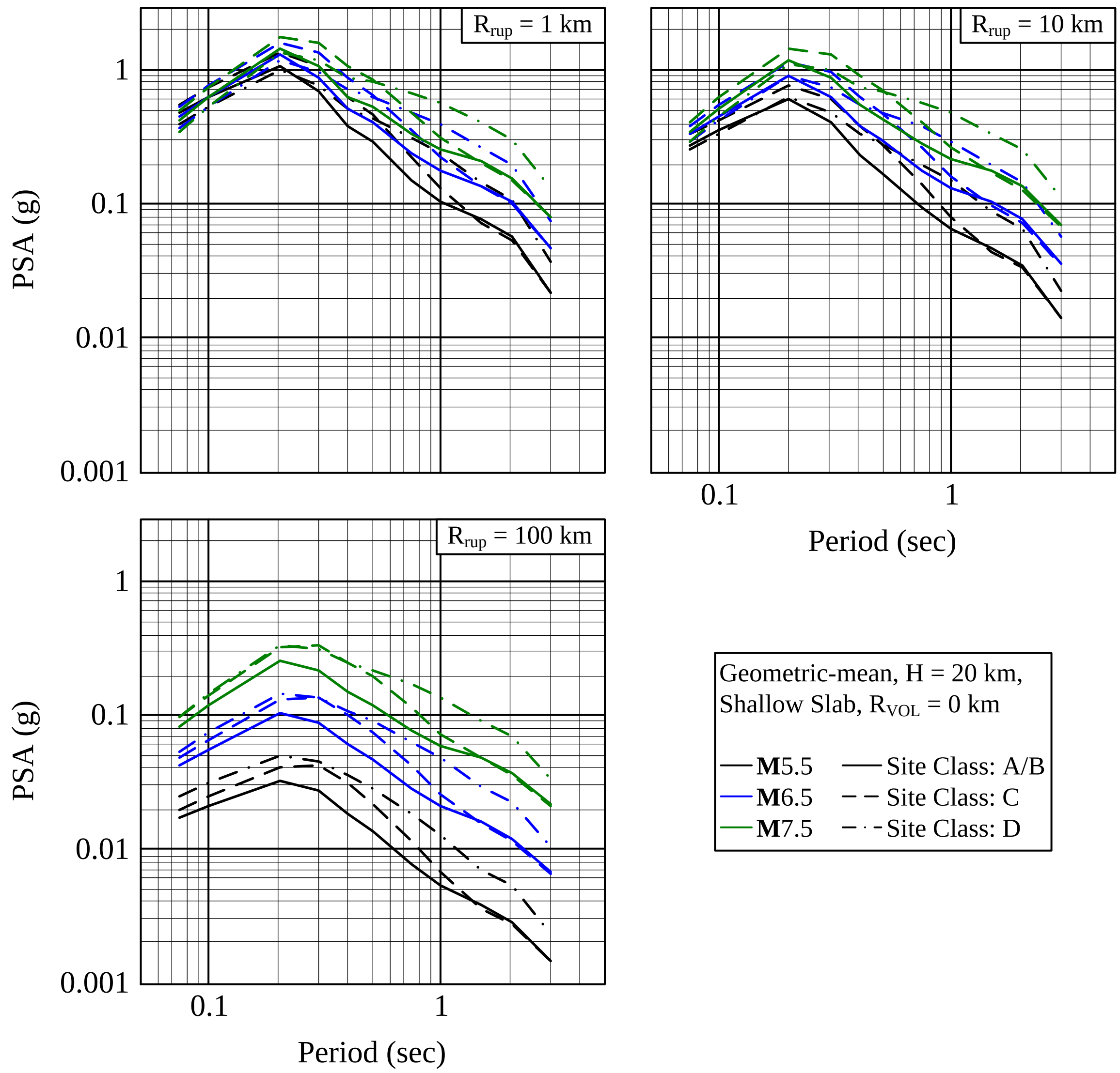


Figure 5-48. PSA as a function of period for various magnitudes, soil types and distances.

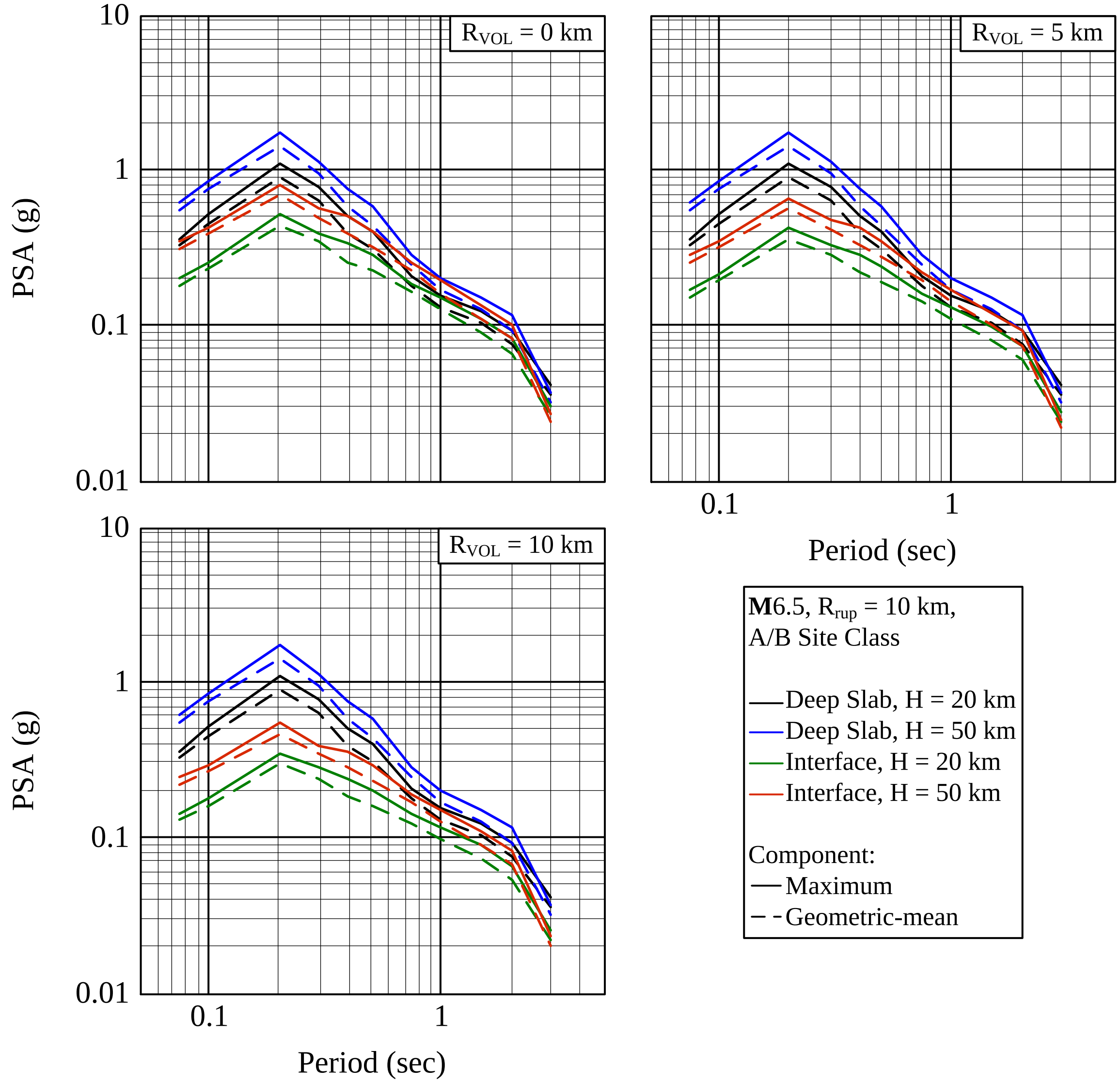


Figure 5-49. PSA as a function of period for various fault types, horizontal components and volcanic zone influence.

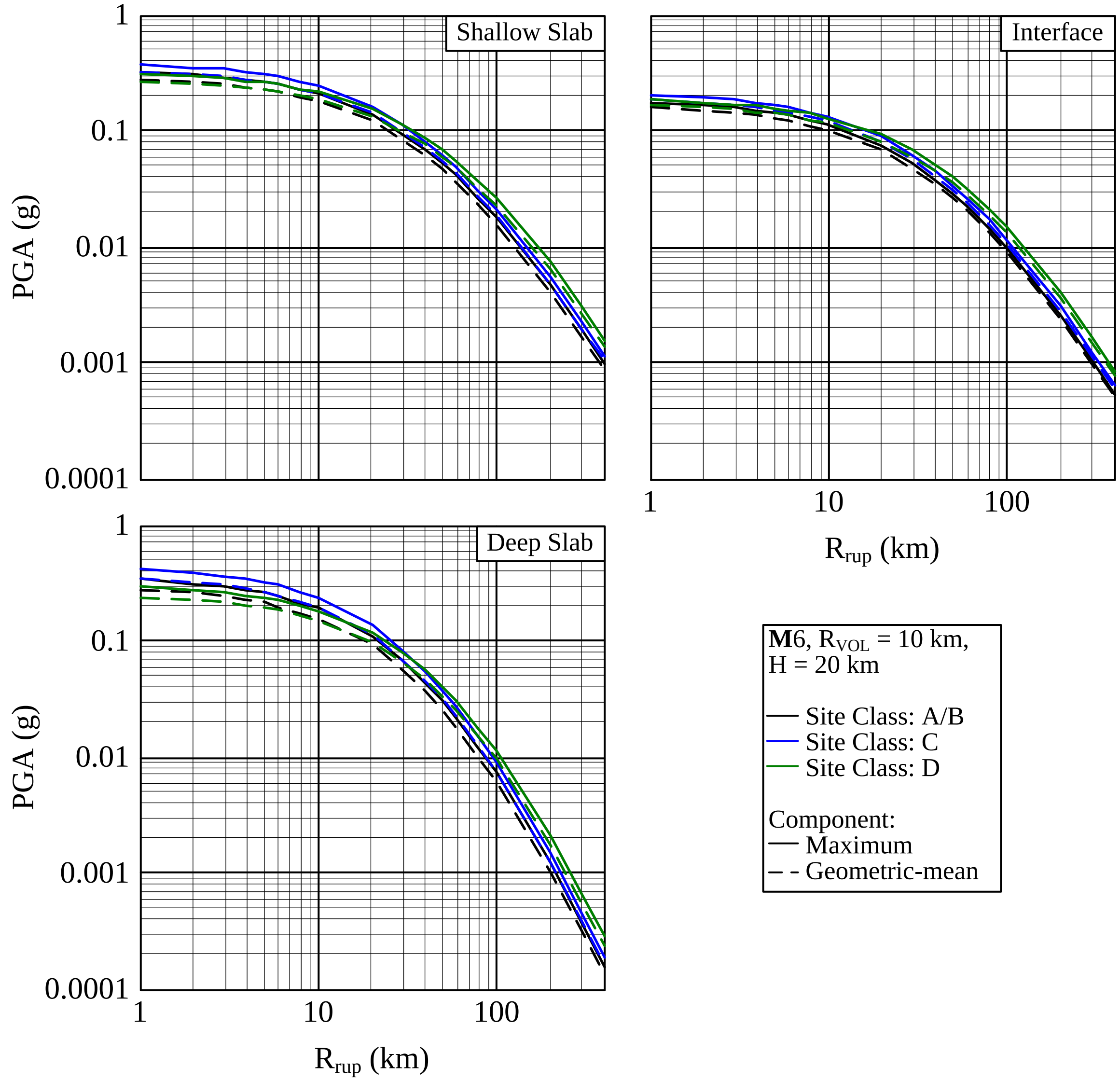


Figure 5-50. PGA as a function of period for various conditions.

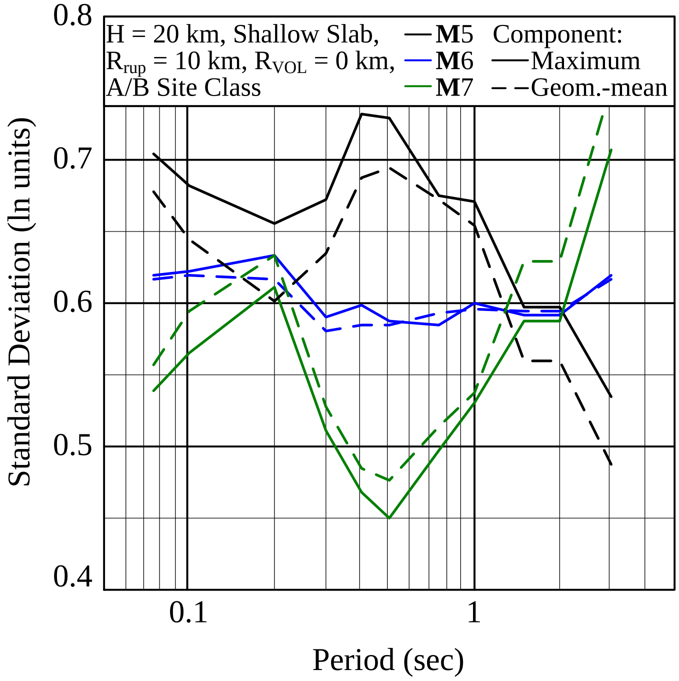


Figure 5-51. Standard deviation as a function of period.

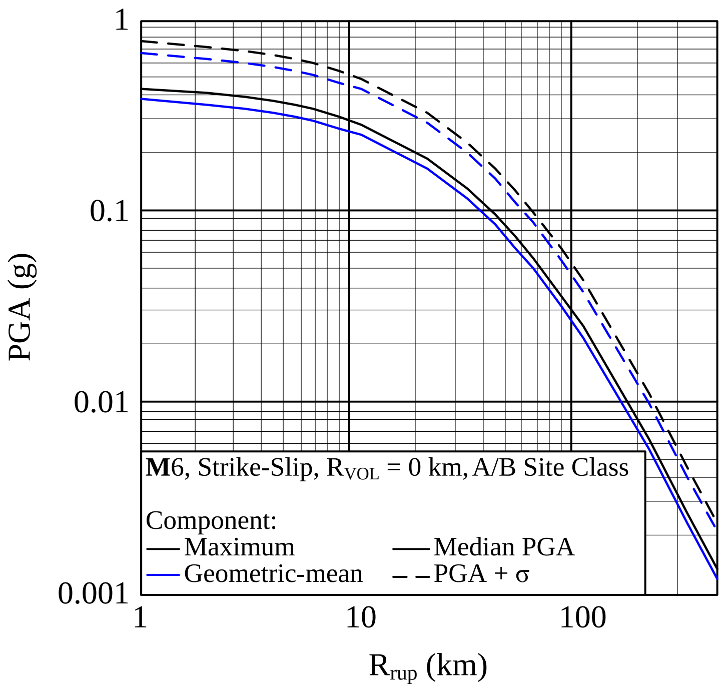


Figure 5-52. Example application of median PGA plus one standard deviation.

5.10.5 Database

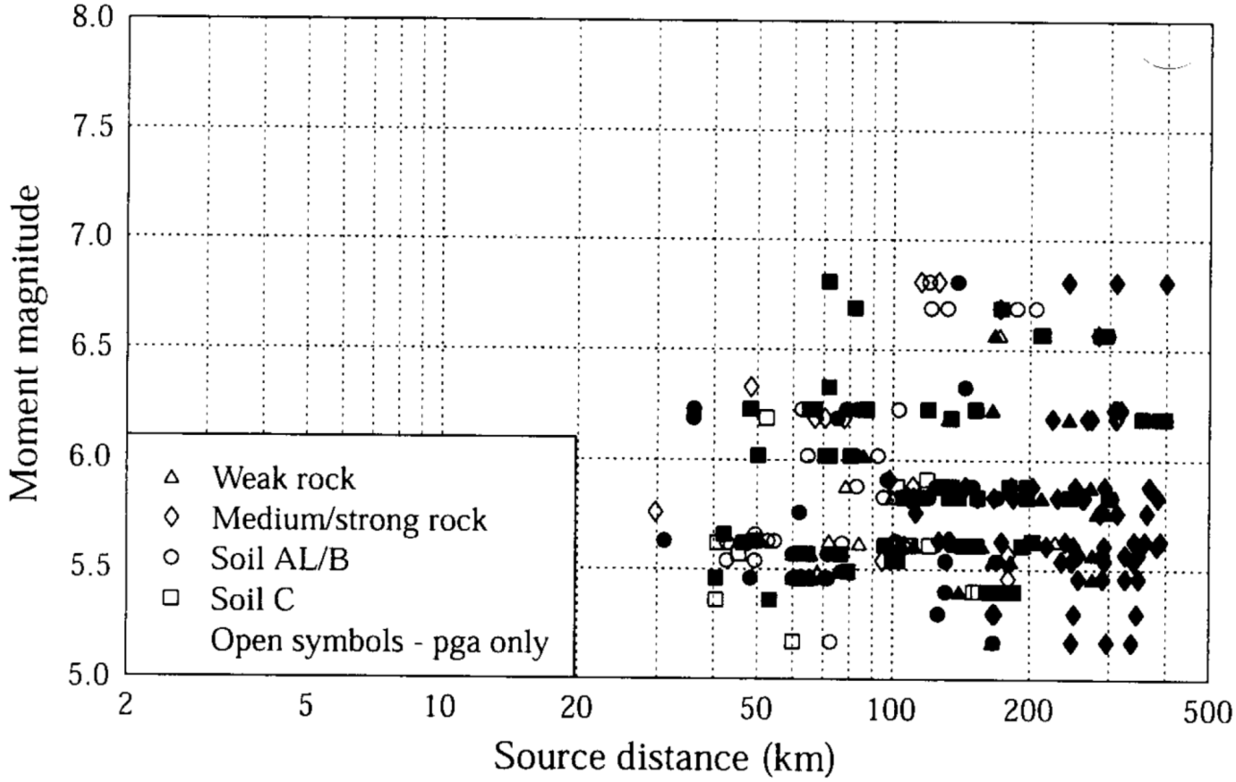


Figure 5-53. Distribution of data for the four site classes by magnitude and distance for crustal earthquakes. Open symbols are for records for which only peak ground accelerations were used, while solid symbols represent response spectrum data.

5.10.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/1/2011
% Virginia Tech
% kgunberg@vt.edu
%
% McVerry, Zhao, Abrahamson and Somerville (subduction zone) attenuation
% equation, 2006
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T          = Period (sec), 0 for PGA
% M          = Magnitude
% Ch         = Horizontal Component: 1 for geometric mean, 0 for maximum
% H          = Focal Depth (km)
% F          = Fault Type: 2 for deep slab, 1 for subduction interface,
%              0 otherwise
% Rrup       = Closest distance to rupture plane (km)
% Rvol       = Length of the part of the source to site path in the volcanic
%              zone (km)
% S          = Soil Type: 0 for NEHRP site class A/B, 1 for C, 2 for D
% ------------------------------------------------------------------------
% Output Variables
% Sa:        Median spectral acceleration prediction (g)
% sigma:     logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = MZAS_2006_sz(T,M,Ch,H,F,Rrup,Rvol,S)
% Coefficients
if Ch == 0
    period   = [0.075   0.10    0.20    0.30    0.40    0.50    0.75    1.0 1.5 2.0 3.0 0   -1];
    c11      = [8.68782 9.37929 10.61479    9.40776 8.50343 8.46463 7.30176 7.08727 6.93264...
                6.64496 5.05488 8.68354 8.10697];
    c12      = [1.414   1.414   1.414   1.414   1.414   1.414   1.414   1.414   1.414   1.414...
                1.414   1.414   1.414];
    c13      = [0   -0.0011 -0.0027 -0.0036 -0.0043 -0.0048 -0.0057 -0.0064 -0.0073 -0.0073...
                -0.0089 0   0];
    c15      = [-2.707  -2.655  -2.528  -2.454  -2.401  -2.360  -2.286  -2.234  -2.160...
                -2.160  -2.033  -2.552  -2.552];
    c17      = [-2.54215    -2.60945    -2.70851    -2.47668    -2.36895    -2.40630...
                -2.26512    -2.27668    -2.28347    -2.28347    -2.03050    -2.56727...
                -2.48795];
    c18      = [1.7818  1.7818  1.7818  1.7818  1.7818  1.7818  1.7818  1.7818  1.7818...
                1.7818  1.7818  1.7818  1.7818];
    c19      = [0.554   0.554   0.554   0.554   0.554   0.554   0.554   0.554   0.554...
                0.554   0.554   0.554   0.554];
    c20      = [0.01850 0.01740 0.01542 0.01278 0.01426 0.01287 0.01080 0.00946 0.00788...
                0.00788 -0.00265    0.01550 0.01622];
    c24      = [-0.48652    -0.61973    -0.67672    -0.59339    -0.30579    -0.24839...
                -0.01298    0.06672 -0.02289    -0.02289    -0.20537    -0.50962...
                -0.41369];
    c29      = [0.31139 0.34059 0.37235 0.56648 0.69911 0.63188 0.51577 0.34048 0.12468...
                0.12468 0.14593 0.30206 0.44307];
    c30      = [-0.280  -0.280  -0.245  -0.195  -0.160  -0.121  -0.050  0.000   0.040   0.040...
                0.040   -0.230  -0.230];
    c43      = [-0.48366    -0.43854    -0.29906    -0.05184    0.20301 0.37026 0.73517...
                0.87764 0.75438 0.75438 0.61545 -0.31769    -0.29648];
    c46      = [-0.03452    -0.03595    -0.03853    -0.03604    -0.03364    -0.03260...
                -0.02877    -0.02561    -0.02034    -0.02034    -0.01673    -0.03279...
                -0.03301];
    sig_M6   = [0.5281  0.5398  0.5703  0.5505  0.5627  0.5680  0.5562  0.5629  0.5394...
                0.5394  0.5701  0.4865  0.5035];
    sig_slope= [-0.0970 -0.0673 -0.0243 -0.0861 -0.1405 -0.1444 -0.0932 -0.0749 -0.0056...
                -0.0056 0.0934  -0.1261 -0.0635];
    tau      = [0.3217  0.3088  0.2726  0.2112  0.2005  0.1476  0.1794  0.2053  0.2411...
                0.2411  0.2406  0.2687  0.2598];
else
    period   = [0.075   0.10    0.20    0.30    0.40    0.50    0.75    1.0 1.5 2.0 3.0 0   -1];
    c11      = [8.69303 9.30400 10.41628    9.21783 8.01150 7.87495 7.26785 6.98741 6.77543...
                6.48775 5.05424 8.57343 8.08611];
```

```
    c12      = [1.414   1.414   1.414   1.414   1.414   1.414   1.414   1.414   1.414   1.414...
                1.414   1.414   1.414];
    c13      = [0   -0.0011 -0.0027 -0.0036 -0.0043 -0.0048 -0.0057 -0.0064 -0.0073 -0.0073...
                -0.0089 0   0];
    c15      = [-2.707  -2.655  -2.528  -2.454  -2.401  -2.360  -2.286  -2.234  -2.160...
                -2.160  -2.033  -2.552  -2.552];
    c17      = [-2.55903    -2.61372    -2.70038    -2.47356    -2.30457    -2.31991...
                -2.28460    -2.28256    -2.27895    -2.27895    -2.05560    -2.56592...
                -2.49894];
    c18      = [1.7818  1.7818  1.7818  1.7818  1.7818  1.7818  1.7818  1.7818  1.7818...
                1.7818  1.7818  1.7818  1.7818];
    c19      = [0.554   0.554   0.554   0.554   0.554   0.554   0.554   0.554   0.554...
                0.554   0.554   0.554   0.554];
    c20      = [0.01821 0.01737 0.01531 0.01304 0.01426 0.01277 0.01055 0.00927 0.00748...
                0.00748 -0.00273    0.01545 0.01590];
    c24      = [-0.52504    -0.61452    -0.65966    -0.56604    -0.33169    -0.24374...
                -0.01583    0.02009 -0.07051    -0.07051    -0.23967    -0.49963...
                -0.43223];
    c29      = [0.27879 0.28619 0.34064 0.53213 0.63272 0.58809 0.50708 0.33002 0.07445...
                0.07445 0.09869 0.27315 0.38730];
    c30      = [-0.280  -0.280  -0.245  -0.195  -0.160  -0.121  -0.050  0.000   0.040...
                0.040   0.040   -0.230  -0.230];
    c43      = [-0.49068    -0.46604    -0.31282    -0.07565    0.17615 0.34775 0.72380...
                0.89239 0.77743 0.77743 0.60938 -0.33716    -0.31036];
    c46      = [-0.03441    -0.03594    -0.03823    -0.03535    -0.03354    -0.03211...
                -0.02857    -0.02500    -0.02008    -0.02008    -0.01587    -0.03255...
                -0.03250];
    sig_M6   = [0.5297  0.5401  0.5599  0.5456  0.5556  0.5658  0.5611  0.5573  0.5419...
                0.5419  0.5809  0.4871  0.5099];
    sig_slope= [-0.0703 -0.0292 0.0172  -0.0566 -0.1064 -0.1123 -0.0836 -0.0620 0.0385...
                0.0385  0.1403  -0.1011 -0.0259];
    tau      = [0.3139  0.3017  0.2583  0.1967  0.1802  0.1440  0.1871  0.2073  0.2405...
                0.2405  0.2053  0.2677  0.2469];
end
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low,sig_low]=MZAS_2006_sz(T_low,M,Ch,H,F,Rrup,Rvol,S);
    [sa_hi, sig_hi] =MZAS_2006_sz(T_hi ,M,Ch,H,F,Rrup,Rvol,S);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sig_T = [sig_low sig_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sig_T,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    DS = F == 2; % DS: 1 for deep slab, 0 otherwise
    SI = F == 1; % SI: 1 for subduction interface, 0 otherwise

    deltaC = S == 1; %deltaC: 1 for NEHRP C soil, 0 otherwise
    deltaD = S == 2; %deltaD: 1 for NEHRP D soil, 0 otherwise

    PGA_ABp = exp(c11(13) + (c12(13)+(c15(13)-c17(13))*c19(13))*(M-6) + c13(13)*(10-M)^3 + ...
        c17(13)*log(Rrup+c18(13)*exp(c19(13)*M)) + c20(13)*H + c24(13)*SI + c46(13)*Rvol*(1-DS));
    PGA_AB  = exp(c11(12) + (c12(12)+(c15(12)-c17(12))*c19(12))*(M-6) + c13(12)*(10-M)^3 + ...
        c17(12)*log(Rrup+c18(12)*exp(c19(12)*M)) + c20(12)*H + c24(12)*SI + c46(12)*Rvol*(1-DS));
    SA_ABp  = exp(c11(i) + (c12(i)+(c15(i)-c17(i))*c19(i))*(M-6) + c13(i)*(10-M)^3 + ...
        c17(i)*log(Rrup+c18(i)*exp(c19(i)*M)) + c20(i)*H + c24(i)*SI + c46(i)*Rvol*(1-DS));

    PGA_ABCDp = exp(log(PGA_ABp) + c29(13)*deltaC + (c30(13)*log(PGA_ABp+0.03)+c43(13))*deltaD);
    PGA_ABCD  = exp(log(PGA_AB) + c29(12)*deltaC + (c30(12)*log(PGA_AB+0.03)+c43(12))*deltaD);
    SA_ABCDp  = exp(log(SA_ABp) + c29(i)*deltaC + (c30(i)*log(PGA_ABp+0.03)+c43(i))*deltaD);

    Sa = SA_ABCDp*(PGA_ABCD/PGA_ABCDp);
    sigma = sqrt((sig_M6(i)+sig_slope(i)*(min(7,max(5,M))-6))^2 + tau(i)^2);
end
```

5.11 Puerto Rico: Motazedian and Atkinson – 2005

5.11.1 Reference

Motazedian, D., and G. Atkinson (2005). Ground-motion Relations for Puerto Rico, *in* Mann, P., ed., Active Tectonics and Seismic Hazards of Puerto Rico, the Virgin Islands and Offshore Areas: Geological Society of America Special Paper 385, p. 61-80.

5.11.2 Abstract

Using a combination of 1289 time series from more than 300 events and 1950 time series from a stochastic model, empirical ground-motion models for the average horizontal component were developed. The model predicts peak ground acceleration (PGA, in cm/s^2), peak ground velocity (PGV in cm/s), and 5%-damped spectral values (PSA, in cm/s^2) for periods ranging from 0.06 to 10.0 s. This model is most applicable for earthquakes between M5.0 and M8.0, for distances up to 200 km and periods of 5 sec or less. Note: the MATLAB code converts all accelerations to g's.

5.11.3 Attenuation Relationship

The spectral acceleration is a function of:

- T – Period (sec), use 0 for PGA, use -1 for PGV
- **M** – Moment magnitude
- R_{rup} – Closest distance to rupture plane (km)

$$\log_{10}(Sa) = c_1 + c_2(M-6) + c_3(M-6)^2 + hingeFunction + c_4 R$$

where:

$$hingeFunction = \begin{cases} (-1.8+0.1M)\log_{10}(R) & for\ R_{rup} \le 75 \\ (-1.8+0.1M)\log_{10}(75) & for\ 75 < R_{rup} \le 100 \\ (-1.8+0.1M)\log_{10}(75) - 0.5\log_{10}\left(\frac{R}{100}\right) & for\ R_{rup} > 100 \end{cases}$$

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

where:

$$\Delta = -7.333 + 2.333M$$

Standard Error

$$\sigma_T = 0.28$$

Coefficients

Table 5-18. Coefficients determined in regression.

T (sec)	c1	c2	c3	c4
10.00	1.62	0.91212	-0.10486	-0.00092
7.69	1.80	0.90635	-0.11886	-0.00081
6.25	1.98	0.89009	-0.13157	-0.00064
5.00	2.16	0.87177	-0.14444	-0.00052
4.00	2.36	0.84583	-0.15306	-0.00048
3.13	2.55	0.81112	-0.16625	-0.00044
2.50	2.74	0.78035	-0.17792	-0.00050
2.00	2.89	0.73416	-0.17060	-0.00056
1.59	3.04	0.67664	-0.15973	-0.00061
1.27	3.20	0.63441	-0.15706	-0.00080
1.00	3.35	0.56986	-0.14377	-0.00086
0.79	3.47	0.49700	-0.11945	-0.00105
0.63	3.58	0.47303	-0.11486	-0.00118
0.50	3.68	0.44246	-0.10831	-0.00126
0.40	3.74	0.40472	-0.08864	-0.00139
0.32	3.83	0.38087	-0.09045	-0.00159
0.25	3.88	0.35932	-0.07932	-0.00185
0.20	3.94	0.33077	-0.06816	-0.00204
0.16	3.97	0.33046	-0.07344	-0.00219
0.13	3.98	0.32515	-0.07216	-0.00234
0.10	3.96	0.32088	-0.06542	-0.00244
0.08	3.94	0.32165	-0.06523	-0.00253
0.06	3.88	0.33249	-0.06818	-0.00251
PGA	3.60	0.35181	-0.06926	-0.00201
PGV	2.35	0.54828	-0.06350	-0.00107

5.11.4 Calibration Plots

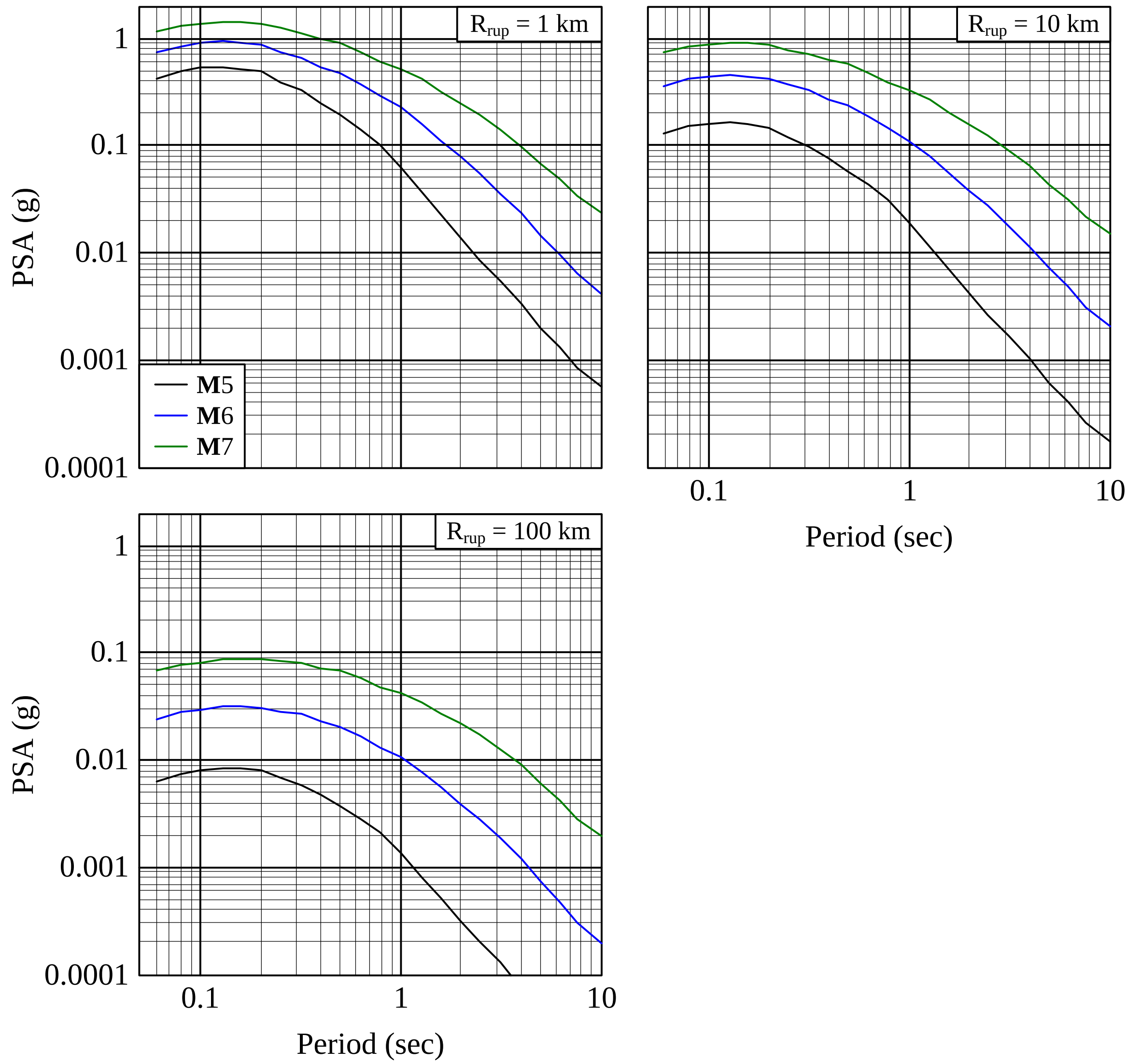


Figure 5-54. PSA as a function of period for various magnitudes and distances.

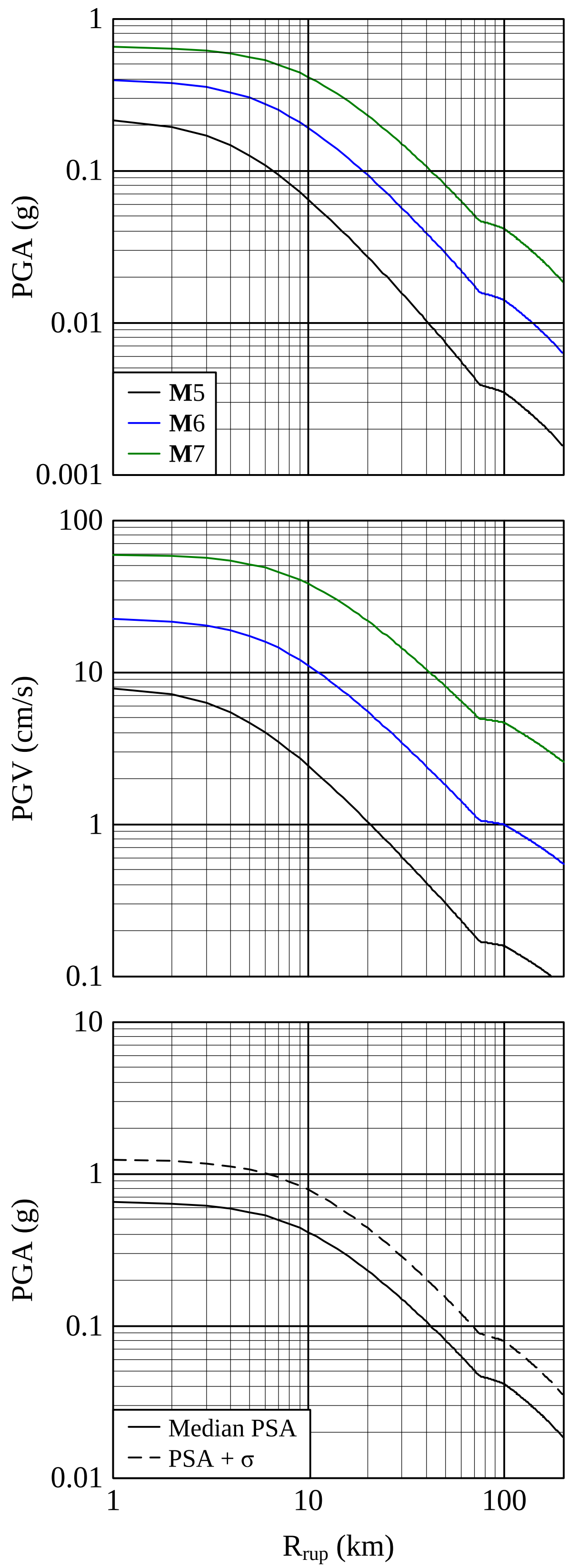


Figure 5-55. PGA and PGV as a function of distance for various magnitudes. Bottom: Example of application of median PGA plus one standard deviation.

5.11.5 Database

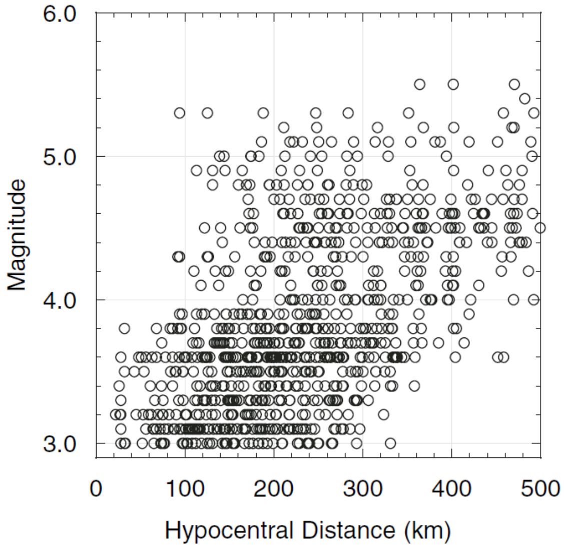


Figure 5-56. Distribution of Puerto Rico ground motion data.

5.11.6 MATLAB Code

```
% by Kathryn A. Gunberg 6/19/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Motazedian and Atkinson attenuation equation, 2005
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T    = Period (sec), 0 for PGA, -1 for PGV
% M    = Moment magnitude
% Rrup = Closest distance to rupture plane (km)
% --------------------------------------------------------------------------
% Output Variables
% Sa:      Median spectral acceleration, PGA and PGV prediction (g, cm/s)
% sigma:   logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = MA_2005(T, M, Rrup)
% Coefficients
period   = [10.00   7.69    6.25    5.00    4.00    3.13    2.50    2.00    1.59    1.27...
            1.00    0.79    0.63    0.50    0.40    0.32    0.25    0.20    0.16    0.13...
            0.10    0.08    0.06    0.00    -1.00];
c1       = [1.62    1.80    1.98    2.16    2.36    2.55    2.74    2.89    3.04    3.20...
            3.35    3.47    3.58    3.68    3.74    3.83    3.88    3.94    3.97    3.98...
            3.96    3.94    3.88    3.60    2.35];
c2       = [0.91212 0.90635 0.89009 0.87177 0.84583 0.81112 0.78035 0.73416 0.67664 0.63441...
            0.56986 0.49700 0.47303 0.44246 0.40472 0.38087 0.35932 0.33077 0.33046 0.32515...
            0.32088 0.32165 0.33249 0.35181 0.54828];
c3       = [-0.10486    -0.11886    -0.13157    -0.14444    -0.15306    -0.16625    -0.17792...
            -0.17060    -0.15973    -0.15706    -0.14377    -0.11945    -0.11486    -0.10831...
            -0.08864    -0.09045    -0.07932    -0.06816    -0.07344    -0.07216    -0.06542...
            -0.06523    -0.06818    -0.06926    -0.06350];
c4       = [-0.00092    -0.00081    -0.00064    -0.00052    -0.00048    -0.00044    -0.00050...
            -0.00056    -0.00061    -0.00080    -0.00086    -0.00105    -0.00118    -0.00126...
            -0.00139    -0.00159    -0.00185    -0.00204    -0.00219    -0.00234    -0.00244...
            -0.00253    -0.00251    -0.00201    -0.00107];
% interpolate between periods if neccesary
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi = min(period(find(period>T)));
    [sa_low, sigma_low] = MA_2005(T_low, M, Rrup);
    [sa_hi,  sigma_hi]  = MA_2005(T_hi,  M, Rrup);
    x = [log10(T_low) log10(T_hi)];
    Y_sa = [log10(sa_low) log10(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = 10^(interp1(x,Y_sa,log10(T)));
    sigma = interp1(x,Y_sigma,log10(T));
else
    i     = find(abs((period - T)) < 0.0001); % Identify the period index
    delta = -7.333 + 2.333*M;
    R     = sqrt(Rrup^2 + delta^2);
    if R <= 75
        hF = (-1.8 + 0.1*M)*log10(R);
    elseif R <= 100
        hF = (-1.8 + 0.1*M)*log10(75);
    else
        hF = (-1.8 + 0.1*M)*log10(75) - 0.5*log10(R/100);
    end
    Sa_pre = 10^(c1(i) + c2(i)*(M-6) + c3(i)*(M-6)^2 + hF + c4(i)*R);
    if T == -1
        Sa = Sa_pre;
    else
        Sa = Sa_pre/980.665;
    end
    sigma = 0.28;
end
```

5.12 Taiwan: Lin and Lee – 2008

5.12.1 Reference

Lin, P.-S., and C.-T. Lee (2008). Ground-Motion Attenuation Relationships for Subduction-Zone Earthquakes in Northeastern Taiwan, *Bulletin of the Seismological Society of America* **98**, 220-240.

Lin, P.-S. (2009). National Central University, Jhongli City, Taiwan. Written communication.

5.12.2 Abstract

Using 4383 records from 54 earthquakes, empirical ground-motion models for the average horizontal component were developed for Taiwan. The model predicts 5%-damped spectral values (in g) for periods ranging from 0.01 to 5.0 s. For interface events, this model is most applicable for earthquakes between M5.3 and M8.1, depths up to 30 km, and for distances between 20 and 300 km. For intraslab events, this model is most applicable for earthquakes between M4.1 and M6.7, depths between 40 and 160 km, and for distances between 40 and 600 km. Please note that the published paper provides regession coefficients for peak ground acceleration. Descrepancies were found using these values as compared to the plots provided in the paper. Though personal communication, Lin has suggested using T = 0.01 for PGA.

5.12.3 Attenuation Relationship

The spectral acceleration is a function of:

T	– Period (sec), use 0.01 or 0 for PGA
M	– Moment magnitude
H	– Focal Depth (km)
F	– Fault type: 0 for interface events, 1 for in-slab events
R_{hypo}	– Hypocentral discance (km)
S	– Soil type: 0 for rock (NERHP B or C), 1 for soil (NERHP D or E)

$$\ln(Sa) = c_1 + c_2\boldsymbol{M} + c_3 \ln\left(R_{hypo} + c_4 e^{c_5\boldsymbol{M}}\right) + c_6 H + c_7 F$$

Standard Error

$$\sigma_T = \sigma_{\ln Y}$$

Coefficients

Table 5-19. Coefficients determined from regression.

	Rock Sites				Soil Sites			
T (sec)	c_1	c_2	c_3	$\sigma_{\ln y}$	c_1	c_2	c_3	$\sigma_{\ln y}$
0.01	-2.500	1.205	-1.895	0.5218	-2.200	1.085	-1.750	0.5800
0.02	-2.490	1.200	-1.880	0.5189	-2.290	1.085	-1.730	0.5730
0.03	-2.280	1.155	-1.875	0.5235	-2.340	1.095	-1.720	0.5774
0.04	-2.000	1.100	-1.860	0.5352	-2.215	1.090	-1.730	0.5808
0.05	-1.900	1.090	-1.855	0.5370	-1.895	1.055	-1.755	0.5937
0.06	-1.725	1.065	-1.840	0.5544	-1.110	1.010	-1.835	0.6123
0.09	-1.265	1.020	-1.815	0.5818	-0.210	0.945	-1.890	0.6481
0.10	-1.220	1.000	-1.795	0.5806	-0.055	0.920	-1.880	0.6535
0.12	-1.470	1.040	-1.770	0.5748	0.055	0.935	-1.895	0.6585
0.15	-1.675	1.045	-1.730	0.5817	-0.040	0.955	-1.880	0.6595
0.17	-1.846	1.065	-1.710	0.5906	-0.340	1.020	-1.885	0.6680
0.20	-2.170	1.085	-1.675	0.6059	-0.800	1.045	-1.820	0.6565
0.24	-2.585	1.105	-1.630	0.6315	-1.575	1.120	-1.755	0.6465
0.30	-3.615	1.215	-1.570	0.6656	-3.010	1.315	-1.695	0.6661
0.36	-4.160	1.255	-1.535	0.7010	-3.680	1.380	-1.660	0.6876
0.40	-4.595	1.285	-1.500	0.7105	-4.250	1.415	-1.600	0.7002
0.46	-5.020	1.325	-1.495	0.7148	-4.720	1.430	-1.545	0.7092
0.50	-5.470	1.365	-1.465	0.7145	-5.220	1.455	-1.490	0.7122
0.60	-6.095	1.420	-1.455	0.7177	-5.700	1.470	-1.445	0.7280
0.75	-6.675	1.465	-1.450	0.7689	-6.450	1.500	-1.380	0.7752
0.85	-7.320	1.545	-1.450	0.7787	-7.250	1.565	-1.325	0.7931
1.00	-8.000	1.620	-1.450	0.7983	-8.150	1.605	-1.235	0.8158
1.50	-9.240	1.705	-1.440	0.8411	-10.300	1.800	-1.165	0.8356
2.00	-10.200	1.770	-1.430	0.8766	-11.620	1.860	-1.070	0.8474
3.00	-11.470	1.830	-1.370	0.8590	-12.630	1.890	-1.060	0.8367
4.00	-12.550	1.845	-1.260	0.8055	-13.420	1.870	-0.990	0.7937
5.00	-13.390	1.805	-1.135	0.7654	-13.750	1.835	-0.975	0.7468
	c_4	c_5	c_6	c_7	c_4	c_5	c_6	c_7
	0.51552	0.63255	0.0075	0.275	0.99178	0.52632	0.004	0.31

5.12.4 Calibration Plots

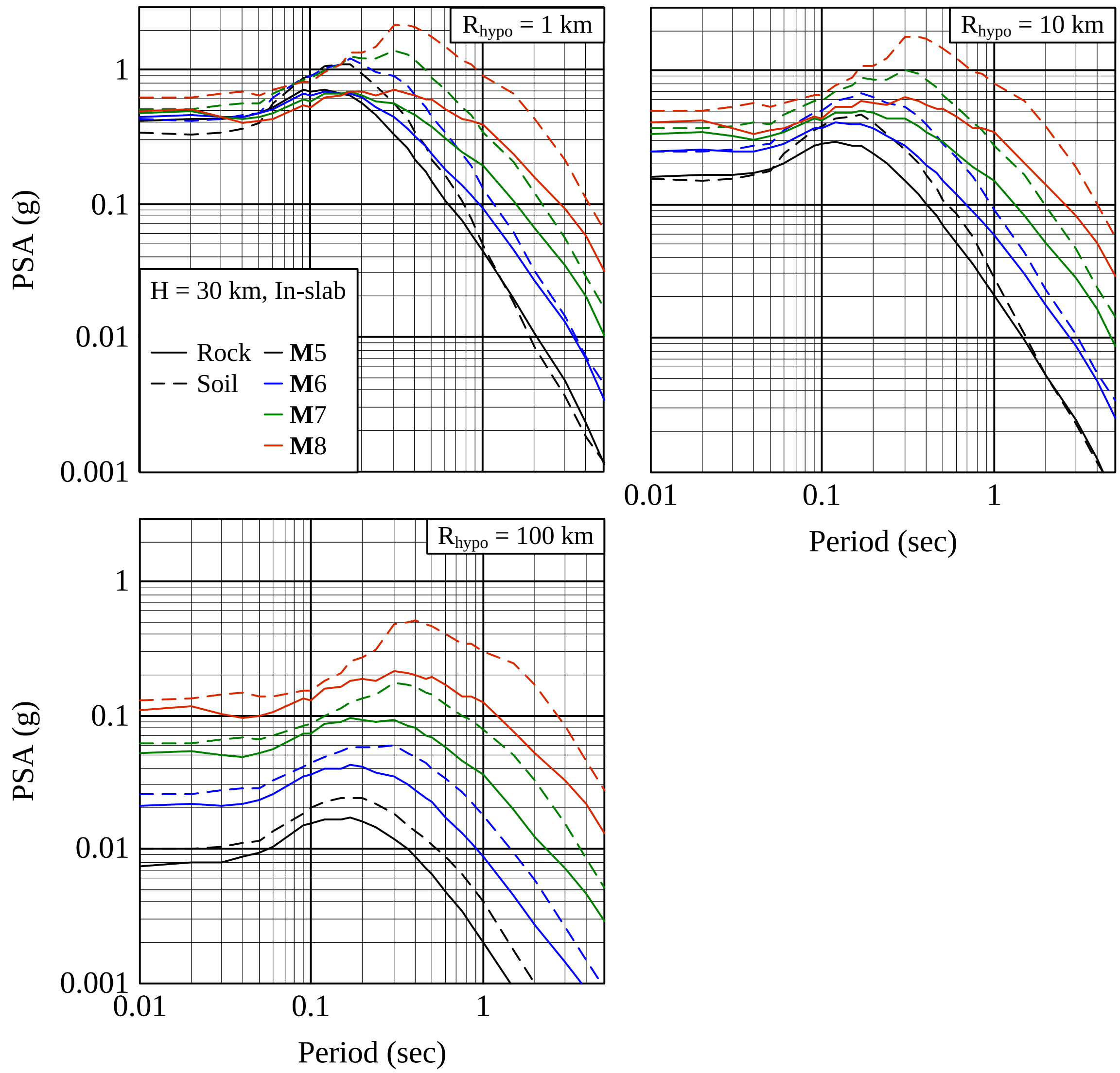


Figure 5-57. PSA as a function of period for given conditions.

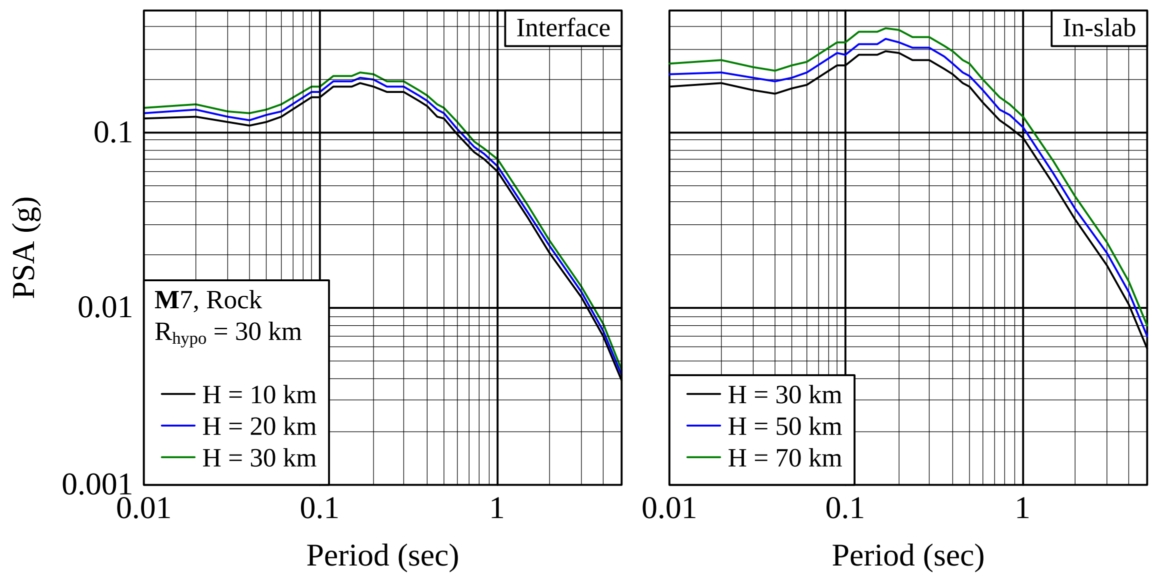


Figure 5-58. PSA as a function of period for given conditions.

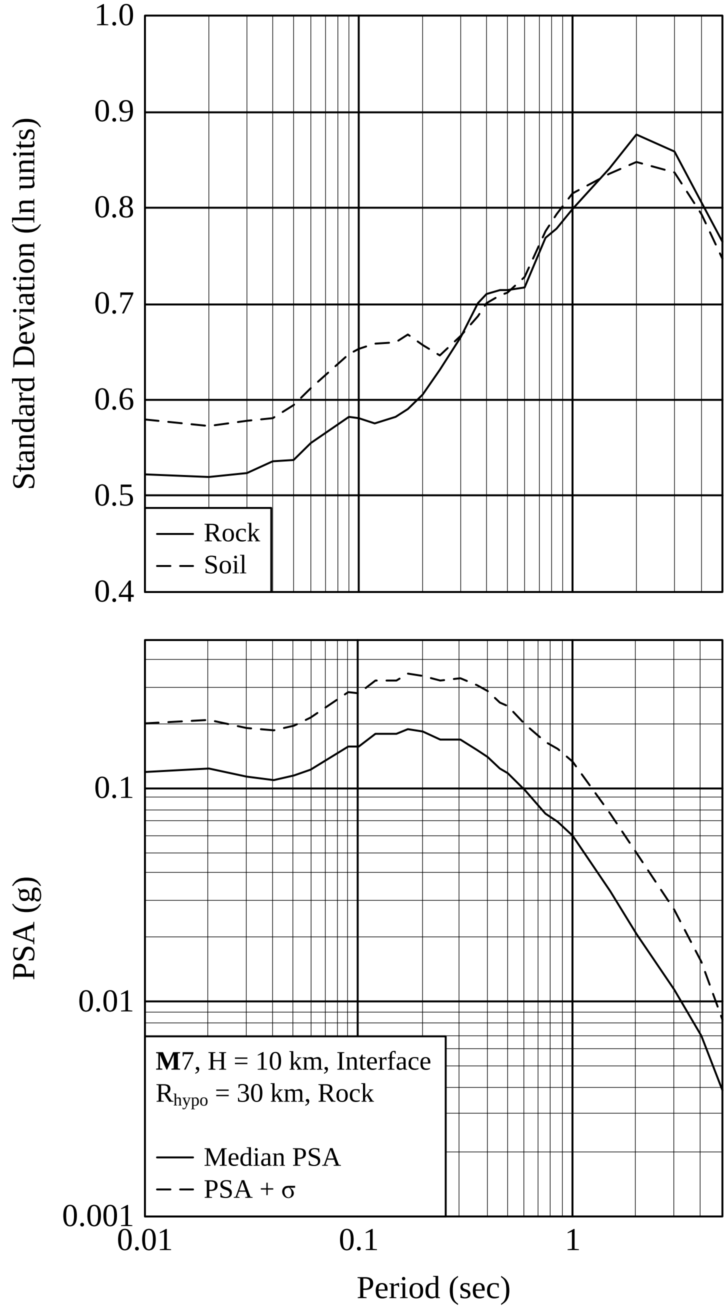


Figure 5-59. Above: standard devitation as a fucnction of period for rock and soil. Below: Example of application of median PSA plus one standard deviation.

5.12.5 Database

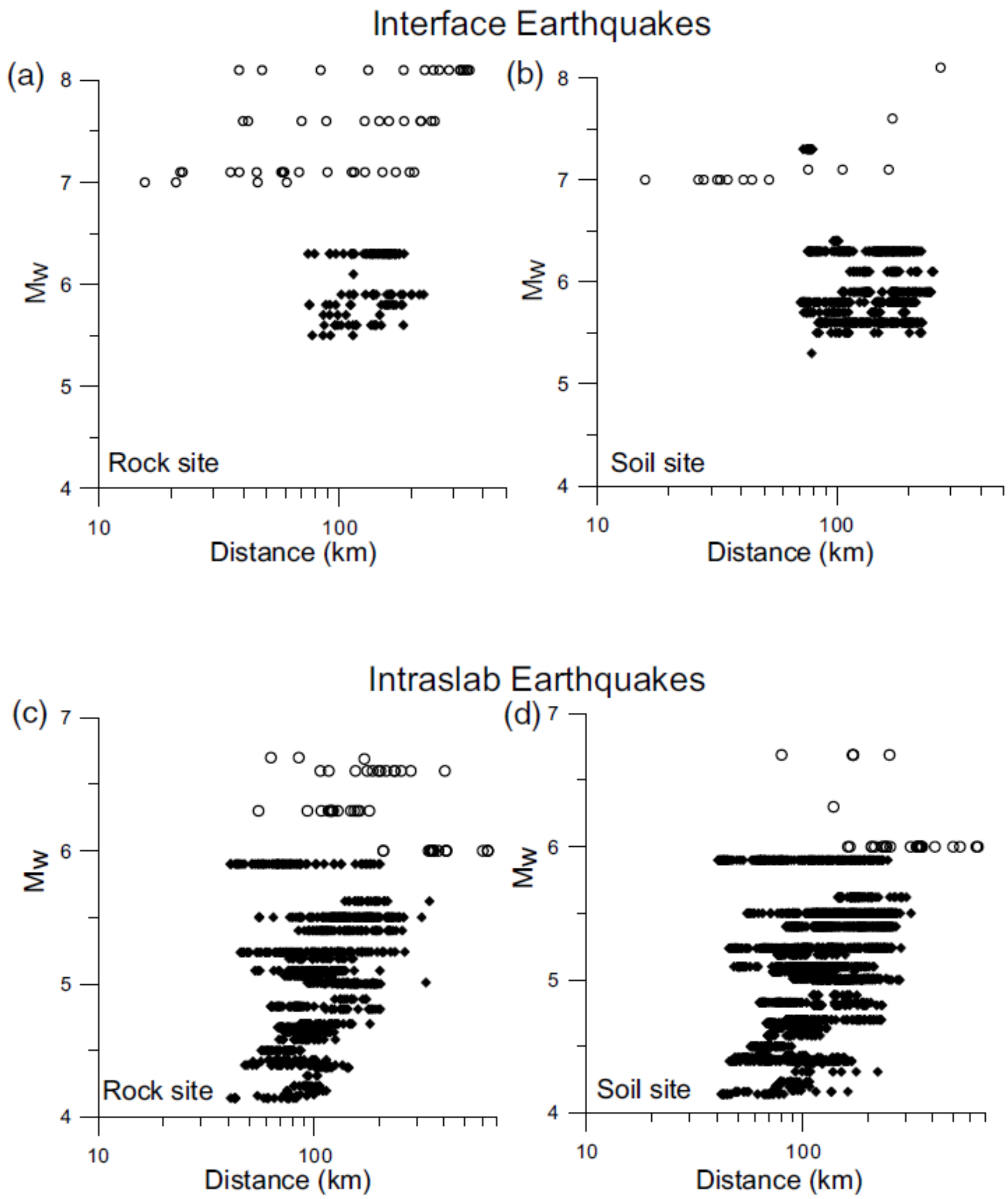


Figure 5-60. The magnitude and distance distribution of the strong-motion data set used in this study. The solid rhomboids represent data from the Taiwan area; the open circles represent data from other areas.

5.12.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/22/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Lin and Lee attenuation equation, 2008
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T         = Period (sec), 0.01 or 0 for PGA
% M         = Moment magnitude
% H         = Focal depth (km)
% F         = Fault type: 0 for interface, 1 for in-slab
% Rhypo     = Hypocentral Distance (km)
% S         = Soil type: 0 for rock (NERHP B/C), 1 for soil (NEHRP D/E)
% ---------------------------------------------------------------------------
% Output Variables
% Sa:       Median spectral acceleration prediction (g)
% sigma:    logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa sigma] = LL_2008(T, M, H, F, Rhypo, S)
% Coefficients
period   = [0.01    0.02    0.03    0.04    0.05    0.06    0.09    0.10    0.12...
            0.15    0.17    0.20    0.24    0.30    0.36    0.40    0.46    0.50    0.60...
            0.75    0.85    1.00    1.50    2.00    3.00    4.00    5.00];
if S == 0
    c1   = [-2.500  -2.490  -2.280  -2.000  -1.900  -1.725  -1.265  -1.220  -1.470...
            -1.675  -1.846  -2.170  -2.585  -3.615  -4.160  -4.595  -5.020  -5.470  -6.095...
            -6.675  -7.320  -8.000  -9.240  -10.200 -11.470 -12.550 -13.390];
    c2   = [1.205   1.200   1.155   1.100   1.090   1.065   1.020   1.000   1.040...
            1.045   1.065   1.085   1.105   1.215   1.255   1.285   1.325   1.365   1.420...
            1.465   1.545   1.620   1.705   1.770   1.830   1.845   1.805];
    c3   = [-1.895  -1.880  -1.875  -1.860  -1.855  -1.840  -1.815  -1.795  -1.770...
            -1.730  -1.710  -1.675  -1.630  -1.570  -1.535  -1.500  -1.495  -1.465  -1.455...
            -1.450  -1.450  -1.450  -1.440  -1.430  -1.370  -1.260  -1.135];
    c4   = 0.51552;
    c5   = 0.63255;
    c6   = 0.0075;
    c7   = 0.275;
    sig  = [0.5218  0.5189  0.5235  0.5352  0.5370  0.5544  0.5818  0.5806  0.5748...
            0.5817  0.5906  0.6059  0.6315  0.6656  0.7010  0.7105  0.7148  0.7145  0.7177...
            0.7689  0.7787  0.7983  0.8411  0.8766  0.8590  0.8055  0.7654];
else
    c1   = [-2.200  -2.290  -2.340  -2.215  -1.895  -1.110  -0.210  -0.055  0.055...
            -0.040  -0.340  -0.800  -1.575  -3.010  -3.680  -4.250  -4.720  -5.220  -5.700...
            -6.450  -7.250  -8.150  -10.300 -11.620 -12.630 -13.420 -13.750];
    c2   = [1.085   1.085   1.095   1.090   1.055   1.010   0.945   0.920   0.935...
            0.955   1.020   1.045   1.120   1.315   1.380   1.415   1.430   1.455   1.470...
            1.500   1.565   1.605   1.800   1.860   1.890   1.870   1.835];
    c3   = [-1.750  -1.730  -1.720  -1.730  -1.755  -1.835  -1.890  -1.880  -1.895...
            -1.880  -1.885  -1.820  -1.755  -1.695  -1.660  -1.600  -1.545  -1.490  -1.445...
            -1.380  -1.325  -1.235  -1.165  -1.070  -1.060  -0.990  -0.975];
    c4   = 0.99178;
    c5   = 0.52632;
    c6   = 0.004;
    c7   = 0.31;
    sig  = [0.5800  0.5730  0.5774  0.5808  0.5937  0.6123  0.6481  0.6535  0.6585...
            0.6595  0.6680  0.6565  0.6465  0.6661  0.6876  0.7002  0.7092  0.7122  0.7280...
            0.7752  0.7931  0.8158  0.8356  0.8474  0.8367  0.7937  0.7468];
end
% interpolate between periods if neccesary
if T == 0
    T = min(period);
end
if (length(find(abs((period - T)) < 0.0001)) == 0)
    T_low = max(period(find(period<T)));
    T_hi  = min(period(find(period>T)));
    [sa_low, sigma_low] = LL_2008(T_low, M, H, F, Rrup, S);
```

```
    [sa_hi,  sigma_hi]  = LL_2008(T_hi,  M, H, F, Rrup, S);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(abs((period - T)) < 0.0001); % Identify the period index
    Sa = exp(c1(i) + c2(i)*M + c3(i)*log(Rhypo + c4*exp(c5*M)) + c6*H + c7*F);
    sigma = sig(i);
end
```

5.13 Turkey: Gülkan and Kalkan – 2002

5.13.1 Reference

Gülkan, P., and E. Kalkan (2002). Attenuation Modeling of Recent Earthquakes in Turkey, *Journal of Seismology* **6**, 397-409.

5.13.2 Abstract

Using 93 records from 19 earthquakes in Turkey, an empirical ground-motion model for the average horizontal component was developed. The model predicts peak ground acceleration (PGA, in g) and 5%-damped spectral values (PSA, in g) for periods ranging from 0.1 to 2 s. The model is applicable for earthquakes between M5.0 and M7.5 and distances up to 150 km.

5.13.3 Attenuation Relationship

The spectral acceleration is a function of:

T – Period (sec), use 0 for PGA
M – Moment magnitude
R_{jb} – Joyner-Boore distance (km)
V_{S30} – Shear wave velocity (m/s) averaged over top 30 m

$$\ln(Sa) = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5\ln(r) + b_V\ln\left(\frac{V_{S30}}{V_A}\right)$$

where:

$$r = \sqrt{{R_{jb}}^2 + h^2}$$

Standard Error

$$\sigma = \sigma_{\ln Y}$$

Coefficients

Table 5-20. Coefficients determined from regression.

T (sec)	b_1	b_2	b_3	b_5	b_V	V_A	h	$\sigma_{\ln(Y)}$
PGA	-0.682	0.253	0.036	-0.562	-0.297	1381	4.48	0.562
0.10	-0.139	0.200	-0.003	-0.553	-0.167	1063	3.76	0.621
0.11	0.031	0.235	-0.007	-0.573	-0.181	1413	3.89	0.618
0.12	0.123	0.228	-0.031	-0.586	-0.208	1501	4.72	0.615
0.13	0.138	0.216	-0.007	-0.590	-0.237	1591	5.46	0.634
0.14	0.100	0.186	0.014	-0.585	-0.249	1833	4.98	0.635
0.15	0.090	0.210	-0.013	-0.549	-0.196	1810	2.77	0.620
0.16	-0.128	0.214	0.007	-0.519	-0.224	2193	1.32	0.627
0.17	-0.107	0.187	0.037	-0.535	-0.243	2433	1.67	0.621
0.18	0.045	0.168	0.043	-0.556	-0.256	2041	2.44	0.599
0.19	0.053	0.180	0.063	-0.570	-0.288	2086	2.97	0.601
0.20	0.127	0.192	0.065	-0.597	-0.303	2238	3.48	0.611
0.22	-0.081	0.214	0.006	-0.532	-0.319	2198	1.98	0.584
0.24	-0.167	0.265	-0.035	-0.531	-0.382	2198	2.55	0.569
0.26	-0.129	0.345	-0.039	-0.552	-0.395	2160	3.45	0.549
0.28	0.140	0.428	-0.096	-0.616	-0.369	2179	4.95	0.530
0.30	0.296	0.471	-0.140	-0.642	-0.346	2149	6.11	0.540
0.32	0.454	0.476	-0.168	-0.653	-0.290	2144	7.38	0.555
0.34	0.422	0.471	-0.152	-0.651	-0.300	2083	8.30	0.562
0.36	0.554	0.509	-0.114	-0.692	-0.287	2043	9.18	0.563
0.38	0.254	0.499	-0.105	-0.645	-0.341	2009	9.92	0.562
0.40	0.231	0.497	-0.105	-0.647	-0.333	1968	9.92	0.604
0.42	0.120	0.518	-0.135	-0.612	-0.313	1905	9.09	0.634
0.44	0.035	0.544	-0.142	-0.583	-0.286	1899	9.25	0.627
0.46	-0.077	0.580	-0.147	-0.563	-0.285	1863	8.98	0.642
0.48	-0.154	0.611	-0.154	-0.552	-0.293	1801	8.96	0.653
0.50	-0.078	0.638	-0.161	-0.565	-0.259	1768	9.06	0.679
0.55	-0.169	0.707	-0.179	-0.539	-0.216	1724	8.29	0.710
0.60	-0.387	0.698	-0.187	-0.506	-0.259	1629	8.24	0.707
0.65	-0.583	0.689	-0.159	-0.500	-0.304	1607	7.64	0.736
0.70	-0.681	0.698	-0.143	-0.517	-0.360	1530	7.76	0.743
0.75	-0.717	0.730	-0.143	-0.516	-0.331	1492	7.12	0.740
0.80	-0.763	0.757	-0.113	-0.525	-0.302	1491	6.98	0.742
0.85	-0.778	0.810	-0.123	-0.529	-0.283	1438	6.57	0.758
0.90	-0.837	0.856	-0.130	-0.512	-0.252	1446	7.25	0.754
0.95	-0.957	0.870	-0.127	-0.472	-0.163	1384	7.24	0.752
1.00	-1.112	0.904	-0.169	-0.443	-0.200	1391	6.63	0.756
1.10	-1.459	0.898	-0.147	-0.414	-0.252	1380	6.21	0.792
1.20	-1.437	0.962	-0.156	-0.463	-0.267	1415	7.17	0.802
1.30	-1.321	1.000	-0.147	-0.517	-0.219	1429	7.66	0.796
1.40	-1.212	1.000	-0.088	-0.584	-0.178	1454	9.10	0.790
1.50	-1.340	0.997	-0.055	-0.582	-0.165	1490	9.86	0.788
1.60	-1.353	0.999	-0.056	-0.590	-0.135	1513	9.94	0.787
1.70	-1.420	0.996	-0.052	-0.582	-0.097	1569	9.55	0.789
1.80	-1.465	0.995	-0.053	-0.581	-0.058	1653	9.35	0.827
1.90	-1.500	0.999	-0.051	-0.592	-0.047	1707	9.49	0.864
2.00	-1.452	1.020	-0.079	-0.612	-0.019	1787	9.78	0.895

5.13.4 Calibration Plots

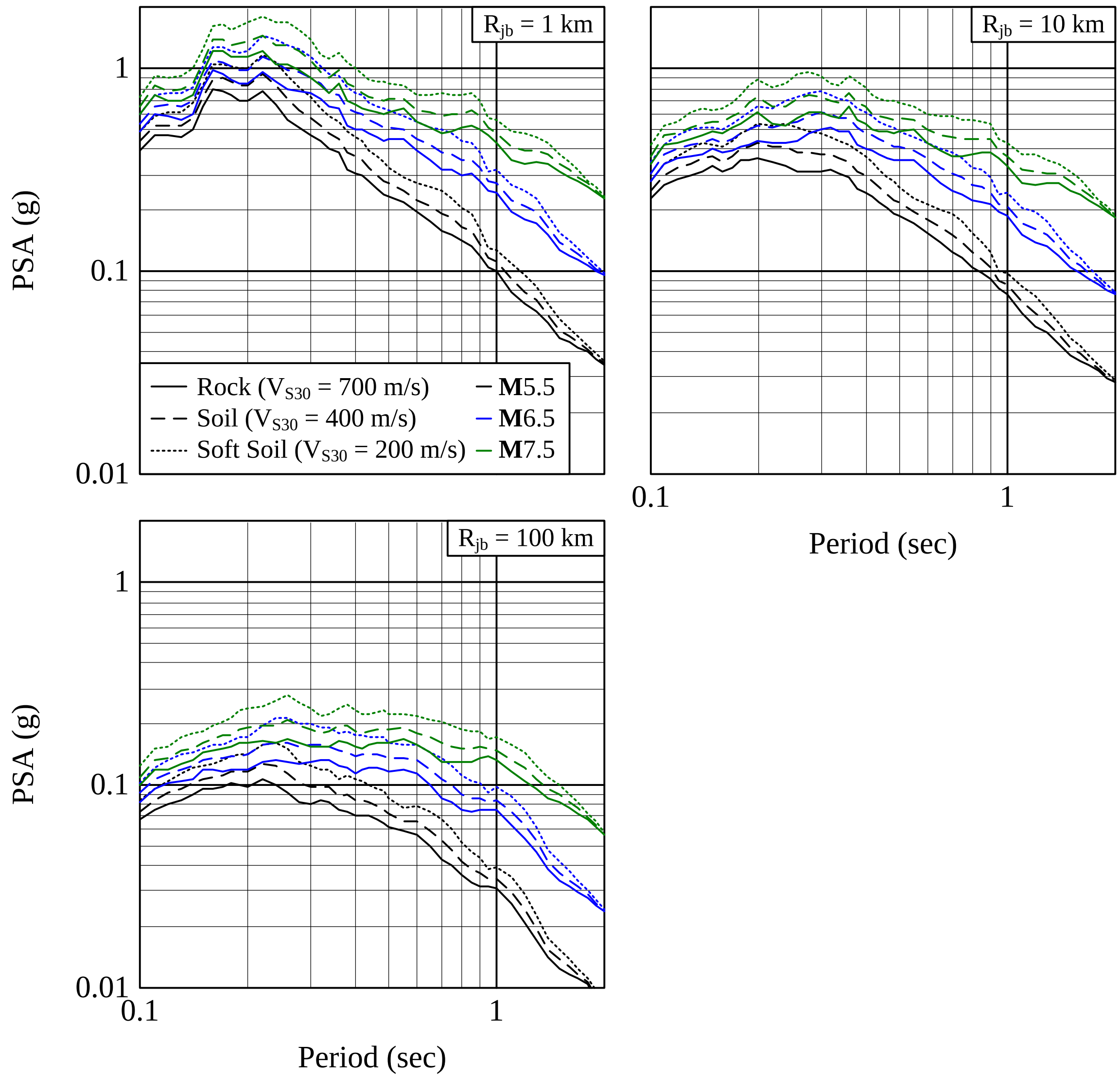


Figure 5-61. PSA as a function of period for various soil types, magnitudes and distances.

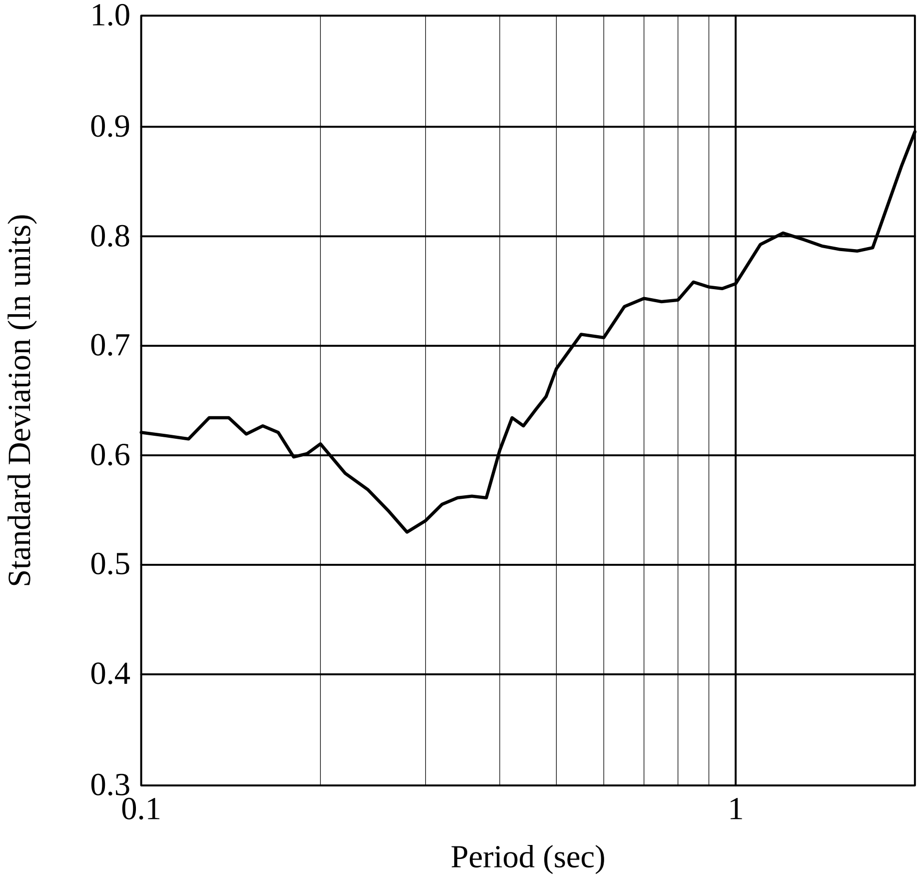


Figure 5-62. Standard deviation as a function of period.

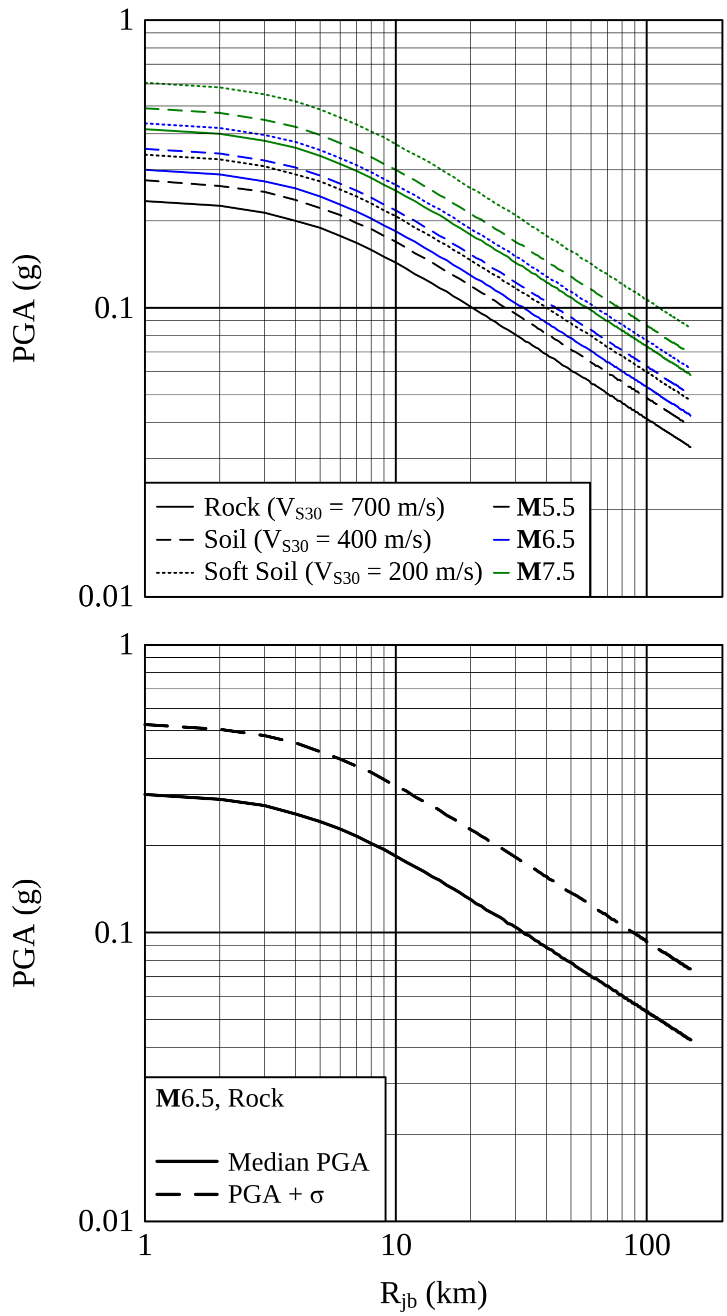


Figure 5-63. Above: PGA as a function of distance. Below: Example of application of median PGA plus one standard deviation.

5.13.5 Database

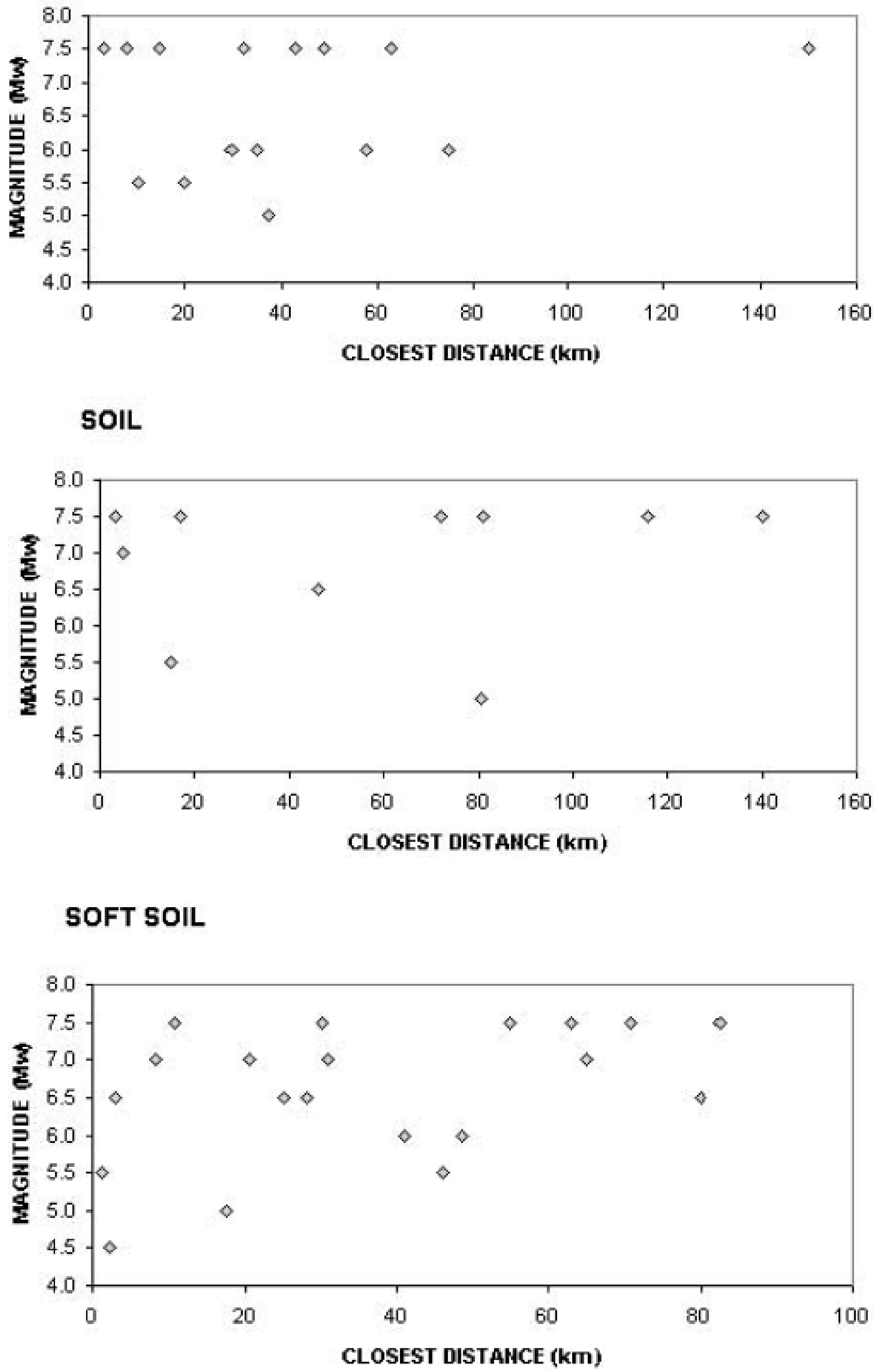


Figure 5-64. The distribution of records in the database in terms of magnitude, distance and local geological conditions.

5.13.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/8/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Gulkan and Kalkan attenuation equation, 2002
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T              = Period (sec), 0 for PGA
% M              = Moment Magnitude
% Rjb            = Joyner-Boore distance (km)
% Vs             = shear wave velocity in upper 30 m (m/s)
%                  (use 200 for soft soil, 400 for soil, 700 for rock)
% --------------------------------------------------------------------------
% Output
% Sa             = median spectral acceleration or PGA prediction (g)
% sigma          = logarithmic standard deviation of Sa prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa, sigma] = GK_2002(T, M, Rjb, Vs30)
% Coefficients
period  =  [0.00    0.10    0.11    0.12    0.13    0.14    0.15    0.16    0.17    0.18...
            0.19    0.20    0.22    0.24    0.26    0.28    0.30    0.32    0.34    0.36...
            0.38    0.40    0.42    0.44    0.46    0.48    0.50    0.55    0.60    0.65...
            0.70    0.75    0.80    0.85    0.90    0.95    1.00    1.10    1.20    1.30...
            1.40    1.50    1.60    1.70    1.80    1.90    2.00];
b1      =  [-0.682  -0.139  0.031   0.123   0.138   0.100   0.090   -0.128  -0.107  0.045...
            0.053   0.127   -0.081  -0.167  -0.129  0.140   0.296   0.454   0.422   0.554...
            0.254   0.231   0.120   0.035   -0.077  -0.154  -0.078  -0.169  -0.387  -0.583...
            -0.681  -0.717  -0.763  -0.778  -0.837  -0.957  -1.112  -1.459  -1.437  -1.321...
            -1.212  -1.340  -1.353  -1.420  -1.465  -1.500  -1.452];
b2      =  [0.253   0.200   0.235   0.228   0.216   0.186   0.210   0.214   0.187   0.168...
            0.180   0.192   0.214   0.265   0.345   0.428   0.471   0.476   0.471   0.509...
            0.499   0.497   0.518   0.544   0.580   0.611   0.638   0.707   0.698   0.689...
            0.698   0.730   0.757   0.810   0.856   0.870   0.904   0.898   0.962   1.000...
            1.000   0.997   0.999   0.996   0.995   0.999   1.020];
b3      =  [0.036   -0.003  -0.007  -0.031  -0.007  0.014   -0.013  0.007   0.037   0.043...
            0.063   0.065   0.006   -0.035  -0.039  -0.096  -0.140  -0.168  -0.152  -0.114...
            -0.105  -0.105  -0.135  -0.142  -0.147  -0.154  -0.161  -0.179  -0.187  -0.159...
            -0.143  -0.143  -0.113  -0.123  -0.130  -0.127  -0.169  -0.147  -0.156  -0.147...
            -0.088  -0.055  -0.056  -0.052  -0.053  -0.051  -0.079];
b5      =  [-0.562  -0.553  -0.573  -0.586  -0.590  -0.585  -0.549  -0.519  -0.535  -0.556...
            -0.570  -0.597  -0.532  -0.531  -0.552  -0.616  -0.642  -0.653  -0.651  -0.692...
            -0.645  -0.647  -0.612  -0.583  -0.563  -0.552  -0.565  -0.539  -0.506  -0.500...
            -0.517  -0.516  -0.525  -0.529  -0.512  -0.472  -0.443  -0.414  -0.463  -0.517...
            -0.584  -0.582  -0.590  -0.582  -0.581  -0.592  -0.612];
bV      =  [-0.297  -0.167  -0.181  -0.208  -0.237  -0.249  -0.196  -0.224  -0.243  -0.256...
            -0.288  -0.303  -0.319  -0.382  -0.395  -0.369  -0.346  -0.290  -0.300  -0.287...
            -0.341  -0.333  -0.313  -0.286  -0.285  -0.293  -0.259  -0.216  -0.259  -0.304...
            -0.360  -0.331  -0.302  -0.283  -0.252  -0.163  -0.200  -0.252  -0.267  -0.219...
            -0.178  -0.165  -0.135  -0.097  -0.058  -0.047  -0.019];
VA      =  [1381    1063    1413    1501    1591    1833    1810    2193    2433    2041 ...
            2086    2238    2198    2198    2160    2179    2149    2144    2083    2043 ...
            2009    1968    1905    1899    1863    1801    1768    1724    1629    1607 ...
            1530    1492    1491    1438    1446    1384    1391    1380    1415    1429 ...
            1454    1490    1513    1569    1653    1707    1787];
h       =  [4.48    3.76    3.89    4.72    5.46    4.98    2.77    1.32    1.67    2.44...
            2.97    3.48    1.98    2.55    3.45    4.95    6.11    7.38    8.30    9.18...
            9.92    9.92    9.09    9.25    8.98    8.96    9.06    8.29    8.24    7.64...
            7.76    7.12    6.98    6.57    7.25    7.24    6.63    6.21    7.17    7.66...
            9.10    9.86    9.94    9.55    9.35    9.49    9.78];
sig     =  [0.562   0.621   0.618   0.615   0.634   0.635   0.620   0.627   0.621   0.599...
            0.601   0.611   0.584   0.569   0.549   0.530   0.540   0.555   0.562   0.563...
            0.562   0.604   0.634   0.627   0.642   0.653   0.679   0.710   0.707   0.736...
            0.743   0.740   0.742   0.758   0.754   0.752   0.756   0.792   0.802   0.796...
            0.790   0.788   0.787   0.789   0.827   0.864   0.895];
% interpolate between periods if neccesary
if (length(find(period == T)) == 0)
```

```
    index_low = sum(period<T);
    T_low = period(index_low);
    T_hi = period(index_low+1);
    [sa_low, sigma_low] = GK_2002(T_low, M, Rjb, Vs30);
    [sa_hi, sigma_hi]   = GK_2002(T_hi,  M, Rjb, Vs30);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
else
    i = find(period == T);
    r = sqrt(Rjb^2 + h(i)^2);
    Sa= exp(b1(i) + b2(i)*(M-6) + b3(i)*(M-6)^2 + b5(i)*log(r) + bV(i)*log(Vs30/VA(i)));
    sigma = sig(i);
end
```

5.14 Turkey: Kalkan and Gülkan – 2004

5.14.1 Reference

Kalkan, E., and P. Gülkan (2004). Empirical Attenuation Equations for Vertical Ground Motion in Turkey, *Earthquake Spectra* **20**(3), 853-882.

5.14.2 Abstract

Using approximately 100 strong-motion records from 47 Turkish Earthquakes, an empirical ground-motion model for the average vertical component was developed in addition to an empirical model for the vertical to horizontal spectral ratio. The model predicts peak ground acceleration (PGA, in g) and 5%-damped spectral values (PSA, in g) for periods ranging from 0.1 to 2 s. The model is applicable for earthquakes between M4.5 and M7.5 and distances up to 200 km.

5.14.3 Attenuation Relationship

The spectral acceleration is a function of:

T – Period (sec), use 0 for PGA
M – Moment magnitude
R_{jb} – Joyner-Boore distance (km)
S – Soil type: 0 for rock, 1 for soil and 2 for soft soil

$$\ln(Sa) = c_1 + \mathrm{c}_2(M-6) + c_3(M-6)^2 + c_4(M-6)^3 + \mathrm{c}_5\ln(r) + \mathrm{c}_6\Gamma_1 + \mathrm{c}_7\Gamma_2$$

where:

$$r = \sqrt{{R_{jb}}^2 + h^2}$$

$$\Gamma_1 = \begin{cases} 1 & for\ S = 1 \\ 0 & otherwise \end{cases}$$

$$\Gamma_2 = \begin{cases} 1 & for\ S = 2 \\ 0 & otherwise \end{cases}$$

$$\mathrm{R} = \left(\frac{\mathrm{Sa_V}}{\mathrm{Sa_H}}\right) = c_1 + \mathrm{c}_2\mathrm{M} + c_3R_{jb} + \mathrm{c}_4\Gamma_1 + \mathrm{c}_5\Gamma_2$$

Note that coefficients in equations for *ln*(*Sa*) and *R* are not the same.

Standard Error

$$\sigma = \sigma_{\mathrm{Rock}}\ \mathrm{OR}\ \sigma_{\mathrm{Soil}}\ \mathrm{OR}\ \sigma_{\mathrm{S.Soil}}$$

Coefficients

Table 5-21. Coefficients for vertical ground motion equation.

T (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	h	σ_{Rock}	σ_{Soil}	$\sigma_{S.\ Soil}$
PGA	0.055	0.387	-0.006	0.041	-0.944	0.277	0.030	7.72	0.629	0.607	0.575
0.10	2.009	0.483	-0.042	-0.007	-1.250	0.163	0.006	14.69	0.672	0.713	0.598
0.11	1.832	0.601	-0.020	-0.085	-1.206	0.160	0.057	14.29	0.684	0.692	0.609
0.12	1.684	0.664	0.014	-0.131	-1.175	0.154	0.030	10.89	0.653	0.695	0.589
0.13	1.732	0.641	-0.023	-0.097	-1.176	0.201	0.008	12.84	0.595	0.692	0.548
0.14	1.753	0.553	-0.017	-0.053	-1.177	0.241	-0.001	13.95	0.586	0.754	0.568
0.15	1.231	0.489	-0.024	-0.020	-1.050	0.191	-0.053	8.93	0.609	0.756	0.583
0.16	1.120	0.512	-0.024	-0.025	-1.024	0.216	-0.063	7.99	0.604	0.735	0.567
0.17	1.110	0.472	-0.043	0.026	-1.058	0.133	-0.035	9.49	0.592	0.602	0.542
0.18	1.294	0.439	-0.054	0.050	-1.055	0.112	-0.068	10.42	0.572	0.602	0.486
0.19	1.202	0.453	-0.040	0.058	-1.053	0.116	0.019	11.10	0.582	0.661	0.540
0.20	0.967	0.484	0.005	0.032	-1.013	0.191	0.023	12.42	0.592	0.678	0.515
0.22	0.857	0.551	-0.020	0.000	-0.997	0.156	0.052	12.44	0.620	0.582	0.465
0.24	0.509	0.424	-0.027	0.077	-0.919	0.263	0.070	11.60	0.629	0.681	0.508
0.26	0.301	0.386	-0.041	0.109	-0.868	0.261	0.011	9.40	0.653	0.681	0.481
0.28	0.043	0.388	-0.049	0.103	-0.808	0.252	0.031	10.08	0.620	0.570	0.520
0.30	0.451	0.422	-0.088	0.119	-0.903	0.230	0.101	13.43	0.645	0.654	0.580
0.32	-0.046	0.420	-0.097	0.127	-0.803	0.360	0.151	11.36	0.607	0.602	0.604
0.34	-0.158	0.465	-0.115	0.122	-0.781	0.379	0.164	10.81	0.620	0.592	0.611
0.36	-0.264	0.491	-0.155	0.125	-0.753	0.359	0.136	8.96	0.615	0.588	0.604
0.38	-0.481	0.433	-0.189	0.150	-0.706	0.389	0.135	7.49	0.576	0.566	0.582
0.40	-0.634	0.347	-0.184	0.197	-0.676	0.421	0.087	7.40	0.599	0.555	0.552
0.42	-0.836	0.361	-0.182	0.192	-0.628	0.428	0.072	6.77	0.622	0.544	0.554
0.44	-1.002	0.424	-0.182	0.160	-0.593	0.423	0.100	6.33	0.628	0.514	0.556
0.46	-1.190	0.461	-0.183	0.137	-0.561	0.439	0.150	5.43	0.655	0.509	0.571
0.48	-1.340	0.494	-0.188	0.116	-0.536	0.456	0.190	4.70	0.674	0.540	0.597
0.50	-1.444	0.517	-0.191	0.095	-0.522	0.422	0.235	4.33	0.777	0.540	0.626
0.55	-1.256	0.545	-0.207	0.099	-0.562	0.426	0.129	5.65	0.692	0.555	0.611
0.60	-1.370	0.548	-0.234	0.120	-0.544	0.424	0.097	5.40	0.696	0.554	0.588
0.65	-1.423	0.573	-0.227	0.121	-0.551	0.352	0.150	5.38	0.693	0.607	0.696
0.70	-1.341	0.695	-0.194	0.071	-0.595	0.225	0.150	5.47	0.682	0.516	0.693
0.75	-1.419	0.724	-0.202	0.073	-0.594	0.188	0.177	5.32	0.679	0.522	0.696
0.80	-1.519	0.713	-0.145	0.061	-0.593	0.265	0.196	6.73	0.696	0.632	0.735
0.85	-1.578	0.761	-0.160	0.036	-0.588	0.312	0.231	6.73	0.689	0.572	0.764
0.90	-1.662	0.742	-0.161	0.053	-0.588	0.314	0.228	6.60	0.683	0.533	0.800
0.95	-1.723	0.727	-0.152	0.076	-0.584	0.288	0.171	5.49	0.687	0.502	0.839
1.00	-1.712	0.752	-0.137	0.079	-0.593	0.206	0.052	4.16	0.721	0.498	0.812
1.10	-1.731	0.837	-0.214	0.072	-0.581	0.173	0.041	4.08	0.721	0.525	0.897
1.20	-1.816	0.833	-0.256	0.097	-0.579	0.233	0.062	4.48	0.645	0.532	0.867
1.30	-1.814	0.910	-0.284	0.080	-0.602	0.256	0.089	4.61	0.677	0.610	0.849
1.40	-1.903	0.928	-0.309	0.072	-0.585	0.231	0.048	4.64	0.681	0.681	0.803
1.50	-1.932	0.974	-0.279	0.025	-0.597	0.160	0.032	4.94	0.675	0.693	0.872
1.60	-2.068	0.965	-0.288	0.038	-0.583	0.178	0.027	4.43	0.678	0.690	0.891
1.70	-2.150	1.023	-0.311	0.021	-0.581	0.230	0.030	3.62	0.705	0.710	0.904
1.80	-2.321	1.010	-0.310	0.034	-0.559	0.273	0.034	3.74	0.735	0.743	0.892
1.90	-2.348	1.048	-0.323	0.016	-0.570	0.301	0.064	4.26	0.738	0.767	0.911
2.00	-2.330	1.111	-0.337	-0.009	-0.593	0.280	0.104	3.09	0.729	0.740	0.906

Table 5-22. Coefficients for spectral ratio equation.

T (sec)	c_1	c_2	c_3	c_4	c_5	σ_{Rock}	σ_{Soil}	$\sigma_{S.\ Soil}$
PGA	0.835	-0.019	-0.0007	-0.028	-0.147	0.322	0.268	0.280
0.10	0.632	0.033	-0.0017	0.015	-0.082	0.425	0.414	0.281
0.11	0.618	0.032	-0.0020	0.025	-0.028	0.387	0.398	0.316
0.12	0.613	0.026	-0.0018	0.000	-0.024	0.328	0.342	0.304
0.13	0.525	0.033	-0.0010	-0.028	-0.072	0.299	0.335	0.305
0.14	0.411	0.043	-0.0008	-0.033	-0.069	0.232	0.329	0.260
0.15	0.347	0.060	-0.0008	-0.054	-0.067	0.256	0.211	0.245
0.16	0.272	0.063	-0.0009	-0.026	-0.085	0.293	0.210	0.254
0.17	0.261	0.062	-0.0006	-0.040	-0.100	0.270	0.175	0.222
0.18	0.268	0.056	-0.0002	-0.014	-0.121	0.256	0.196	0.214
0.19	0.302	0.046	0.0000	-0.050	-0.120	0.256	0.191	0.214
0.20	0.353	0.035	0.0001	-0.052	-0.119	0.268	0.202	0.233
0.22	0.612	-0.010	0.0004	-0.035	-0.125	0.277	0.219	0.224
0.24	0.622	-0.010	0.0004	-0.045	-0.159	0.322	0.210	0.198
0.26	0.633	-0.014	0.0005	-0.030	-0.150	0.322	0.228	0.224
0.28	0.717	-0.031	0.0007	-0.020	-0.157	0.277	0.245	0.209
0.30	0.678	-0.023	0.0006	-0.010	-0.161	0.276	0.233	0.221
0.32	0.525	-0.004	0.0007	0.034	-0.135	0.215	0.265	0.224
0.34	0.487	0.001	0.0009	0.022	-0.156	0.214	0.323	0.219
0.36	0.383	0.006	0.0007	0.066	-0.087	0.266	0.303	0.233
0.38	0.438	-0.003	0.0007	0.070	-0.095	0.271	0.283	0.242
0.40	0.482	-0.011	0.0009	0.089	-0.110	0.282	0.299	0.236
0.42	0.468	-0.007	0.0008	0.088	-0.120	0.275	0.266	0.214
0.44	0.422	-0.001	0.0009	0.058	-0.111	0.266	0.214	0.214
0.46	0.420	-0.003	0.0009	0.043	-0.095	0.258	0.200	0.206
0.48	0.452	-0.009	0.0009	0.040	-0.085	0.258	0.210	0.204
0.50	0.530	-0.022	0.0010	0.036	-0.075	0.328	0.232	0.223
0.55	0.561	-0.024	0.0009	0.027	-0.077	0.273	0.228	0.242
0.60	0.643	-0.038	0.0011	0.016	-0.085	0.340	0.244	0.276
0.65	0.607	-0.032	0.0011	-0.020	-0.080	0.323	0.256	0.274
0.70	0.594	-0.028	0.0010	-0.015	-0.085	0.316	0.310	0.228
0.75	0.550	-0.024	0.0010	-0.040	-0.065	0.294	0.253	0.205
0.80	0.681	-0.047	0.0013	-0.049	-0.058	0.315	0.219	0.200
0.85	0.746	-0.058	0.0013	-0.041	-0.062	0.333	0.200	0.211
0.90	0.829	-0.071	0.0014	-0.041	-0.066	0.342	0.219	0.221
0.95	0.916	-0.083	0.0013	-0.022	-0.076	0.356	0.256	0.236
1.00	0.848	-0.063	0.0008	-0.021	-0.096	0.359	0.290	0.214
1.10	0.848	-0.059	0.0007	0.000	-0.120	0.366	0.327	0.206
1.20	0.848	-0.065	0.0008	0.018	-0.096	0.363	0.328	0.206
1.30	0.794	-0.054	0.0009	0.006	-0.099	0.313	0.315	0.179
1.40	0.836	-0.060	0.0009	0.020	-0.095	0.317	0.341	0.191
1.50	0.850	-0.062	0.0008	0.003	-0.090	0.311	0.314	0.202
1.60	0.796	-0.053	0.0008	0.001	-0.092	0.299	0.283	0.196
1.70	0.736	-0.042	0.0008	0.010	-0.090	0.306	0.310	0.219
1.80	0.721	-0.038	0.0008	0.004	-0.070	0.309	0.303	0.245
1.90	0.727	-0.037	0.0008	0.004	-0.076	0.304	0.283	0.232
2.00	0.640	-0.018	0.0004	-0.004	-0.065	0.315	0.290	0.255

5.14.4 Calibration Plots

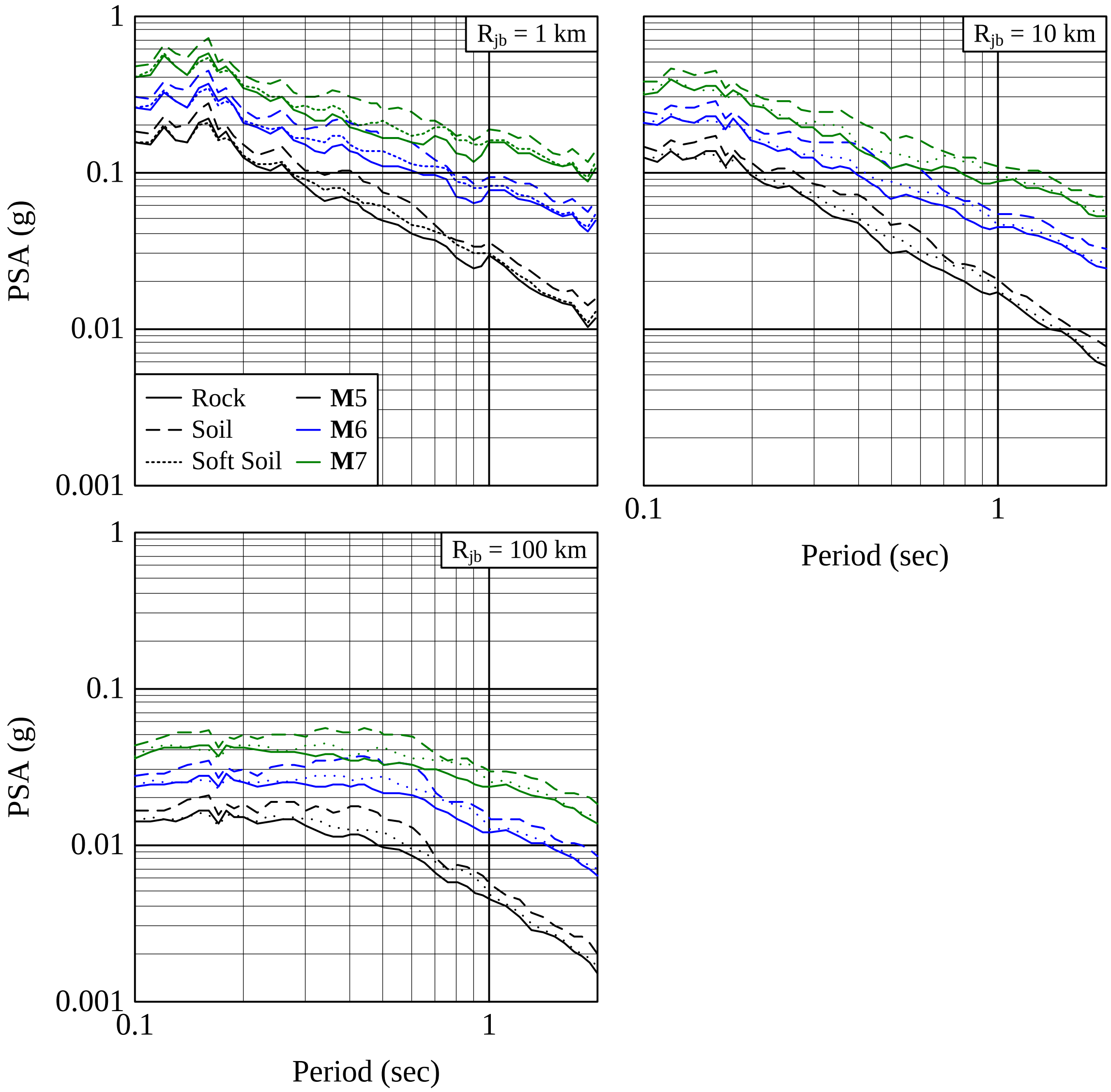


Figure 5-65. PSA as a function of period for various soil types, magnitudes, and distances.

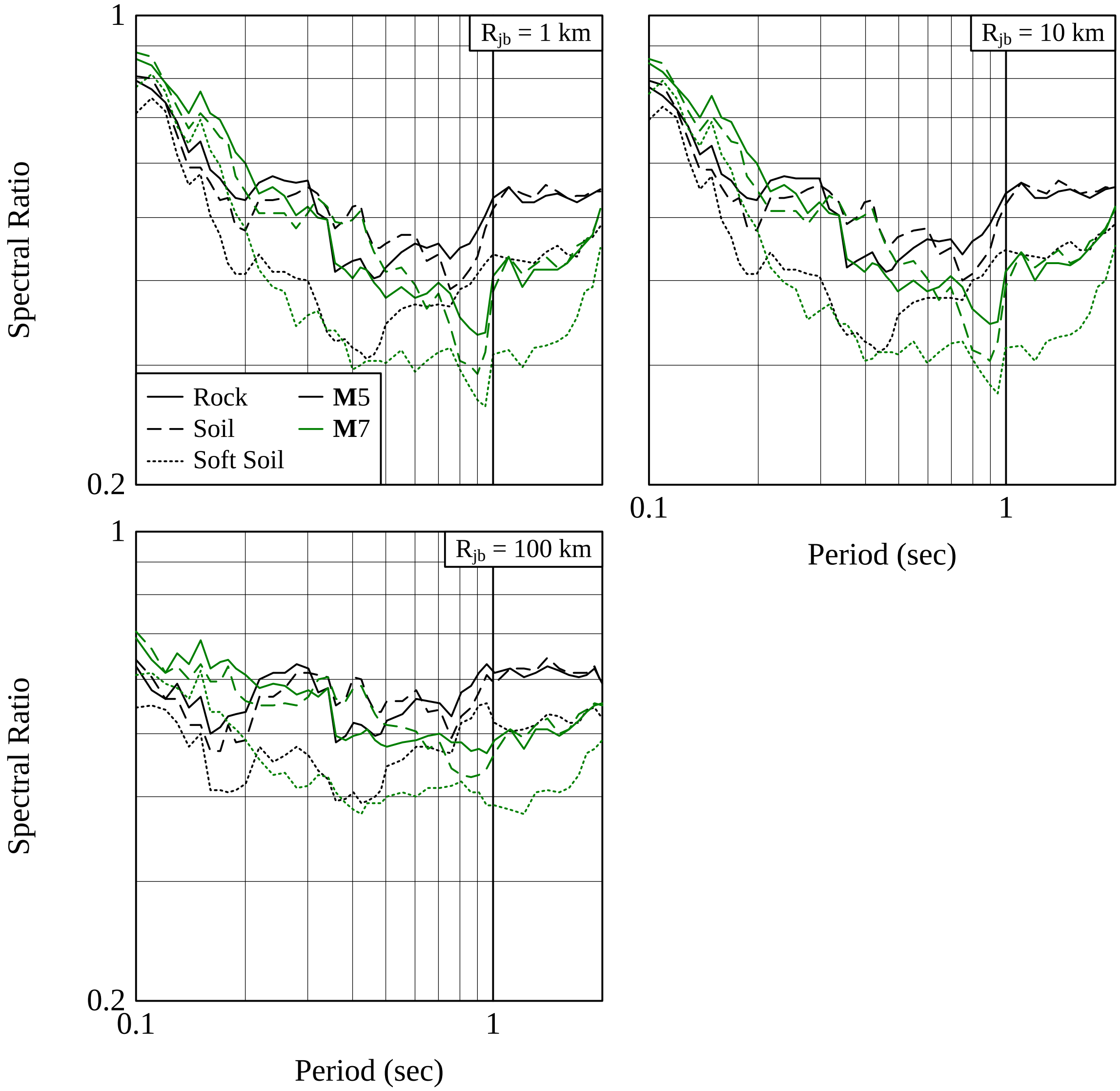


Figure 5-66. Spectral ratio as a function of period for various soil types, magnitudes and distances.

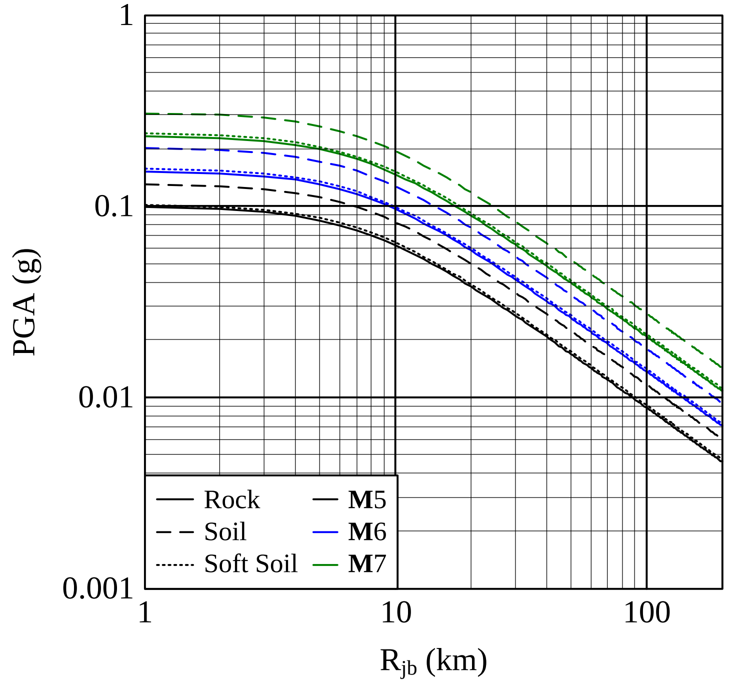


Figure 5-67. PGA as a function of distance for various soil types and magnitudes.

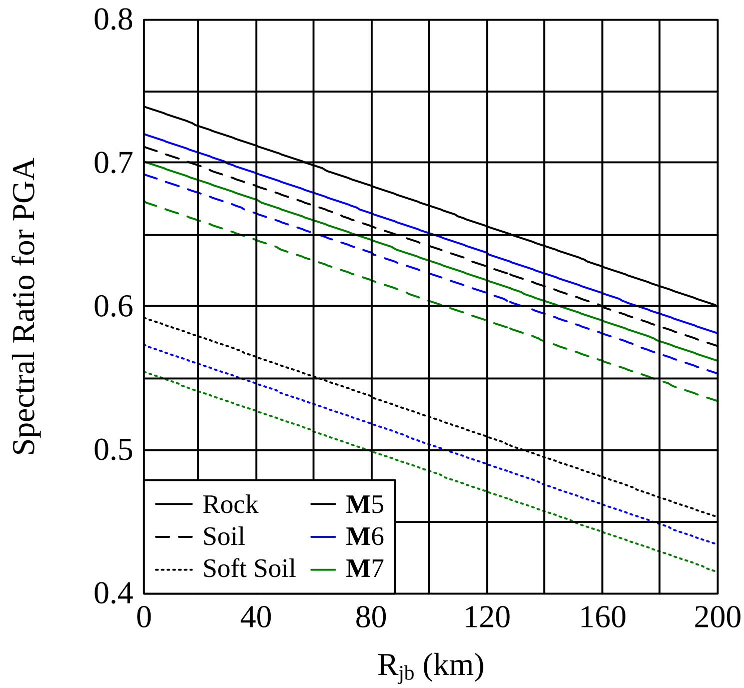


Figure 5-68. Spectral ratio for PGA as a function of distance for various soil types and magnitudes.

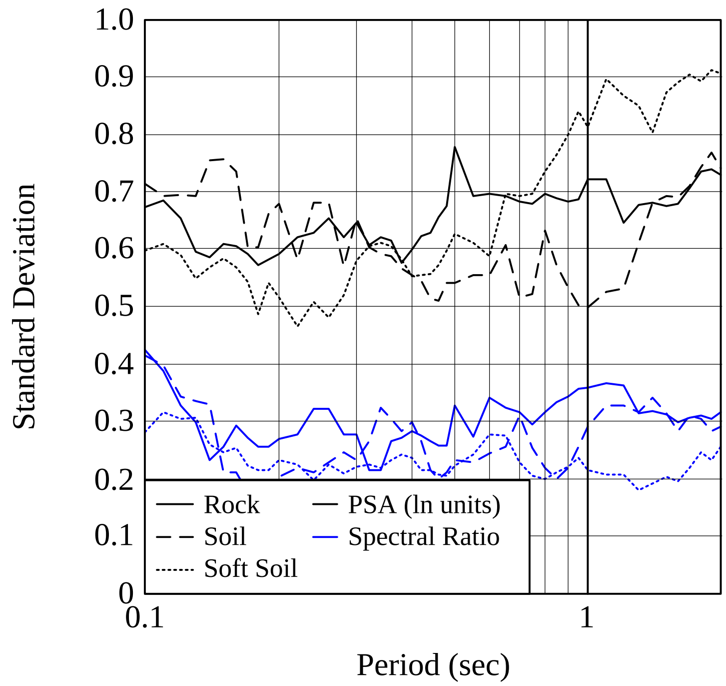


Figure 5-69. Various standard deviations as a function of period.

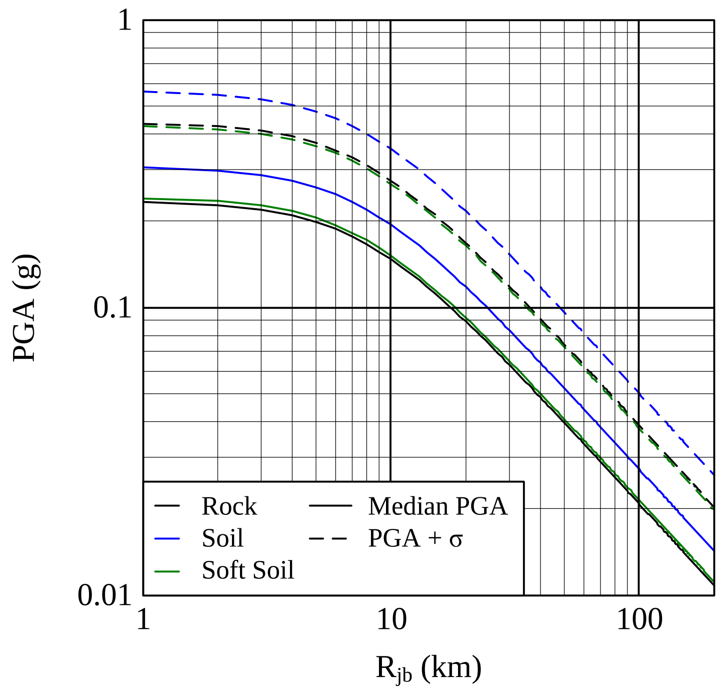


Figure 5-70. Example of application of median PGA plus one standard deviation.

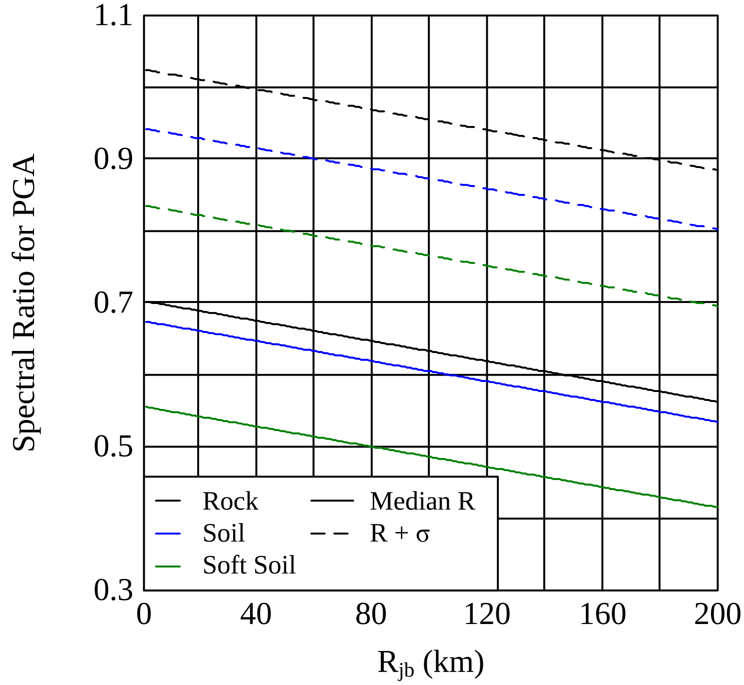


Figure 5-71. Example of application of median spectral ratio for PGA plus one standard deviation.

5.14.5 Database

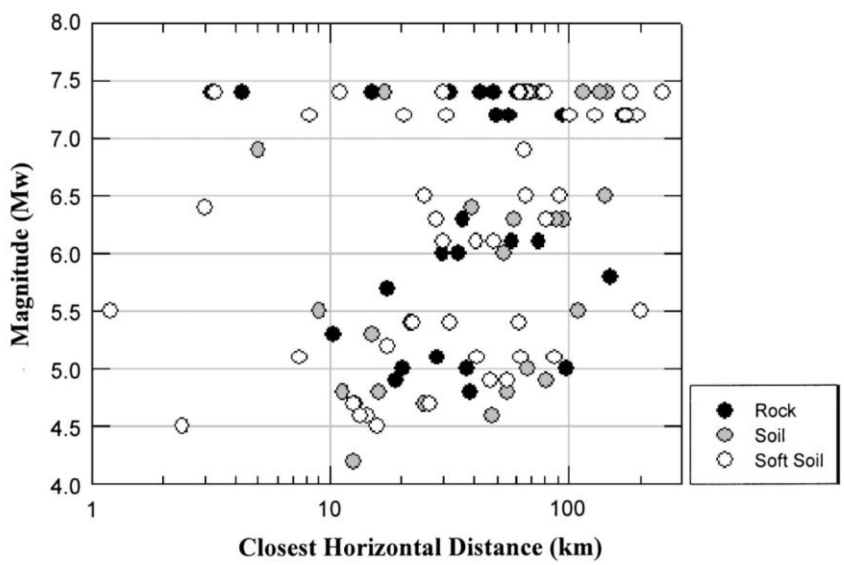


Figure 5-72. Distribution of records in the database with respect to magnitude and closest horizontal distance for rock, soil and soft-soil site conditions.

5.14.6 MATLAB Code

```
% by Kathryn A. Gunberg 5/8/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Kalkan and Gulkan attenuation equation, 2004
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T              = Period (sec), 0 for PGA
% M              = Moment Magnitude
% Rjb            = Joyner-Boore distance (km)
% S              = Soil type: 0 for rock, 1 for soil, 2 for soft soil
% --------------------------------------------------------------------------
% Output
% Sa             = median spectral acceleration or PGA prediction (g)
% sigma          = logarithmic standard deviation of Sa prediction
% R              = Vertical to horizontal spectral ratio
% sigmaR         = logarithmic standard deviation of R prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Sa, sigma, R, sigmaR] = KG_2004(T, M, Rjb, S)
% Coefficients
period  =  [0.00    0.10    0.11    0.12    0.13    0.14    0.15    0.16    0.17    0.18...
            0.19    0.20    0.22    0.24    0.26    0.28    0.30    0.32    0.34    0.36...
            0.38    0.40    0.42    0.44    0.46    0.48    0.50    0.55    0.60    0.65...
            0.70    0.75    0.80    0.85    0.90    0.95    1.00    1.10    1.20    1.30...
            1.40    1.50    1.60    1.70    1.80    1.90    2.00];
c1      =  [0.055   2.009   1.832   1.684   1.732   1.753   1.231   1.120   1.110   1.294...
            1.202   0.967   0.857   0.509   0.301   0.043   0.451   -0.046  -0.158  -0.264...
            -0.481  -0.634  -0.836  -1.002  -1.190  -1.340  -1.444  -1.256  -1.370  -1.423...
            -1.341  -1.419  -1.519  -1.578  -1.662  -1.723  -1.712  -1.731  -1.816  -1.814...
            -1.903  -1.932  -2.068  -2.150  -2.321  -2.348  -2.330];
c2      =  [0.387   0.483   0.601   0.664   0.641   0.553   0.489   0.512   0.472   0.439...
            0.453   0.484   0.551   0.424   0.386   0.388   0.422   0.420   0.465   0.491...
            0.433   0.347   0.361   0.424   0.461   0.494   0.517   0.545   0.548   0.573...
            0.695   0.724   0.713   0.761   0.742   0.727   0.752   0.837   0.833   0.910...
            0.928   0.974   0.965   1.023   1.010   1.048   1.111];
c3      =  [-0.006  -0.042  -0.020  0.014   -0.023  -0.017  -0.024  -0.024  -0.043  -0.054...
            -0.040  0.005   -0.020  -0.027  -0.041  -0.049  -0.088  -0.097  -0.115  -0.155...
            -0.189  -0.184  -0.182  -0.182  -0.183  -0.188  -0.191  -0.207  -0.234  -0.227...
            -0.194  -0.202  -0.145  -0.160  -0.161  -0.152  -0.137  -0.214  -0.256  -0.284...
            -0.309  -0.279  -0.288  -0.311  -0.310  -0.323  -0.337];
c4      =  [0.041   -0.007  -0.085  -0.131  -0.097  -0.053  -0.020  -0.025  0.026   0.050...
            0.058   0.032   0.000   0.077   0.109   0.103   0.119   0.127   0.122   0.125...
            0.150   0.197   0.192   0.160   0.137   0.116   0.095   0.099   0.120   0.121...
            0.071   0.073   0.061   0.036   0.053   0.076   0.079   0.072   0.097   0.080...
            0.072   0.025   0.038   0.021   0.034   0.016   -0.009];
c5      =  [-0.944  -1.250  -1.206  -1.175  -1.176  -1.177  -1.050  -1.024  -1.058  -1.055...
            -1.053  -1.013  -0.997  -0.919  -0.868  -0.808  -0.903  -0.803  -0.781  -0.753...
            -0.706  -0.676  -0.628  -0.593  -0.561  -0.536  -0.522  -0.562  -0.544  -0.551...
            -0.595  -0.594  -0.593  -0.588  -0.588  -0.584  -0.593  -0.581  -0.579  -0.602...
            -0.585  -0.597  -0.583  -0.581  -0.559  -0.570  -0.593];
h       =  [7.72    14.69   14.29   10.89   12.84   13.95   8.93    7.99    9.49    10.42...
            11.10   12.42   12.44   11.60   9.40    10.08   13.43   11.36   10.81   8.96...
            7.49    7.40    6.77    6.33    5.43    4.70    4.33    5.65    5.40    5.38...
            5.47    5.32    6.73    6.73    6.60    5.49    4.16    4.08    4.48    4.61...
            4.64    4.94    4.43    3.62    3.74    4.26    3.09];
cr1     =  [0.835   0.632   0.618   0.613   0.525   0.411   0.347   0.272   0.261   0.268...
            0.302   0.353   0.612   0.622   0.633   0.717   0.678   0.525   0.487   0.383...
            0.438   0.482   0.468   0.422   0.420   0.452   0.530   0.561   0.643   0.607...
            0.594   0.550   0.681   0.746   0.829   0.916   0.848   0.848   0.848   0.794...
            0.836   0.850   0.796   0.736   0.721   0.727   0.640];
cr2     =  [-0.019  0.033   0.032   0.026   0.033   0.043   0.060   0.063   0.062   0.056...
            0.046   0.035   -0.010  -0.010  -0.014  -0.031  -0.023  -0.004  0.001   0.006...
            -0.003  -0.011  -0.007  -0.001  -0.003  -0.009  -0.022  -0.024  -0.038  -0.032...
            -0.028  -0.024  -0.047  -0.058  -0.071  -0.083  -0.063  -0.059  -0.065  -0.054...
            -0.060  -0.062  -0.053  -0.042  -0.038  -0.037  -0.018];
cr3     =  [-0.0007 -0.0017 -0.0020 -0.0018 -0.0010 -0.0008 -0.0008 -0.0009 -0.0006 -0.0002...
```

```
            0.0000  0.0001  0.0004  0.0004  0.0005  0.0007  0.0006  0.0007  0.0009  0.0007...
            0.0007  0.0009  0.0008  0.0009  0.0009  0.0009  0.0010  0.0009  0.0011  0.0011...
            0.0010  0.0010  0.0013  0.0013  0.0014  0.0013  0.0008  0.0007  0.0008  0.0009...
            0.0009  0.0008  0.0008  0.0008  0.0008  0.0008  0.0004];
if S == 0
    cS  =  zeros(1,length(period));
    crS =  zeros(1,length(period));
    sig =  [0.629   0.672   0.684   0.653   0.595   0.586   0.609   0.604   0.592   0.572...
            0.582   0.592   0.620   0.629   0.653   0.620   0.645   0.607   0.620   0.615...
            0.576   0.599   0.622   0.628   0.655   0.674   0.777   0.692   0.696   0.693...
            0.682   0.679   0.696   0.689   0.683   0.687   0.721   0.721   0.645   0.677...
            0.681   0.675   0.678   0.705   0.735   0.738   0.729];
    sigr=  [0.322   0.425   0.387   0.328   0.299   0.232   0.256   0.293   0.270   0.256...
            0.256   0.268   0.277   0.322   0.322   0.277   0.276   0.215   0.214   0.266...
            0.271   0.282   0.275   0.266   0.258   0.258   0.328   0.273   0.340   0.323...
            0.316   0.294   0.315   0.333   0.342   0.356   0.359   0.366   0.363   0.313...
            0.317   0.311   0.299   0.306   0.309   0.304   0.315];
elseif S == 1
    cS  =  [0.277   0.163   0.160   0.154   0.201   0.241   0.191   0.216   0.133   0.112...
            0.116   0.191   0.156   0.263   0.261   0.252   0.230   0.360   0.379   0.359...
            0.389   0.421   0.428   0.423   0.439   0.456   0.422   0.426   0.424   0.352...
            0.225   0.188   0.265   0.312   0.314   0.288   0.206   0.173   0.233   0.256...
            0.231   0.160   0.178   0.230   0.273   0.301   0.280];
    crS =  [-0.028  0.015   0.025   0.000   -0.028  -0.033  -0.054  -0.026  -0.040  -0.014...
            -0.050  -0.052  -0.035  -0.045  -0.030  -0.020  -0.010  0.034   0.022   0.066...
            0.070   0.089   0.088   0.058   0.043   0.040   0.036   0.027   0.016   -0.020...
            -0.015  -0.040  -0.049  -0.041  -0.041  -0.022  -0.021  0.000   0.018   0.006...
            0.020   0.003   0.001   0.010   0.004   0.004   -0.004];
    sig =  [0.607   0.713   0.692   0.695   0.692   0.754   0.756   0.735   0.602   0.602...
            0.661   0.678   0.582   0.681   0.681   0.570   0.654   0.602   0.592   0.588...
            0.566   0.555   0.544   0.514   0.509   0.540   0.540   0.555   0.554   0.607...
            0.516   0.522   0.632   0.572   0.533   0.502   0.498   0.525   0.532   0.610...
            0.681   0.693   0.690   0.710   0.743   0.767   0.740];
    sigr=  [0.268   0.414   0.398   0.342   0.335   0.329   0.211   0.210   0.175   0.196...
            0.191   0.202   0.219   0.210   0.228   0.245   0.233   0.265   0.323   0.303...
            0.283   0.299   0.266   0.214   0.200   0.210   0.232   0.228   0.244   0.256...
            0.310   0.253   0.219   0.200   0.219   0.256   0.290   0.327   0.328   0.315...
            0.341   0.314   0.283   0.310   0.303   0.283   0.290];
else
    cS  =  [0.030   0.006   0.057   0.030   0.008   -0.001  -0.053  -0.063  -0.035  -0.068...
            0.019   0.023   0.052   0.070   0.011   0.031   0.101   0.151   0.164   0.136...
            0.135   0.087   0.072   0.100   0.150   0.190   0.235   0.129   0.097   0.150...
            0.150   0.177   0.196   0.231   0.228   0.171   0.052   0.041   0.062   0.089...
            0.048   0.032   0.027   0.030   0.034   0.064   0.104];
    crS =  [-0.147  -0.082  -0.028  -0.024  -0.072  -0.069  -0.067  -0.085  -0.100  -0.121...
            -0.120  -0.119  -0.125  -0.159  -0.150  -0.157  -0.161  -0.135  -0.156  -0.087...
            -0.095  -0.110  -0.120  -0.111  -0.095  -0.085  -0.075  -0.077  -0.085  -0.080...
            -0.085  -0.065  -0.058  -0.062  -0.066  -0.076  -0.096  -0.120  -0.096  -0.099...
            -0.095  -0.090  -0.092  -0.090  -0.070  -0.076  -0.065];
    sig =  [0.575   0.598   0.609   0.589   0.548   0.568   0.583   0.567   0.542   0.486...
            0.540   0.515   0.465   0.508   0.481   0.520   0.580   0.604   0.611   0.604...
            0.582   0.552   0.554   0.556   0.571   0.597   0.626   0.611   0.588   0.696...
            0.693   0.696   0.735   0.764   0.800   0.839   0.812   0.897   0.867   0.849...
            0.803   0.872   0.891   0.904   0.892   0.911   0.906];
    sigr=  [0.280   0.281   0.316   0.304   0.305   0.260   0.245   0.254   0.222   0.214...
            0.214   0.233   0.224   0.198   0.224   0.209   0.221   0.224   0.219   0.233...
            0.242   0.236   0.214   0.214   0.206   0.204   0.223   0.242   0.276   0.274...
            0.228   0.205   0.200   0.211   0.221   0.236   0.214   0.206   0.206   0.179...
            0.191   0.202   0.196   0.219   0.245   0.232   0.255];
end
    % interpolate between periods if neccesary
if (length(find(period == T)) == 0)
    index_low = sum(period<T);
    T_low = period(index_low);
    T_hi = period(index_low+1);
    [sa_low, sigma_low, R_low, sigmaR_low] = GK_2002(T_low, M, Rjb, S);
    [sa_hi,  sigma_hi,  R_hi,  sigmaR_hi]  = GK_2002(T_hi,  M, Rjb, S);
    x = [log(T_low) log(T_hi)];
    Y_sa = [log(sa_low) log(sa_hi)];
    Y_sigma = [sigma_low sigma_hi];
    Y_R = [log(R_low) log(R_hi)];
```

```
    Y_sigmaR = [sigmaR_low sigmaR_hi];
    Sa = exp(interp1(x,Y_sa,log(T)));
    sigma = interp1(x,Y_sigma,log(T));
    R = exp(interp1(x,Y_R,log(T)));
    sigmaR = interp1(x,Y_sigmaR,log(T));
else
    i = find(period == T);
    r = sqrt(Rjb^2 + h(i)^2);
    Sa= exp(c1(i) + c2(i)*(M-6) + c3(i)*(M-6)^2 + c4(i)*(M-6)^3 + c5(i)*log(r) + cS(i));
    sigma = sig(i);
    R = cr1(i) + cr2(i)*M + cr3(i)*Rjb + crS(i);
    sigmaR = sigr(i);
end
```

6 OTHER PARAMETERS

6.1 Arias Intensity: Travasarou, Bray and Abrahamson – 2003

6.1.1 Reference

Travasarou, T., J. D. Bray, and N. A. Abrahamson (2003). Empirical Attenuation Relationship for Arias Intensity, *Earthquake Engineering and Structural Dynamics* **32**, 1133-1155.

6.1.2 Abstract

Using 1208 ground-motion records from 75 earthquakes, an empirical ground-motion model for Arias intensity was developed. The model predicts Arias intensity (I_a, in m/s) and is applicable for shallow crustal earthquakes in active plate margins for earthquakes between M4.7 and M7.6 and distances up to 250 km. The model is not applicable to subduction and intraplate earthquakes.

6.1.3 Attenuation Relationship

The Arias intensity is a function of:

- **M** – Moment magnitude
- R_{rup} – Closest distance to rupture plane (km)
- F – Fault type: 0 for strike-slip, 1 for normal and 2 for reverse
- S – Site category: 0 for B, 1 for C and 2 for D (see Table 6-1)

$$\ln(I_a) = c_1 + c_2(M-6) + c_3\ln(M/6) + c_4\ln\left(\sqrt{R_{rup}{}^2 + h^2}\right) + S_C\big(s_{11} + s_{12}(M-6)\big) + S_D\big(s_{21} + s_{22}(M-6)\big) + f_1F_N + f_2F_R$$

where:

$$S_C = \begin{cases} 1 & for\ S = 1 \\ 0 & otherwise \end{cases} \qquad F_N = \begin{cases} 1 & for\ F = 1 \\ 0 & otherwise \end{cases}$$

$$S_D = \begin{cases} 1 & for\ S = 2 \\ 0 & otherwise \end{cases} \qquad F_R = \begin{cases} 1 & for\ F = 2 \\ 0 & otherwise \end{cases}$$

Standard Error

$$\sigma_{tot}(M, I_a, S) = \sqrt{\sigma(I_a, S)^2 + \tau(M)^2}$$

where:

$$\sigma(I_a, S) = \begin{cases} \sigma_1 & for\ I_a \leq 0.013\ m/s \\ \sigma_1 - 0.106(\ln(I_a) - \ln(0.0132)) & for\ 0.013 < I_a < 0.125\ m/s \\ \sigma_2 & for\ I_a \geq 0.125\ m/s \end{cases}$$

$$\tau(M) = 0.611 - 0.047(M - 4.7)$$

Table 6-1. Description of site categories.

Site Category	Description
B	Rock, most 'unweathered' California rock cases ($V_S \geq 760$ m/s or < 6 m of soil)
C	Weathered soft rock and shallow stiff soil (< 60 m of soil)
D	Deep stiff Holocene or Pleistocene soil (> 60 m of soil and no 'soft' soils)

Coefficients

Table 6-2. Coefficients for empirical equation.

c_1	2.800
c_2	-1.981
c_3	20.72
c_4	-1.703
h	8.78
s_{11}	0.454
s_{12}	0.101
s_{21}	0.479
s_{22}	0.334
f_1	-0.166
f_2	0.512

Table 6-3. Coefficients for standard deviation.

Site Category	σ_1	σ_2
B	1.18	0.94
C	1.17	0.93
D	0.96	0.73

6.1.4 Calibration Plots

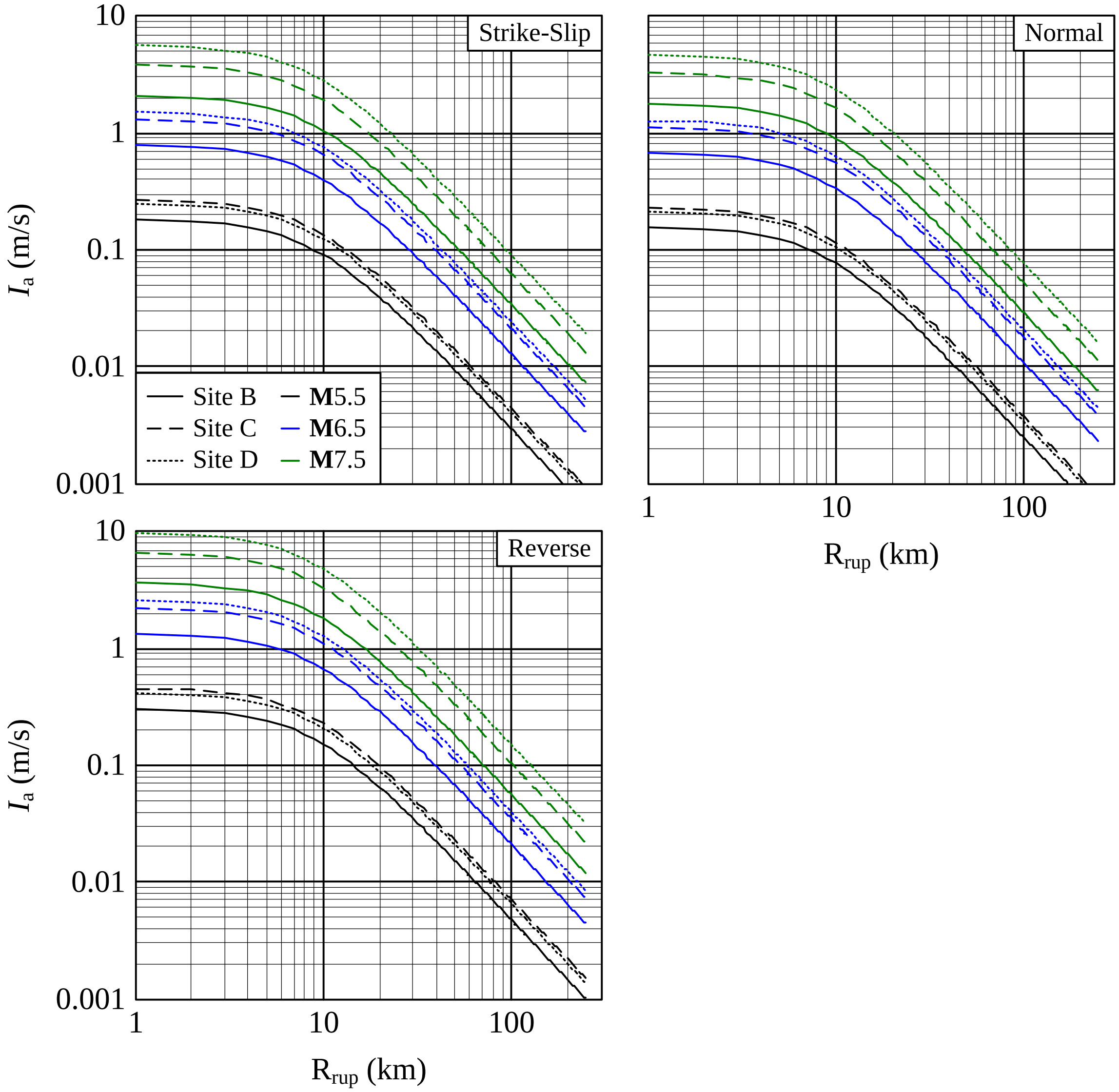


Figure 6-1. Arias Intensity as a function of distance for various soil classes and fault types.

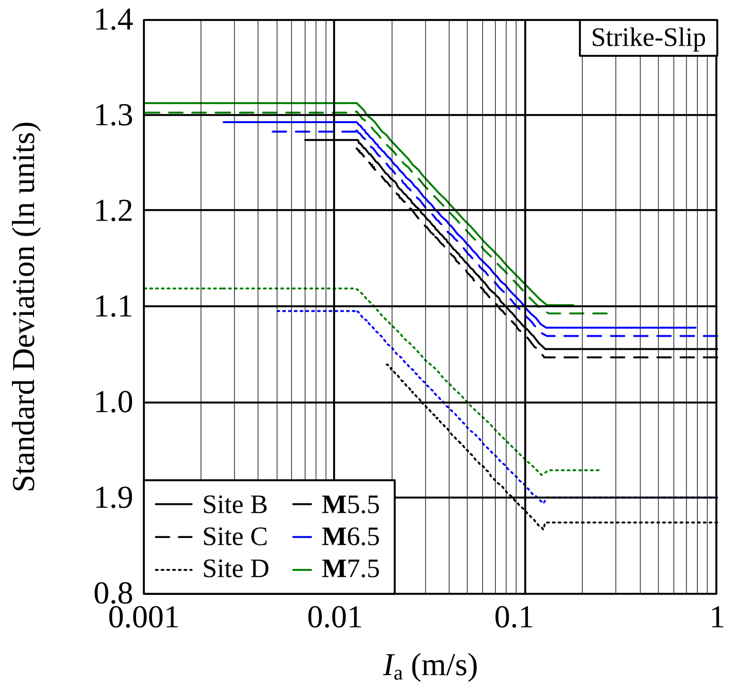


Figure 6-2. Standard deviation as a function of Arias Intensiy for various magnitudes and soil types.

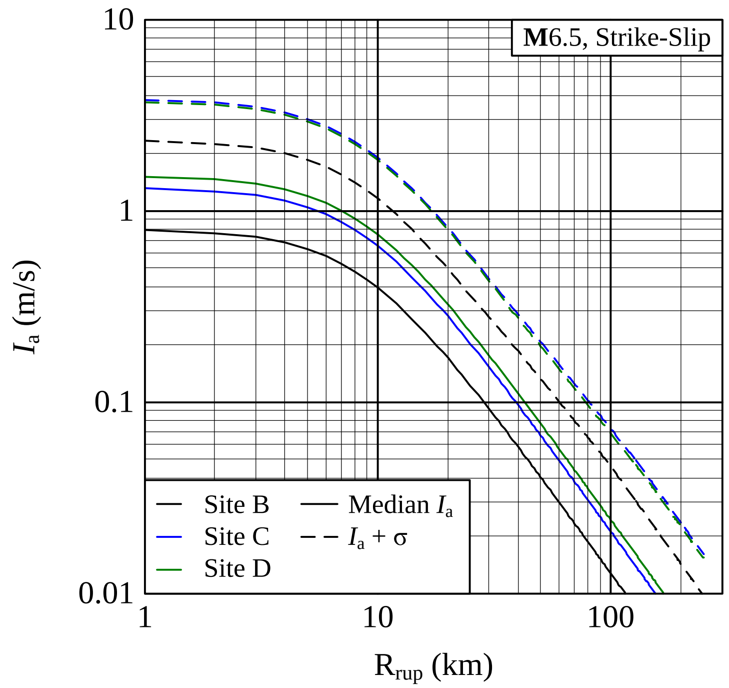


Figure 6-3. Example of application of median Arias Intensity plus one standard deviation.

6.1.5 Database

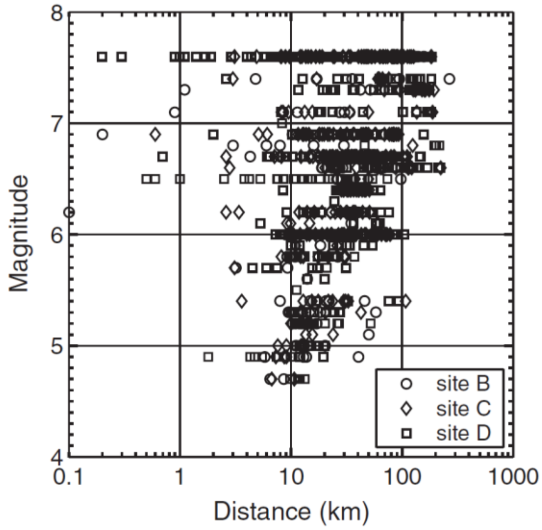


Figure 6-4. Distribution of the data used in the regression analysis with respect to magnitude, distance and site category.

6.1.6 MATLAB Code

```
% by Kathryn A. Gunberg 6/24/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Travasarou, Bray and Abrahamson attenuation equation for Arias Intensity,
% 2003
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% M             = Moment Magnitude
% Rrup          = Closest distance to rupture plane (km)
% F             = Fault type: 0 for strike-slip, 1 for normal, 2 for reverse
% S             = Soil category: 0 for B, 1 for C, 2 for D
% -----------------------------------------------------------------------
% Output
% Ia            = median Arias Intensity prediction
% sigma         = logarithmic standard deviation of Arias Intensity
%                 prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Ia, sigma] = TBA_2003(M, Rrup, F, S)
% Coefficients
FN = 0;
FR = 0;
if F == 1
    FN = 1;
elseif F == 2
    FR = 1;
end
SC = 0;
SD = 0;
if S == 0
    sig1 = 1.18;
    sig2 = 0.94;
elseif S == 1
    SC = 1;
    sig1 = 1.17;
    sig2 = 0.93;
elseif S == 2
    SD = 1;
    sig1 = 0.96;
    sig2 = 0.73;
end
Ia= exp(2.8 - 1.981*(M-6) + 20.72*log(M/6) - 1.703*log(sqrt(Rrup^2 + 8.78^2)) + ...
    SC*(0.454 + 0.101*(M-6)) + SD*(0.479 + 0.334*(M-6)) - 0.166*FN + 0.512*FR);
if Ia <= 0.013
    sig = sig1;
elseif Ia < 0.125
    sig = sig1 - 0.106*(log(Ia) - log(0.0132));
else
    sig = sig2;
end
tau = 0.611 - 0.047*(M-4.7);
sigma = sqrt(sig^2 + tau^2);
end
```

6.2 Arias Intensity: Lee and Green – 2009

6.2.1 References

Lee, Jongwon (2009). Engineering Characterization of Earthquake Ground Motions, PhD dissertation, University of Michigan.

Lee, J. and Green, R.A. (2011). Predictive Equations for the Arias Intensity of Earthquake Ground Motions, *in preparation*.

6.2.2 Abstract

Using 324 three-component ground motion records from active seismic regions and 310 three-component ground motion records (both recorded and scaled) for stable continental regions, empirical models for Arias intensity were developed (I_a, in m/s). The model is applicable for either shallow crustal earthquakes in active plate margins (i.e. WUS) or shallow stable continental regions (i.e. CEUS) for earthquakes between M5.0 and M7.6 and distances up to 200 km (up to 100 km for M5-6 earthquakes). The model is not applicable to subduction zone earthquakes.

6.2.3 Attenuation Relationship

The Arias intensity is a function of:

- **M** – Moment magnitude
- G – Region: 1 for WUS, 0 for CEUS
- R_{rup} – Closest distance to rupture plane (km)
- S – Site category: 0 for rock, 1 for soil

$$\ln I_a = c_1 + c_2(M-6) + c_3(M-6)^2 + c_4 \ln(M/6) + c_5 \ln\sqrt{{R_{rup}}^2 + h^2} + S[s_1 + s_2(M-6)]$$

Standard Error

$$\sigma_{tot} = \sqrt{\sigma^2 + \tau^2}$$

Coefficients

Table 6-4. Regression coefficients and errors.

CEUS

c_1	c_2	c_3	c_4	c_5	h	s_1	s_2	τ	σ	σ_{tot}
3.22	-107.59	7.91	651.14	-1.28	6.06	0.56	-0.45	0.67	0.89	1.11

WUS

c_1	c_2	c_3	c_4	c_5	h	s_1	s_2	τ	σ	σ_{tot}
3.10	-1.11	0.00	15.13	-1.65	7.24	0.51	-0.095	0.68	0.84	1.08

6.2.4 *Calibration Plots*

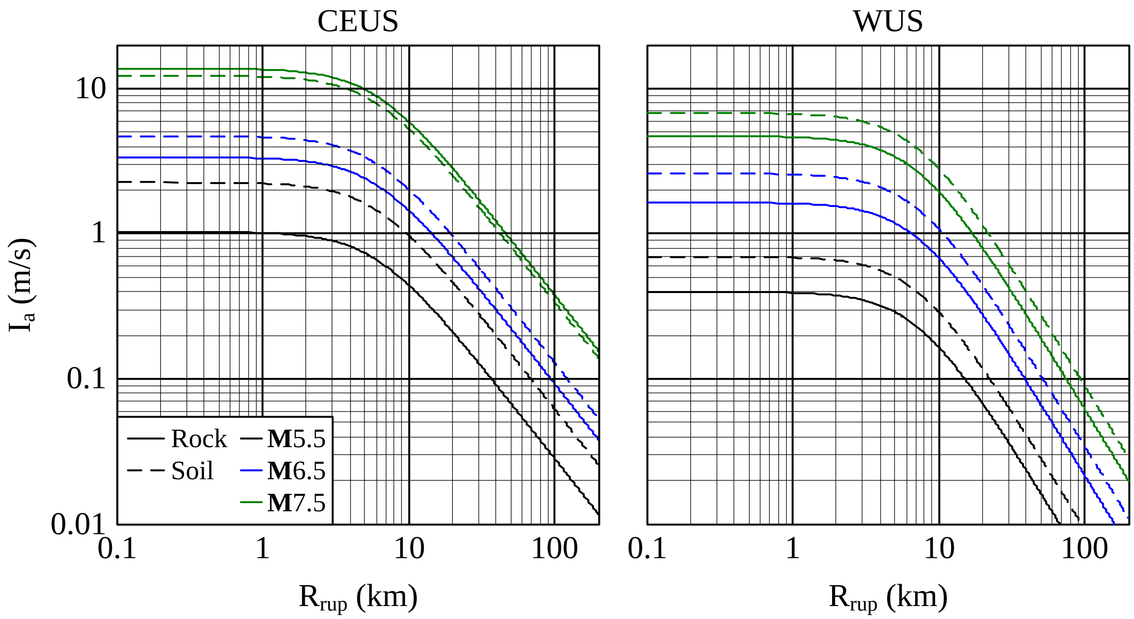


Figure 6-5. Arias Intensity as a function of distance for given parameters.

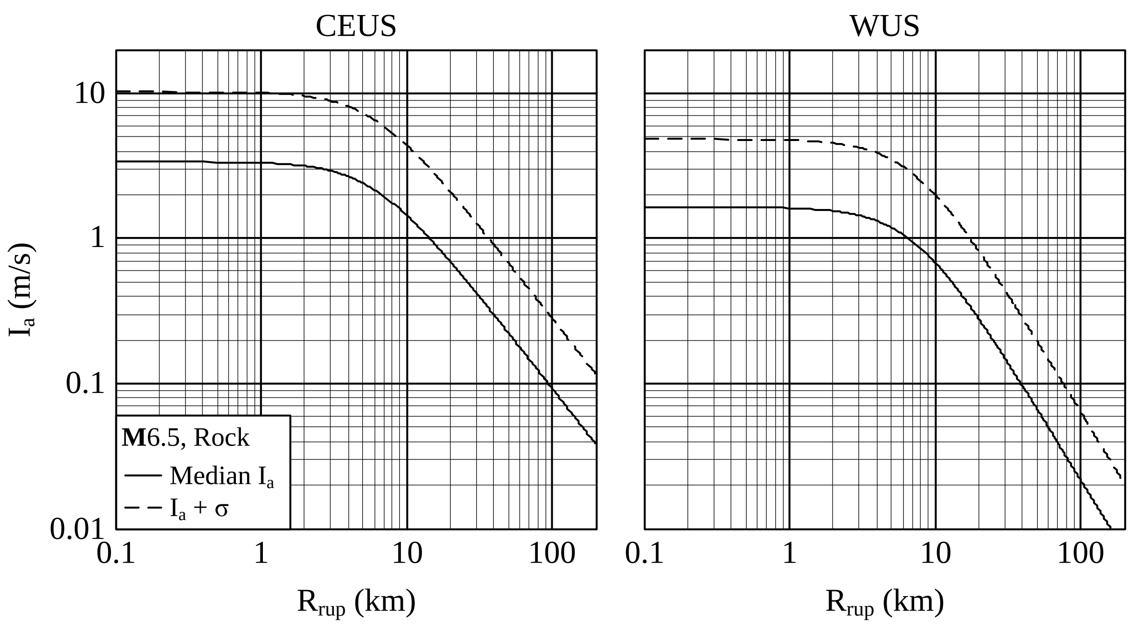


Figure 6-6. Example of application of arias intensity plus one standard deviation.

6.2.5 Database

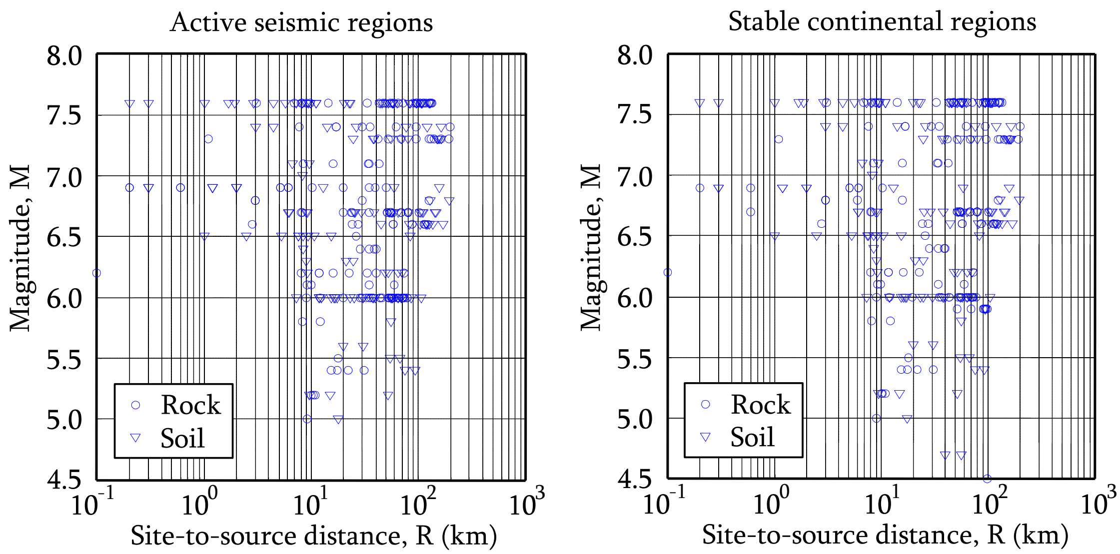


Figure 6-7. Earthquake magnitude and site-to-source distance distributions of the strong ground motion data set.

6.2.6 MATLAB Code

```
% by Kathryn A. Gunberg 8/4/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Lee and Green Arias intensity equation, 2009
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% M     = Moment Magnitude
% G     = Region: 1 for WUS, 0 for CEUS
% Rrup  = Closest distance to rupture plane (km)
% S     = Soil category: 0 for rock, 1 for soil
% -------------------------------------------------------------------------
% Output
% Ia    = Arias Intensity (sec)
% sigma = logarithmic standard deviation of Ia prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Ia, sigma] = LG_2009_Ia(M, G, Rrup, S)
if G == 0
    c1   = 3.22;
    c2   = -107.59;
    c3   = 7.91;
    c4   = 651.14;
    c5   = -1.28;
    h    = 6.06;
    s1   = 0.56;
    s2   = -0.45;
    tau  = 0.67;
    sig  = 0.89;
    sigt = 1.11;
else
    c1   = 3.10;
    c2   = -1.11;
    c3   = 0.00;
    c4   = 15.13;
    c5   = -1.65;
    h    = 7.24;
    s1   = 0.51;
    s2   = -0.095;
    tau  = 0.68;
    sig  = 0.84;
    sigt = 1.08;
end
Ia = exp(c1 + c2*(M-6) + c3*(M-6)^2 + c4*log(M/6) + c5*log(sqrt(Rrup^2 + h^2)) + ...
         S*(s1 + s2*(M-6)));
sigma = sigt;
```

6.3 Characteristic Period: Rathje, Faraj, Russell and Bray – 2004

6.3.1 Reference

Rathje, E. M., F. Faraj, S. Russell, and J. D. Bray (2004). Empirical Relationships for Frequency Content Parameters of Earthquake Ground Motions, *Earthquake Spectra* **20**(1), 119-144.

Rathje, E. M. (2009). University of Texas – Austin, Austin, TX. Written communication.

6.3.2 Abstract

Using 1208 ground-motion records from 71 earthquakes, an empirical ground-motion model for frequency content parameters was developed. The model predicts the mean period (T_m, in sec), the average spectral period (T_{avg}, in sec) and the smoothed spectral predominant period (T_o, in sec). The model is applicable for shallow crustal earthquakes in active plate margins, earthquakes between M4.7 and M7.6 (with a minimum of M5.0 for T_m) and distances up to 250 km. The model is not applicable to subduction and intraplate earthquakes.

6.3.3 Attenuation Relationship

The spectral period is a function of:

- SP – Period type: 1 for mean (T_m), 2 for average (T_{avg}), 3 for smoothed predominant (T_o)
- **M** – Moment magnitude
- R_{rup} – Closest distance to rupture plane (km)
- FD – Forward Directivity: 1 if M ≥ 6, R_{rup} ≤ 20 km, azimuth ≤ 30°, and rupture length ratio ≥ 0.5, 0 otherwise
- S – Site category: 0 for B, 1 for C and 2 for D (see Table 6-5)

$$\ln(T) = c_1 + c_2(M-6) + c_3 R_{rup} + c_4 S_C + c_5 S_D + c_6\left(1 - R_{rup}/20\right)FD$$

where:

$$S_C = \begin{cases} 1 & for\ site\ category\ C \\ 0 & otherwise \end{cases} \qquad S_D = \begin{cases} 1 & for\ site\ category\ D \\ 0 & otherwise \end{cases}$$

Standard Error

$$\sigma_{tot} = \sqrt{\sigma(S)^2 + \tau^2}$$

Table 6-5. Description of site categories.

Site Category	Description
B	Rock, most 'unweathered' California rock cases ($V_S \geq 760$ m/s or < 6 m of soil)
C	Weathered soft rock and shallow stiff soil (< 60 m of soil)
D	Deep stiff Holocene or Pleistocene soil (> 60 m of soil and no 'soft' soils)

Coefficients

Table 6-6. Coefficients for model.

Coeff.	T_m	T_{avg}	T_o
c_1	-1.00	-0.89	-1.78
c_2	0.18	0.29	0.30
c_3	0.0038	0.003	0.0045
c_4	0.078	0.07	0.15
c_5	0.27	0.25	0.33
c_6	0.40	0.37	0.24

Table 6-7. Coefficients for standard deviation.

	T_m	T_{avg}	T_o
σ_B	0.42	0.38	0.38
σ_C	0.38	0.36	0.33
σ_D	0.31	0.29	0.31
τ	0.17	0.13	0.22

6.3.4 Calibration Plots

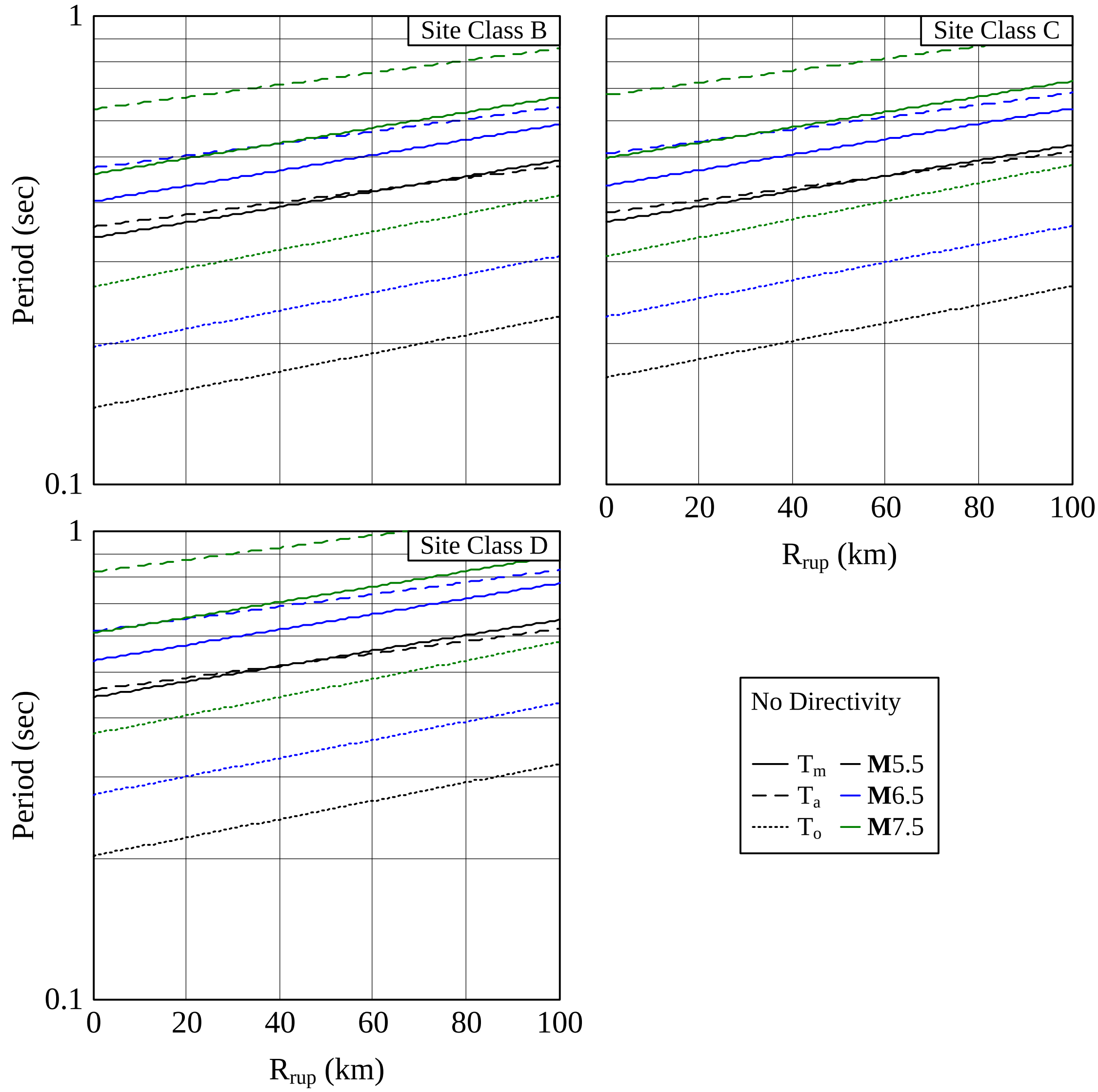


Figure 6-8. Period as a function of distance for given conditions.

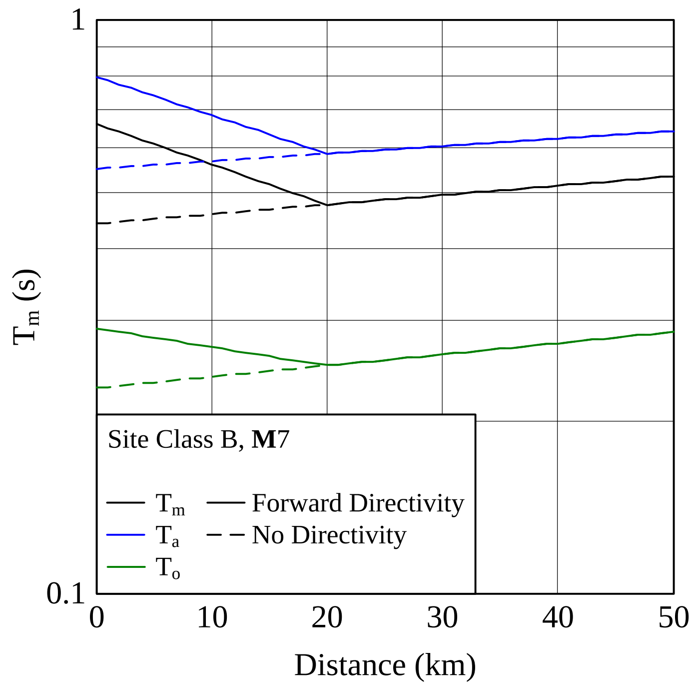


Figure 6-9. Effects of directivity for conditions shown.

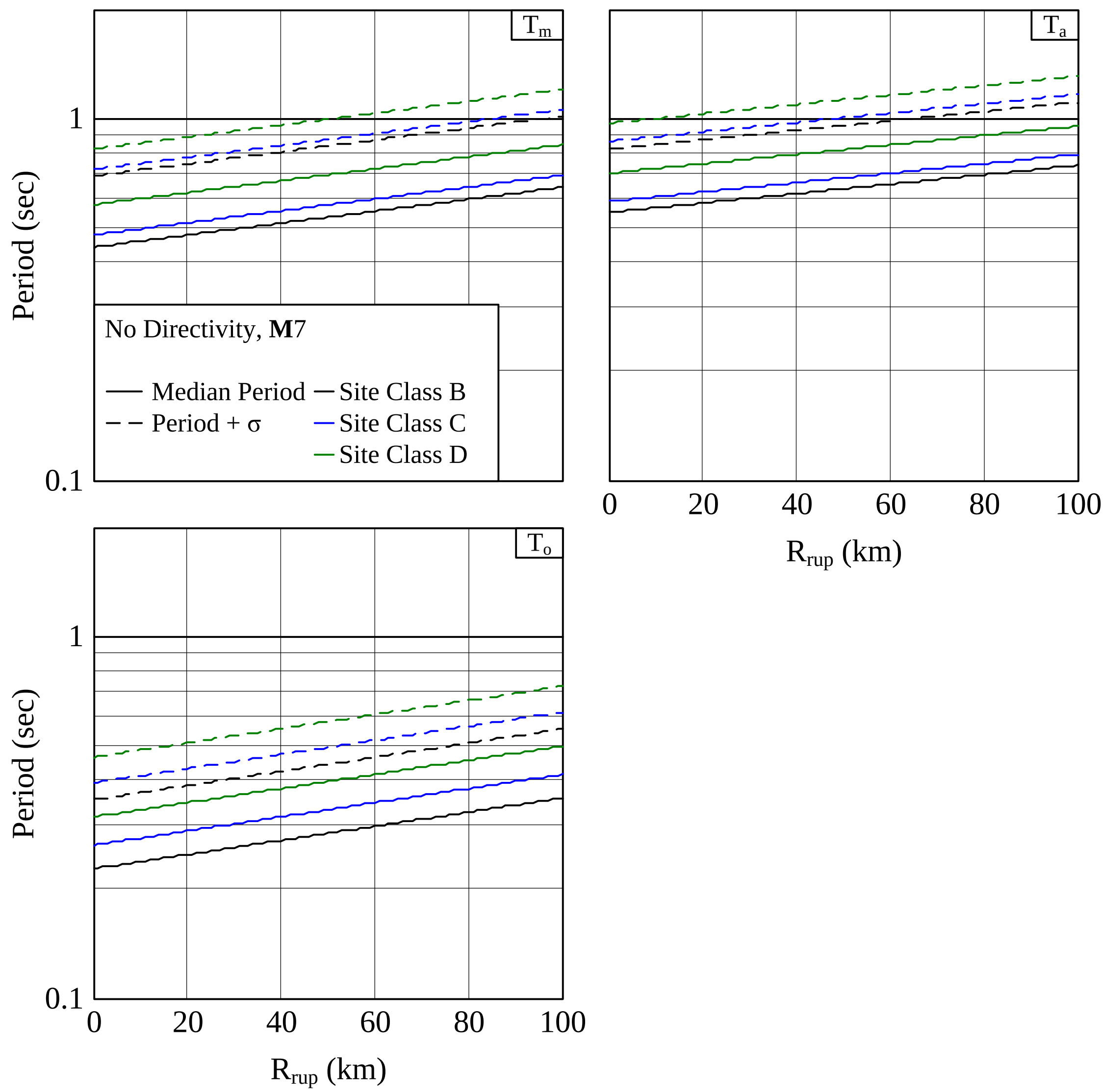
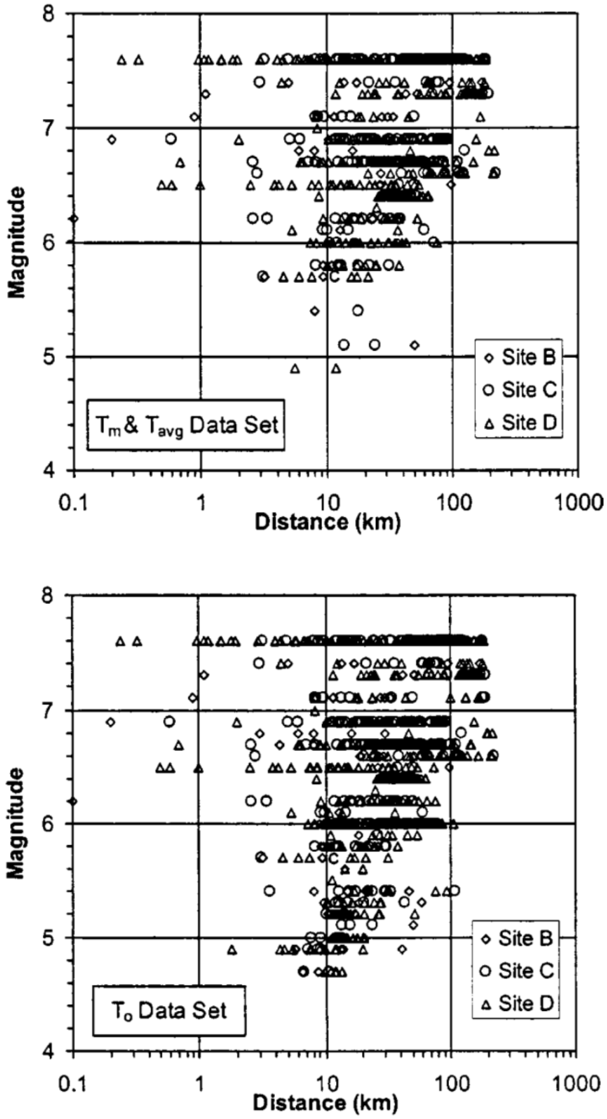


Figure 6-10. Example of application of median period plus one standard deviation.

6.3.5 Database



(a)

(b)

Figure 6-11. Distributino of data for (a) T_m and T_{avg} data set and (b) T_o data set.

6.3.6 MATLAB Code

```
% by Kathryn A. Gunberg 6/30/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Rathje, Faraj, Russell and Bray attenuation equation, 2004
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% SP             = Spectral period output type, 1 for mean, 2 for average, 3
%                  for smoothed predominant
% M              = Moment Magnitude
% Rrup           = Closest distance to rupture plane (km)
% FD             = Forward Directivity: 1 if M ? 6, Rrup ? 20 km, azimuth ?
%                  30°, and rupture length ratio ? 0.5, 0 otherwise
% S              = Soil category: 0 for B, 1 for C, 2 for D
% --------------------------------------------------------------------------
% Output
% T              = Mean period, average spectral period or smoothed spectral
%                  predominant period
% sigma          = logarithmic standard deviation of spectral period
%                  prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [T, sigma] = RFRB_2004(SP, M, Rrup, FD, S)
if SP == 1
    M = min(M,7.25);
end
SC = 0;
SD = 0;
sig = [0.42 0.38    0.38];
if S == 1
    SC = 1;
    sig  = [0.38    0.36    0.33];
elseif S == 2
    SD = 1;
    sig  = [0.31    0.29    0.31];
end
c1   = [-1.00   -0.89   -1.78];
c2   = [0.18    0.29    0.30];
c3   = [0.0038  0.0030  0.0045];
c4   = [0.078   0.07    0.15];
c5   = [0.27    0.25    0.33];
c6   = [0.40    0.37    0.24];
tau  = [0.17    0.13    0.22];
T = exp(c1(SP) + c2(SP)*(M-6) + c3(SP)*Rrup + c4(SP)*SC + c5(SP)*SD + c6(SP)*(1-Rrup/20)*FD);
sigma = sqrt(sig(SP)^2 + tau(SP)^2);
end
```

6.4 Characteristic Period: Lee and Green – 2009

6.4.1 References

Lee, Jongwon (2009). Engineering Characterization of Earthquake Ground Motions, PhD dissertation, University of Michigan.

Lee, J. and Green, R.A. (2011). Predictive Equations for the Predominant Period of Earthquake Ground Motions, *in preparation*.

6.4.2 Abstract

Using 324 three-component ground motion records from active seismic regions and 310 three-component ground motion records (both recorded and scaled) for stable continental regions, empirical models for frequency content parameters were developed. The model predicts the predominant spectral period (T_p, in sec), the smoothed spectral predominant period (T_o, in sec), the average spectral period (T_{avg}, in sec), mean period (T_m, in sec), and the spectral velocity-acceleration ratio periods ($T_{V/A50}$ and $T_{V/A84}$, in sec). The model is applicable for either shallow crustal earthquakes in active plate margins (i.e. WUS) or shallow stable continental regions (i.e. CEUS) for earthquakes between M5.0 and M7.6 and distances up to 200 km (up to 100 km for M5-6 earthquakes). The model is not applicable to subduction zone earthquakes.

6.4.3 Attenuation Relationship

The spectral period is a function of:

T	– Period type: 1 for T_p, 2 for T_0, 3 for T_{avg}, 4 for T_m, 5 for $T_{V/A50}$, 6 for $T_{V/A84}$
M	– Moment magnitude
G	– Region: 1 for WUS, 0 for CEUS
R_{rup}	– Closest distance to rupture plane (km)
FD	– Forward Directivity: 1 to include, 0 otherwise
S	– Site category: 0 for rock, 1 for soil

$$\ln(T) = c_1 + c_2(M-6) + c_3 R_{rup} + S\left[s_1 + s_2(M-6) + s_3 R_{rup}\right] + c_4 FD \ln\left(\frac{\min\left(R_{rup}, R_c\right)}{R_c}\right)$$

where:

$$R_c = \begin{cases} 20\ km & for\ WUS \\ 25\ km & for\ CEUS \end{cases}$$

Standard Error

$$\sigma_{tot} = \sqrt{\sigma^2 + \tau^2}$$

Coefficients

Table 6-8. Regression coefficients and errors.

CEUS										
T	c_1	c_2	c_3	c_4	s_1	s_2	s_3	τ	σ	σ_{tot}
T_p	-2.95	-0.110	0.0012	-0.016	1.13	0.660	-0.00051	0.09	0.63	0.64
T_0	-2.59	0.043	0.0020	-0.005	0.85	0.460	-0.00270	0.18	0.33	0.38
T_{avg}	-1.37	0.470	0.0034	-0.130	0.32	0.074	-0.00290	0.22	0.36	0.42
T_m	-1.65	0.330	0.0026	-0.140	0.42	0.160	-0.00250	0.25	0.36	0.44
$T_{V/A50}$	-2.20	0.240	0.0062	-0.110	0.71	0.300	-0.00430	0.24	0.42	0.48
$T_{V/A84}$	-1.99	0.250	0.0055	-0.100	0.57	0.290	-0.00370	0.24	0.42	0.48

WUS										
T	c_1	c_2	c_3	c_4	s_1	s_2	s_3	τ	σ	σ_{tot}
T_p	-1.67	0.18	0.0032	-0.110	-0.022	0.220	0.00082	0.23	0.51	0.56
T_0	-1.67	0.22	0.0047	-0.097	0.140	0.170	-0.00120	0.20	0.36	0.41
T_{avg}	-1.03	0.40	0.0034	-0.110	0.230	0.091	-0.00210	0.19	0.32	0.37
T_m	-1.17	0.27	0.0037	-0.120	0.240	0.120	-0.00160	0.22	0.34	0.40
$T_{V/A50}$	-1.50	0.30	0.0040	-0.150	0.230	0.130	-0.00038	0.20	0.43	0.47
$T_{V/A84}$	-1.43	0.37	0.0042	-0.150	0.250	0.090	-0.00065	0.20	0.43	0.47

6.4.4 Calibration Plots

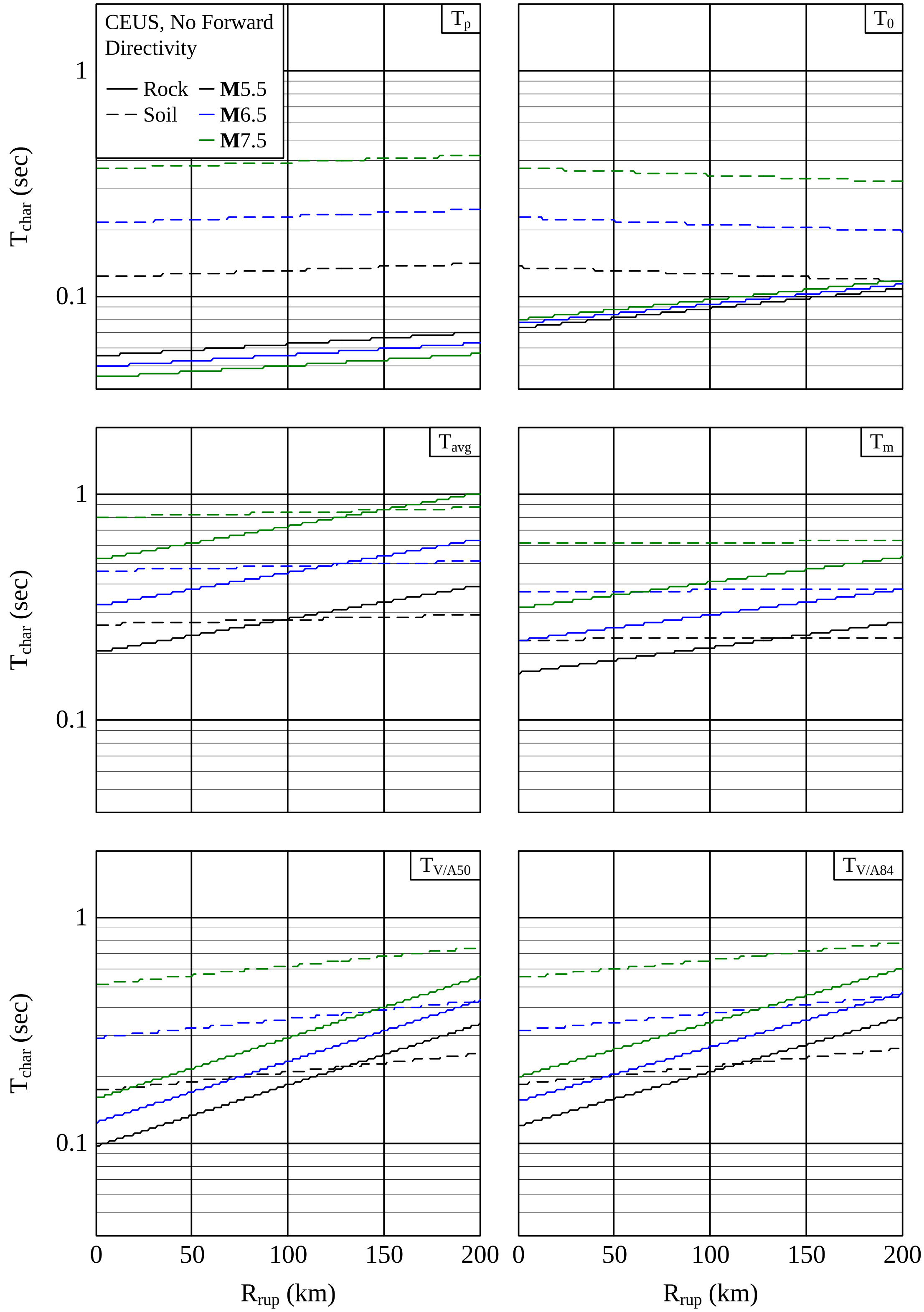


Figure 6-12. Characteristic period versus distance for given conditions.

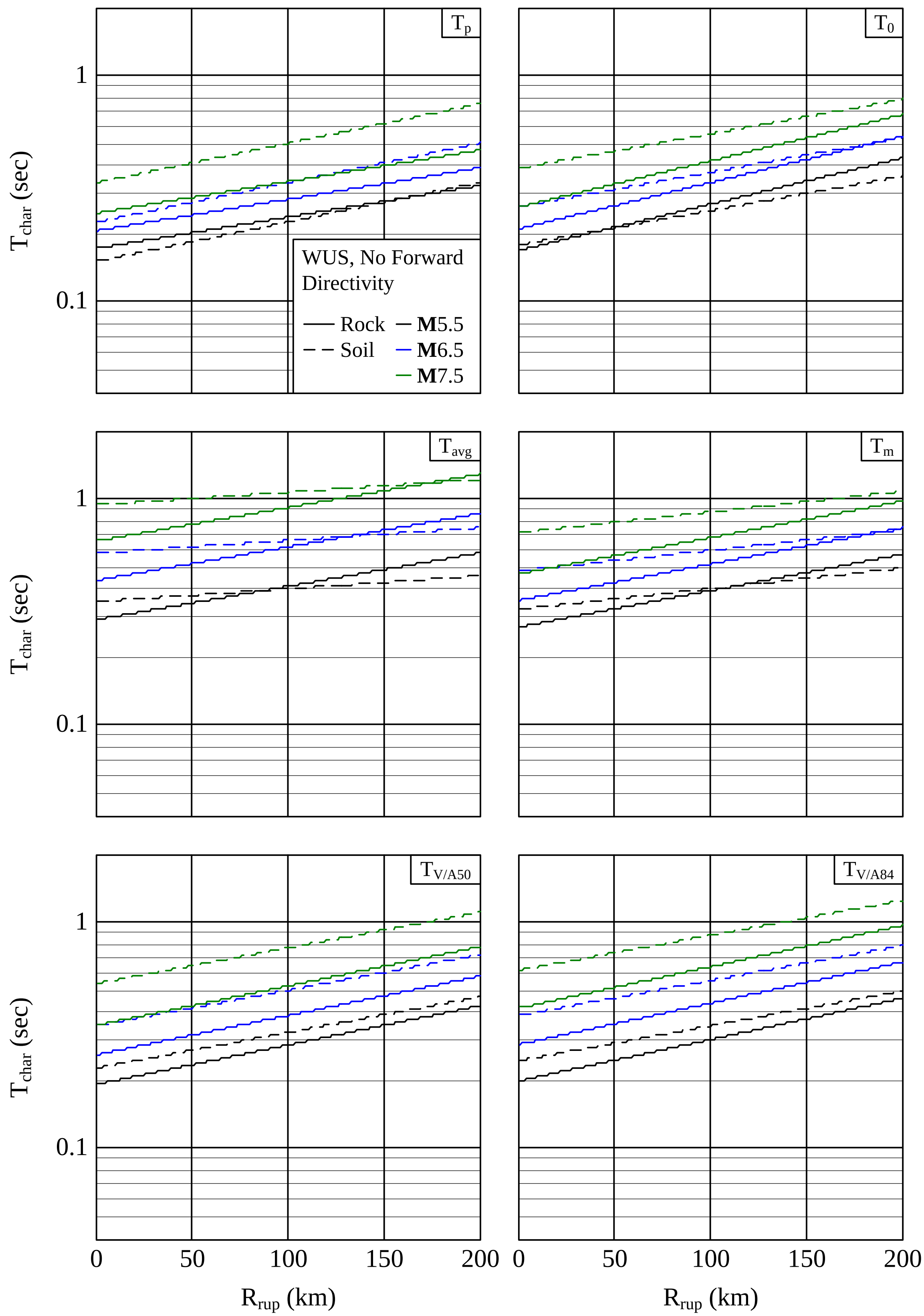


Figure 6-13. Characteristic period versus distance for given conditions.

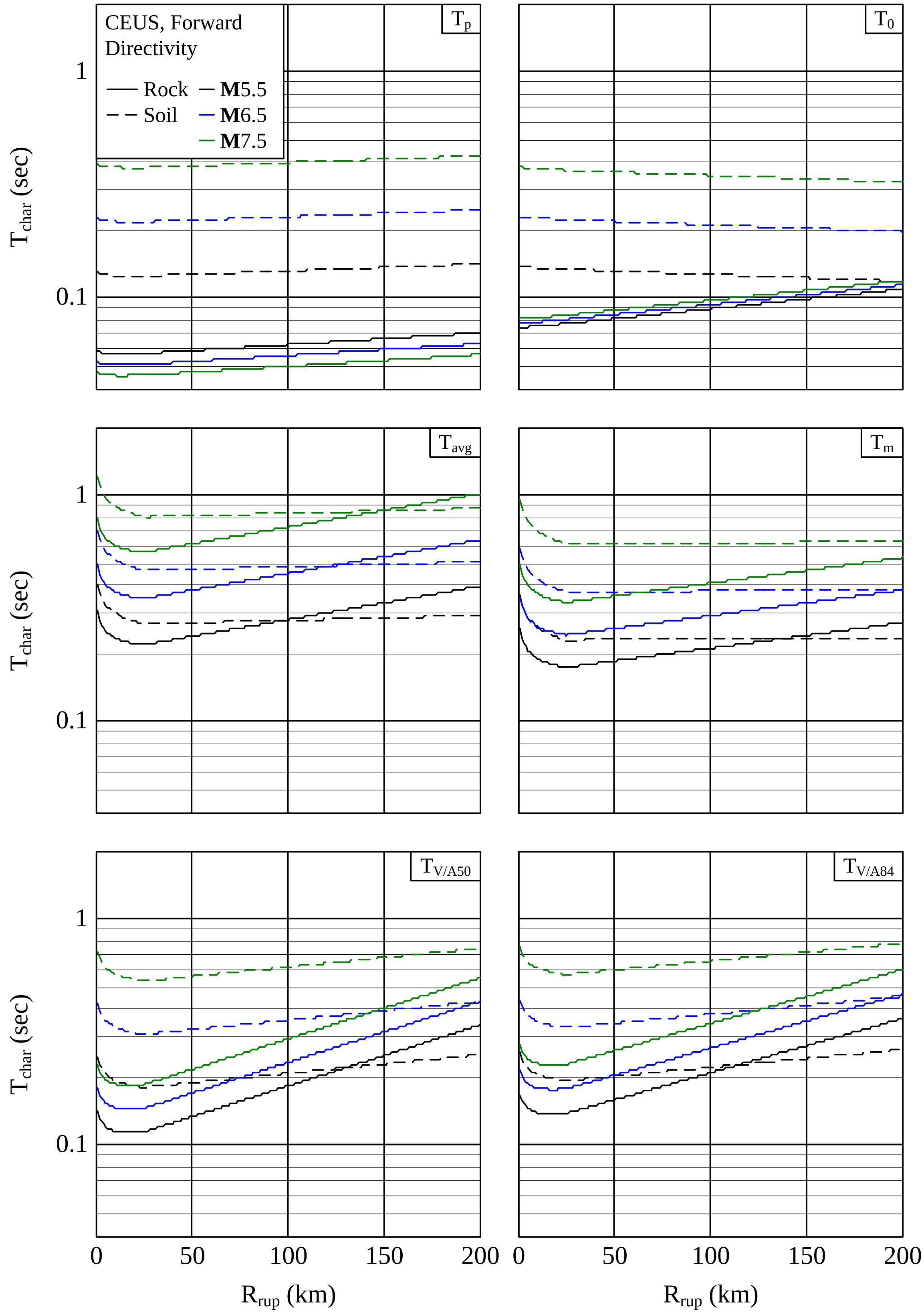


Figure 6-14. Characteristic period versus distance for given conditions.

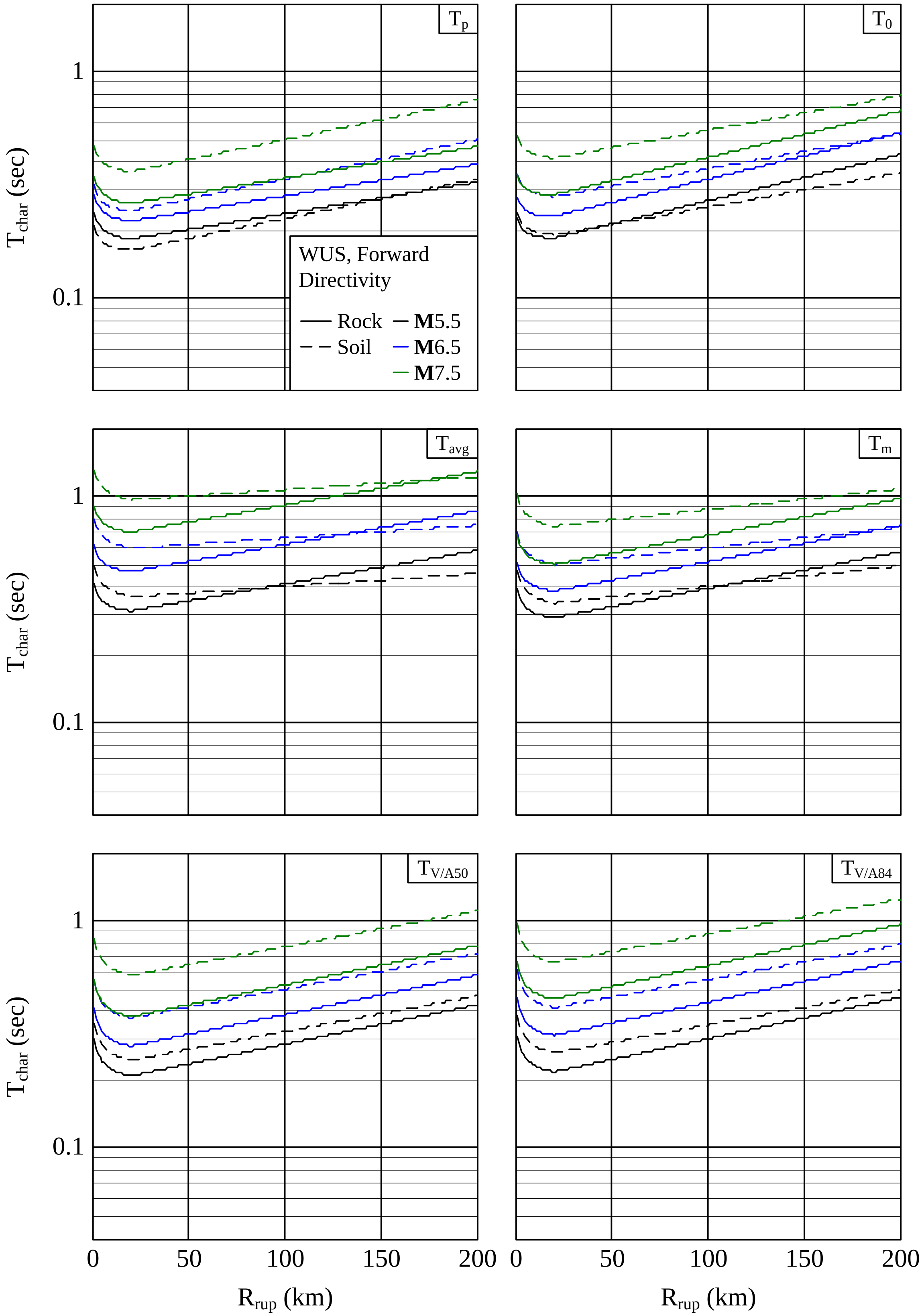


Figure 6-15. Characteristic period versus distance for given conditions.

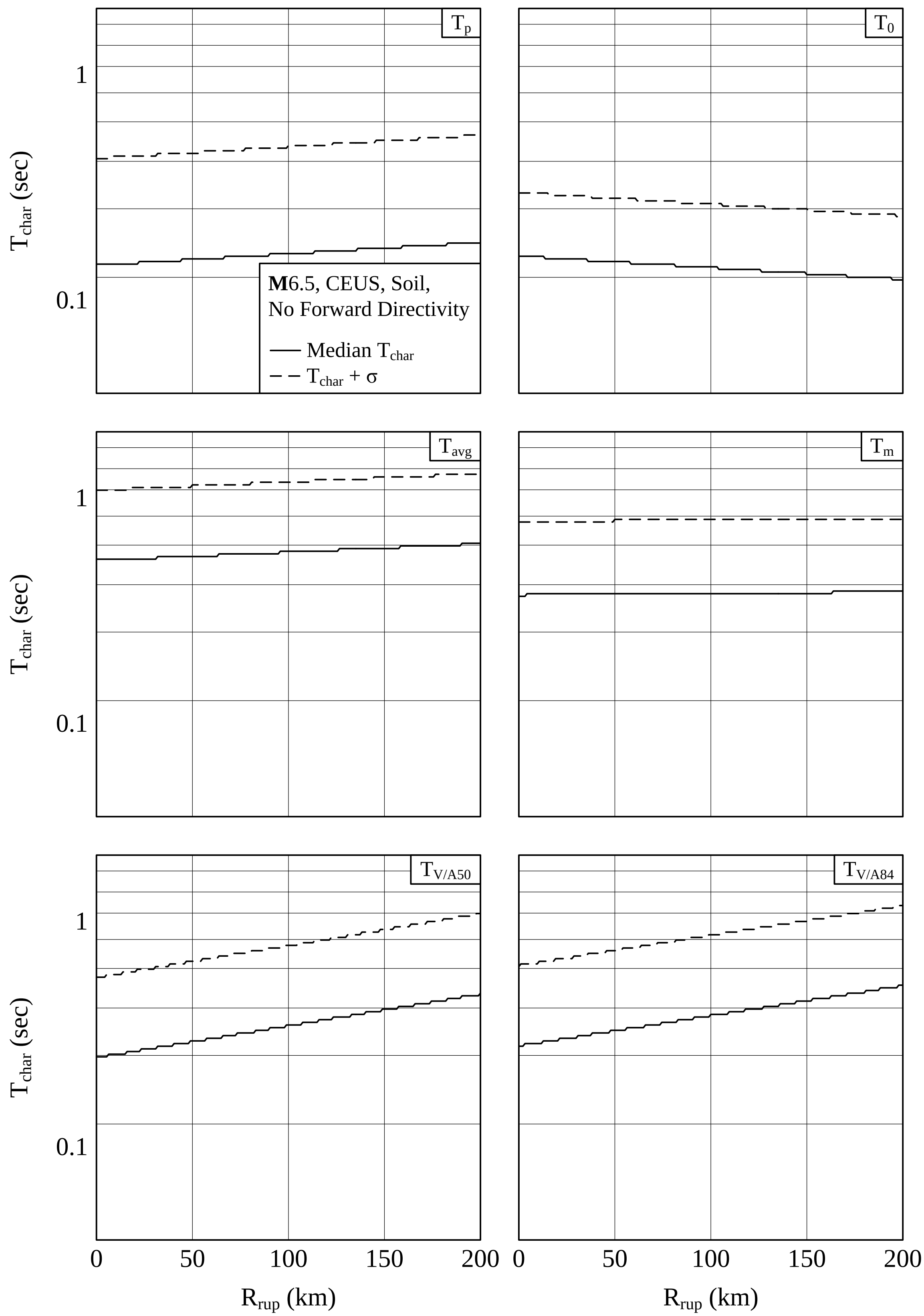


Figure 6-16. Example of application of median characteristic period plus one standard deviation.

6.4.5 Database

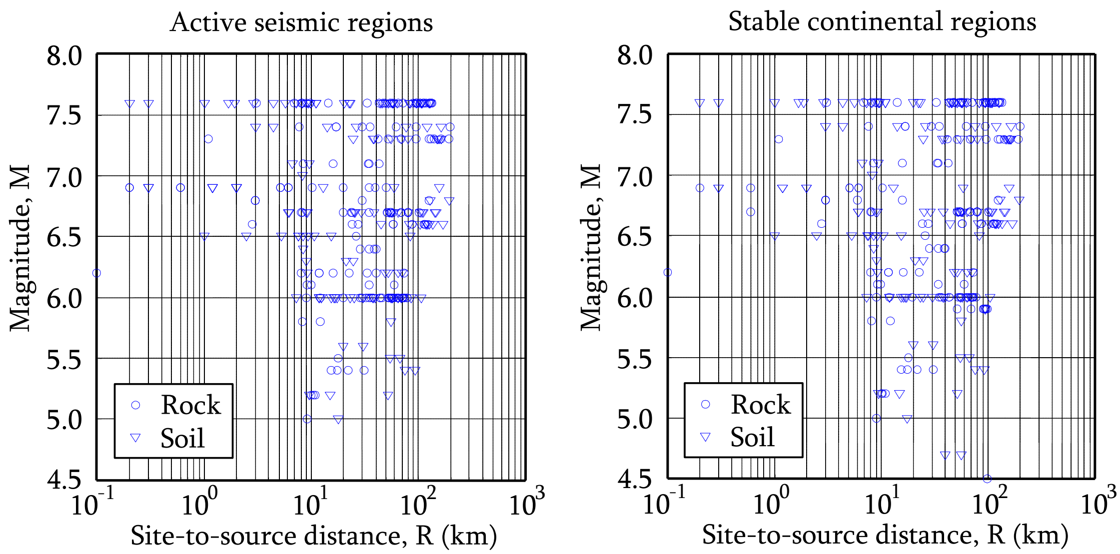


Figure 6-17. Earthquake magnitude and site-to-source distance distributions of the strong ground motion data set.

6.4.6 MATLAB Code

```
% by Kathryn A. Gunberg 6/30/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Lee and Green characteristic period equation, 2009
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T     = Spectral period: 1 for Tp, 2 for T0, 3 for Tavg, 4 for Tm, 5 for
%         Ta/v50, 6 for Ta/v84
% M     = Moment Magnitude
% G     = Region: 1 for WUS, 0 for CEUS
% Rrup  = Closest distance to rupture plane (km)
% FD    = Forward Directivity: 1 for forward directivity, 0 otherwise
% S     = Soil category: 0 for rock, 1 for soil
% --------------------------------------------------------------------------
% Output
% Tchar = Characteristic period
% sigma = logarithmic standard deviation of spectral period prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Tchar, sigma] = LG_2009_Tchar(T, M, G, Rrup, FD, S)
if G == 0
    Rc   = 25;
    c1   = [-2.95   -2.59   -1.37   -1.65   -2.20   -1.99];
    c2   = [-0.110  0.043   0.470   0.330   0.240   0.250];
    c3   = [0.0012  0.0020  0.0034  0.0026  0.0062  0.0055];
    c4   = [-0.016  -0.005  -0.130  -0.140  -0.110  -0.100];
    s1   = [1.13    0.85    0.32    0.42    0.71    0.57];
    s2   = [0.660   0.460   0.074   0.160   0.300   0.290];
    s3   = [-0.00051 -0.00270 -0.00290 -0.00250 -0.00430 -0.00370];
    tau  = [0.09    0.18    0.22    0.25    0.24    0.24];
    sig  = [0.63    0.33    0.36    0.36    0.42    0.42];
    sigt = [0.64    0.38    0.42    0.44    0.48    0.48];
else
    Rc   = 20;
    c1   = [-1.67   -1.67   -1.03   -1.17   -1.50   -1.43];
    c2   = [0.18    0.22    0.40    0.27    0.30    0.37];
    c3   = [0.0032  0.0047  0.0034  0.0037  0.0040  0.0042];
    c4   = [-0.110  -0.097  -0.110  -0.120  -0.150  -0.150];
    s1   = [-0.022  0.140   0.230   0.240   0.230   0.250];
    s2   = [0.220   0.170   0.091   0.120   0.130   0.090];
    s3   = [0.00082 -0.00120 -0.00210 -0.00160 -0.00038 -0.00065];
    tau  = [0.23    0.20    0.19    0.22    0.20    0.20];
    sig  = [0.51    0.36    0.32    0.34    0.43    0.43];
    sigt = [0.56    0.41    0.37    0.40    0.47    0.47];
end
if Rrup > Rc
    FD = 0;
end
Tchar = exp(c1(T) + c2(T)*(M-6) + c3(T)*Rrup + FD*c4(T)*log(Rrup/Rc) + ...
         S*(s1(T) + s2(T)*(M-6) + s3(T)*Rrup));
sigma = sigt(T);
```

6.5 Damping Correction Factors: Cameron and Green – 2007

6.5.1 References

Cameron, W. I., and R. A. Green (2007). Damping Correction Factors for Horizontal Ground-Motion Response Spectra, *Bulletin of the Seismological Society of America* **97**(3), 934-960.

6.5.2 Abstract

Using 648 pairs of horizontal ground motion records from active seismic regions and 628 pairs of horizontal ground motion records (28 recorded and 592 scaled) for stable continental regions, an empirical model for damping correction factors (DCFs) was developed. The DCFs presented here are used to adjust response spectral values corresponding to damping 5% of critical to other damping levels (specifically: 2, 7, 10, 15, 20, 30, 40, and 50%). DCFs are provided for either shallow crustal earthquakes in active plate margins (i.e. WUS) or shallow stable continental regions (i.e. CEUS). DCFs are further divided into "rock" sites (i.e., V_{S30} > 360 m/s: NEHRP site classes A, B, and C) and "deep soil" sites (i.e., V_{S30} < 360 m/s: NEHRP site classes D and E). The DCFs are applicicable for earthquakes between M5.0 and M7.6 and distances up to 200 km (up to 100 km for M5-6 earthquakes). The model is not applicable to subduction zone earthquakes. Note that there are no calibration plots for this model; the model can be verified with the tables. A MS Excel spreadsheet is provided.

6.5.3 Damping Correction Factors

The DCFs are a function of:

T – Period
M – Moment magnitude
G – Region: 1 for WUS, 0 for CEUS
R_{rup} – Closest distance to rupture plane (km)
S – Site category: 0 for rock, 1 for deep soil
ξ – % Damping Required (1, 2, 7, 10 15, 20, 30, 40, or 50%)

See tables below for DCF values. (Note: for border line cases, M6 for example, use both sets of DCF and take a bound of the resulting spectra.)

Table 6-9. Median and Standard Deviation of the Natural Log of the Damping Correction Factors for $\xi \geq 2\%$ WUS Rock Motions.

T	$\xi = 2\%$		$\xi = 7\%$		$\xi = 10\%$		$\xi = 15\%$		$\xi = 20\%$		$\xi = 30\%$		$\xi = 40\%$		$\xi = 50\%$	
(sec)	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$
M 5-6																
0.05	1.111	0.122	0.961	0.053	0.919	0.110	0.876	0.162	0.848	0.196	0.808	0.240	0.778	0.266	0.754	0.286
0.1	1.223	0.131	0.921	0.054	0.838	0.111	0.748	0.170	0.691	0.207	0.613	0.266	0.560	0.307	0.519	0.339
0.2	1.280	0.118	0.889	0.052	0.776	0.110	0.649	0.175	0.563	0.219	0.457	0.279	0.391	0.313	0.342	0.339
0.3	1.302	0.100	0.884	0.042	0.767	0.085	0.641	0.126	0.558	0.148	0.448	0.179	0.378	0.206	0.328	0.223
0.5	1.232	0.100	0.907	0.044	0.807	0.089	0.692	0.142	0.611	0.179	0.500	0.232	0.429	0.264	0.377	0.288
0.8	1.248	0.128	0.906	0.055	0.805	0.116	0.697	0.181	0.624	0.222	0.521	0.282	0.451	0.329	0.399	0.365
1	1.230	0.133	0.915	0.055	0.825	0.117	0.724	0.180	0.652	0.227	0.555	0.284	0.487	0.328	0.437	0.361
1.3	1.163	0.119	0.934	0.051	0.860	0.105	0.775	0.163	0.715	0.205	0.626	0.264	0.559	0.310	0.507	0.348
1.5	1.189	0.132	0.935	0.054	0.865	0.111	0.781	0.182	0.722	0.230	0.643	0.290	0.585	0.331	0.539	0.366
2	1.121	0.116	0.945	0.054	0.883	0.114	0.810	0.185	0.757	0.235	0.684	0.305	0.635	0.347	0.594	0.382
3	1.114	0.114	0.954	0.056	0.909	0.113	0.852	0.185	0.808	0.239	0.747	0.305	0.701	0.355	0.664	0.396
4	1.073	0.091	0.960	0.050	0.915	0.111	0.856	0.194	0.816	0.249	0.760	0.328	0.720	0.383	0.688	0.426
5	1.059	0.085	0.968	0.048	0.931	0.102	0.883	0.174	0.845	0.232	0.791	0.315	0.751	0.372	0.722	0.414
7.5	1.022	0.048	0.989	0.022	0.975	0.051	0.953	0.096	0.935	0.135	0.903	0.196	0.876	0.242	0.852	0.279
10	1.010	0.027	0.995	0.013	0.987	0.030	0.974	0.057	0.962	0.083	0.941	0.126	0.922	0.161	0.906	0.190
M 6-7																
0.05	1.060	0.078	0.981	0.031	0.961	0.065	0.938	0.098	0.922	0.116	0.898	0.140	0.879	0.160	0.863	0.176
0.1	1.220	0.123	0.934	0.048	0.871	0.096	0.806	0.147	0.762	0.180	0.701	0.230	0.654	0.269	0.617	0.298
0.2	1.328	0.125	0.886	0.050	0.778	0.102	0.662	0.157	0.588	0.191	0.494	0.240	0.434	0.272	0.389	0.298
0.3	1.322	0.121	0.884	0.047	0.770	0.089	0.650	0.132	0.572	0.159	0.471	0.196	0.406	0.219	0.359	0.235
0.5	1.289	0.111	0.894	0.052	0.783	0.103	0.664	0.145	0.583	0.173	0.472	0.211	0.398	0.237	0.346	0.254
0.8	1.253	0.125	0.901	0.054	0.793	0.110	0.675	0.160	0.592	0.192	0.480	0.234	0.406	0.264	0.353	0.287
1	1.268	0.116	0.896	0.054	0.786	0.109	0.665	0.164	0.584	0.197	0.476	0.235	0.405	0.258	0.354	0.278
1.3	1.260	0.106	0.900	0.049	0.799	0.098	0.687	0.149	0.610	0.184	0.506	0.230	0.436	0.263	0.384	0.287
1.5	1.249	0.122	0.906	0.052	0.808	0.099	0.700	0.149	0.627	0.179	0.528	0.217	0.460	0.247	0.408	0.272
2	1.195	0.120	0.921	0.054	0.835	0.111	0.739	0.173	0.671	0.217	0.572	0.280	0.505	0.320	0.455	0.349
3	1.174	0.104	0.927	0.050	0.843	0.107	0.744	0.181	0.675	0.233	0.579	0.306	0.516	0.351	0.469	0.386
4	1.171	0.107	0.924	0.056	0.841	0.118	0.749	0.190	0.685	0.245	0.595	0.325	0.535	0.377	0.490	0.417
5	1.118	0.094	0.943	0.047	0.877	0.097	0.797	0.158	0.734	0.210	0.648	0.289	0.590	0.347	0.545	0.392
7.5	1.074	0.078	0.965	0.040	0.921	0.089	0.863	0.153	0.815	0.204	0.742	0.278	0.690	0.335	0.650	0.376
10	1.045	0.062	0.977	0.033	0.946	0.074	0.906	0.125	0.874	0.166	0.823	0.227	0.780	0.275	0.743	0.315
M 7+																
0.05	1.071	0.098	0.977	0.037	0.953	0.075	0.928	0.109	0.911	0.128	0.886	0.156	0.869	0.173	0.854	0.189
0.1	1.236	0.147	0.934	0.057	0.871	0.114	0.811	0.170	0.773	0.204	0.718	0.257	0.677	0.297	0.646	0.327
0.2	1.309	0.134	0.900	0.059	0.803	0.114	0.706	0.173	0.643	0.213	0.558	0.269	0.500	0.313	0.458	0.349
0.3	1.325	0.113	0.888	0.053	0.780	0.103	0.665	0.161	0.588	0.199	0.494	0.244	0.433	0.276	0.390	0.303
0.5	1.349	0.131	0.883	0.048	0.774	0.092	0.660	0.141	0.589	0.172	0.494	0.217	0.430	0.245	0.385	0.264
0.8	1.328	0.120	0.883	0.051	0.766	0.100	0.649	0.149	0.570	0.184	0.468	0.231	0.401	0.262	0.354	0.284
1	1.260	0.108	0.900	0.047	0.793	0.098	0.676	0.149	0.597	0.181	0.492	0.224	0.423	0.250	0.374	0.269
1.3	1.280	0.126	0.892	0.050	0.777	0.099	0.657	0.144	0.580	0.175	0.480	0.212	0.416	0.236	0.369	0.255
1.5	1.273	0.113	0.900	0.044	0.792	0.089	0.672	0.138	0.594	0.169	0.494	0.209	0.428	0.240	0.379	0.260
2	1.255	0.124	0.901	0.051	0.798	0.099	0.686	0.148	0.613	0.178	0.514	0.227	0.448	0.263	0.399	0.292
3	1.227	0.122	0.909	0.051	0.812	0.102	0.698	0.157	0.620	0.187	0.519	0.222	0.453	0.250	0.404	0.270
1	1.187	0.103	0.916	0.047	0.823	0.098	0.715	0.159	0.640	0.205	0.536	0.267	0.467	0.307	0.417	0.333
5	1.176	0.102	0.920	0.049	0.829	0.101	0.722	0.162	0.647	0.205	0.544	0.270	0.475	0.313	0.424	0.345
7.5	1.136	0.089	0.933	0.049	0.853	0.106	0.757	0.177	0.686	0.230	0.585	0.312	0.515	0.373	0.462	0.421
10	1.115	0.085	0.942	0.046	0.874	0.101	0.788	0.173	0.722	0.232	0.627	0.321	0.562	0.384	0.511	0.437

Table 6-10. Median and Standard Deviation of the Natural Log of the Damping Correction Factors for $\xi \geq 2\%$ WUS Deep Soil Motions.

T	$\xi = 2\%$		$\xi = 7\%$		$\xi = 10\%$		$\xi = 15\%$		$\xi = 20\%$		$\xi = 30\%$		$\xi = 40\%$		$\xi = 50\%$	
(sec)	Median	σ_{lnDCF}	Median	σ_{lnDCF}	Median	σ_{lnDCF}	Median	σ_{lnDCF}	Median	σ_{lnDCF}	Median	σ_{lnDCF}	Median	σ_{lnDCF}	Median	σ_{lnDCF}
M 5-6																
0.05	1.088	0.110	0.976	0.032	0.953	0.061	0.929	0.092	0.911	0.113	0.881	0.144	0.855	0.168	0.832	0.185
0.1	1.236	0.130	0.925	0.052	0.846	0.104	0.762	0.154	0.706	0.187	0.629	0.236	0.573	0.273	0.532	0.299
0.2	1.322	0.124	0.885	0.044	0.768	0.088	0.646	0.137	0.572	0.170	0.479	0.212	0.418	0.243	0.373	0.260
0.3	1.255	0.118	0.899	0.051	0.786	0.103	0.657	0.156	0.572	0.186	0.465	0.224	0.395	0.250	0.344	0.269
0.5	1.260	0.106	0.903	0.051	0.795	0.104	0.672	0.163	0.587	0.200	0.477	0.236	0.402	0.260	0.348	0.278
0.8	1.250	0.108	0.903	0.051	0.793	0.105	0.675	0.155	0.596	0.186	0.491	0.228	0.423	0.254	0.374	0.272
1	1.266	0.119	0.907	0.050	0.810	0.097	0.706	0.144	0.634	0.181	0.536	0.233	0.468	0.265	0.417	0.291
1.3	1.261	0.106	0.905	0.047	0.806	0.095	0.697	0.145	0.626	0.173	0.534	0.207	0.472	0.233	0.426	0.252
1.5	1.227	0.115	0.910	0.049	0.812	0.102	0.704	0.156	0.634	0.189	0.545	0.238	0.483	0.272	0.438	0.300
2	1.164	0.108	0.933	0.051	0.856	0.105	0.769	0.165	0.708	0.210	0.626	0.266	0.566	0.303	0.522	0.329
3	1.086	0.068	0.962	0.034	0.920	0.071	0.864	0.125	0.820	0.165	0.755	0.223	0.707	0.269	0.669	0.302
4	1.065	0.086	0.973	0.040	0.944	0.079	0.910	0.116	0.885	0.136	0.843	0.176	0.807	0.209	0.777	0.235
5	1.035	0.059	0.986	0.026	0.969	0.056	0.945	0.095	0.926	0.122	0.899	0.151	0.874	0.175	0.850	0.195
7.5	1.012	0.035	0.995	0.014	0.988	0.032	0.978	0.056	0.972	0.069	0.961	0.093	0.948	0.114	0.937	0.130
10	1.002	0.010	0.998	0.006	0.996	0.014	0.992	0.023	0.989	0.029	0.981	0.041	0.973	0.053	0.966	0.063
M 6-7																
0.05	1.061	0.089	0.982	0.029	0.964	0.059	0.947	0.088	0.935	0.108	0.918	0.131	0.905	0.147	0.893	0.159
0.1	1.206	0.131	0.938	0.056	0.876	0.114	0.812	0.173	0.770	0.211	0.714	0.266	0.674	0.307	0.643	0.339
0.2	1.302	0.132	0.893	0.052	0.786	0.101	0.674	0.151	0.603	0.193	0.516	0.251	0.461	0.290	0.422	0.320
0.3	1.309	0.123	0.889	0.049	0.776	0.096	0.659	0.151	0.583	0.187	0.487	0.232	0.424	0.266	0.379	0.290
0.5	1.311	0.123	0.890	0.053	0.775	0.103	0.652	0.159	0.569	0.197	0.462	0.244	0.393	0.272	0.344	0.292
0.8	1.300	0.122	0.887	0.050	0.770	0.098	0.645	0.149	0.564	0.176	0.462	0.207	0.395	0.225	0.346	0.236
1	1.281	0.127	0.896	0.055	0.787	0.112	0.670	0.166	0.590	0.200	0.481	0.246	0.411	0.269	0.362	0.281
1.3	1.266	0.114	0.896	0.047	0.789	0.094	0.670	0.143	0.591	0.170	0.485	0.201	0.416	0.221	0.367	0.236
1.5	1.256	0.115	0.901	0.047	0.798	0.099	0.683	0.152	0.605	0.183	0.500	0.222	0.431	0.245	0.380	0.266
2	1.211	0.104	0.912	0.048	0.815	0.102	0.705	0.161	0.630	0.198	0.526	0.248	0.456	0.282	0.404	0.309
3	1.190	0.102	0.920	0.048	0.831	0.101	0.731	0.162	0.661	0.204	0.564	0.262	0.497	0.301	0.446	0.335
4	1.167	0.114	0.928	0.051	0.847	0.106	0.753	0.164	0.685	0.205	0.593	0.267	0.531	0.311	0.483	0.349
5	1.143	0.095	0.936	0.045	0.866	0.096	0.781	0.165	0.719	0.215	0.632	0.283	0.569	0.333	0.522	0.372
7.5	1.082	0.077	0.961	0.041	0.914	0.090	0.851	0.157	0.802	0.205	0.728	0.272	0.675	0.321	0.633	0.359
10	1.049	0.062	0.974	0.034	0.942	0.074	0.899	0.125	0.865	0.167	0.807	0.232	0.764	0.278	0.728	0.313
M 7+																
0.05	1.040	0.065	0.989	0.021	0.977	0.044	0.964	0.068	0.955	0.085	0.943	0.101	0.934	0.110	0.926	0.117
0.1	1.167	0.117	0.956	0.047	0.914	0.097	0.872	0.143	0.846	0.168	0.810	0.203	0.785	0.223	0.764	0.240
0.2	1.299	0.127	0.908	0.052	0.819	0.102	0.730	0.153	0.672	0.184	0.601	0.226	0.558	0.258	0.525	0.283
0.3	1.322	0.123	0.897	0.050	0.800	0.094	0.701	0.139	0.635	0.169	0.551	0.203	0.498	0.226	0.458	0.246
0.5	1.326	0.114	0.891	0.052	0.782	0.101	0.673	0.148	0.602	0.178	0.506	0.211	0.442	0.227	0.395	0.241
0.8	1.342	0.117	0.884	0.051	0.769	0.100	0.645	0.149	0.563	0.182	0.457	0.219	0.388	0.242	0.340	0.258
1	1.311	0.121	0.888	0.048	0.769	0.095	0.640	0.141	0.556	0.168	0.448	0.199	0.381	0.217	0.333	0.231
1.3	1.286	0.108	0.887	0.043	0.770	0.089	0.643	0.141	0.559	0.173	0.453	0.213	0.385	0.234	0.338	0.250
1.5	1.294	0.115	0.893	0.046	0.782	0.093	0.659	0.141	0.576	0.171	0.471	0.204	0.402	0.227	0.353	0.245
2	1.266	0.111	0.897	0.049	0.791	0.098	0.677	0.145	0.597	0.177	0.492	0.222	0.422	0.251	0.372	0.269
3	1.270	0.114	0.903	0.051	0.803	0.100	0.693	0.150	0.616	0.184	0.515	0.234	0.445	0.266	0.393	0.290
4	1.216	0.103	0.910	0.045	0.811	0.093	0.700	0.144	0.622	0.180	0.518	0.223	0.449	0.252	0.398	0.275
5	1.186	0.093	0.916	0.043	0.824	0.091	0.715	0.149	0.637	0.187	0.529	0.237	0.456	0.269	0.403	0.295
7.5	1.153	0.084	0.930	0.041	0.849	0.086	0.750	0.145	0.677	0.190	0.573	0.260	0.503	0.306	0.451	0.344
10	1.129	0.088	0.942	0.043	0.873	0.092	0.786	0.154	0.722	0.198	0.628	0.266	0.561	0.318	0.509	0.358

Table 6-11 Median and Standard Deviation of the Natural Log of the Damping Correction Factors for $\xi \geq 2\%$ CEUS Rock Motions.

T	$\xi = 2\%$		$\xi = 7\%$		$\xi = 10\%$		$\xi = 15\%$		$\xi = 20\%$		$\xi = 30\%$		$\xi = 40\%$		$\xi = 50\%$	
(sec)	Median	σ_{1nDCF}	Median	σ_{1nDCF}	Median	σ_{1nDCF}	Median	σ_{1nDCF}	Median	σ_{1nDCF}	Median	σ_{1nDCF}	Median	σ_{1nDCF}	Median	σ_{1nDCF}
M 5-6																
0.05	1.394	0.106	0.889	0.056	0.785	0.100	0.680	0.139	0.607	0.173	0.519	0.212	0.465	0.237	0.426	0.256
0.1	1.312	0.132	0.895	0.049	0.790	0.100	0.676	0.149	0.601	0.183	0.502	0.235	0.437	0.273	0.390	0.300
0.2	1.305	0.109	0.885	0.052	0.770	0.109	0.646	0.176	0.561	0.224	0.452	0.286	0.381	0.326	0.329	0.350
0.3	1.275	0.118	0.899	0.054	0.794	0.103	0.673	0.151	0.591	0.187	0.480	0.230	0.407	0.263	0.356	0.290
0.5	1.241	0.118	0.908	0.050	0.818	0.099	0.711	0.160	0.634	0.204	0.523	0.263	0.449	0.302	0.395	0.331
0.8	1.203	0.118	0.919	0.054	0.832	0.110	0.728	0.172	0.654	0.219	0.556	0.279	0.489	0.328	0.438	0.366
1	1.183	0.129	0.921	0.059	0.836	0.113	0.739	0.170	0.673	0.213	0.580	0.276	0.517	0.319	0.469	0.355
1.3	1.163	0.115	0.934	0.052	0.858	0.117	0.773	0.181	0.714	0.223	0.630	0.281	0.567	0.320	0.518	0.350
1.5	1.176	0.123	0.942	0.052	0.875	0.111	0.795	0.177	0.741	0.214	0.663	0.270	0.604	0.309	0.557	0.341
2	1.135	0.103	0.942	0.048	0.883	0.101	0.816	0.167	0.768	0.212	0.700	0.274	0.652	0.310	0.614	0.338
3	1.084	0.093	0.958	0.048	0.910	0.104	0.855	0.175	0.817	0.227	0.761	0.300	0.718	0.355	0.684	0.395
4	1.067	0.078	0.967	0.042	0.926	0.096	0.881	0.155	0.848	0.198	0.795	0.266	0.756	0.320	0.726	0.359
5	1.041	0.065	0.979	0.034	0.952	0.078	0.916	0.132	0.890	0.169	0.846	0.234	0.813	0.278	0.787	0.314
7.5	1.013	0.037	0.993	0.023	0.982	0.055	0.966	0.102	0.953	0.132	0.932	0.174	0.911	0.210	0.892	0.240
10	1.005	0.017	0.997	0.010	0.993	0.021	0.987	0.040	0.980	0.058	0.968	0.090	0.956	0.119	0.945	0.137
M 6-7																
0.05	1.398	0.110	0.882	0.057	0.770	0.105	0.665	0.138	0.602	0.151	0.519	0.169	0.465	0.178	0.427	0.184
0.1	1.336	0.118	0.898	0.050	0.796	0.095	0.692	0.133	0.623	0.160	0.536	0.188	0.478	0.208	0.434	0.227
0.2	1.395	0.121	0.871	0.054	0.752	0.106	0.632	0.158	0.555	0.193	0.457	0.238	0.395	0.264	0.351	0.287
0.3	1.307	0.118	0.888	0.047	0.777	0.094	0.664	0.136	0.588	0.166	0.489	0.206	0.422	0.232	0.374	0.241
0.5	1.284	0.118	0.897	0.054	0.787	0.108	0.670	0.158	0.589	0.186	0.477	0.223	0.406	0.244	0.356	0.264
0.8	1.249	0.123	0.907	0.049	0.807	0.100	0.695	0.156	0.615	0.190	0.506	0.233	0.433	0.263	0.378	0.286
1	1.252	0.119	0.903	0.059	0.804	0.114	0.690	0.173	0.611	0.210	0.507	0.252	0.436	0.280	0.383	0.300
1.3	1.245	0.103	0.903	0.051	0.804	0.103	0.692	0.165	0.616	0.204	0.513	0.253	0.442	0.287	0.389	0.311
1.5	1.247	0.114	0.904	0.047	0.805	0.096	0.697	0.150	0.623	0.190	0.521	0.241	0.452	0.276	0.401	0.302
2	1.210	0.117	0.923	0.054	0.836	0.108	0.736	0.170	0.663	0.218	0.562	0.283	0.491	0.329	0.438	0.363
3	1.176	0.104	0.927	0.047	0.847	0.099	0.752	0.166	0.683	0.214	0.583	0.281	0.516	0.329	0.468	0.365
4	1.158	0.103	0.929	0.053	0.849	0.114	0.758	0.183	0.693	0.233	0.601	0.307	0.540	0.359	0.494	0.399
5	1.104	0.091	0.948	0.046	0.887	0.098	0.812	0.160	0.753	0.208	0.668	0.283	0.607	0.342	0.563	0.385
7.5	1.054	0.062	0.971	0.033	0.933	0.077	0.879	0.139	0.837	0.185	0.773	0.256	0.727	0.307	0.690	0.349
10	1.025	0.037	0.986	0.022	0.969	0.049	0.943	0.087	0.921	0.118	0.880	0.169	0.844	0.213	0.812	0.249
M 7+																
0.05	1.410	0.123	0.875	0.050	0.757	0.093	0.641	0.128	0.569	0.143	0.483	0.159	0.433	0.164	0.397	0.166
0.1	1.384	0.129	0.881	0.055	0.770	0.103	0.657	0.153	0.588	0.175	0.506	0.197	0.455	0.220	0.418	0.238
0.2	1.384	0.119	0.886	0.049	0.778	0.105	0.667	0.163	0.597	0.199	0.506	0.247	0.448	0.279	0.406	0.306
0.3	1.323	0.112	0.901	0.054	0.800	0.106	0.688	0.159	0.612	0.194	0.514	0.235	0.451	0.264	0.407	0.286
0.5	1.314	0.125	0.895	0.051	0.789	0.101	0.677	0.149	0.603	0.178	0.510	0.211	0.448	0.230	0.401	0.248
0.8	1.306	0.120	0.895	0.056	0.788	0.109	0.670	0.163	0.590	0.197	0.485	0.243	0.419	0.281	0.372	0.308
1	1.258	0.103	0.901	0.050	0.795	0.102	0.679	0.152	0.601	0.183	0.498	0.227	0.430	0.261	0.382	0.281
1.3	1.293	0.112	0.889	0.048	0.772	0.095	0.651	0.141	0.572	0.172	0.468	0.214	0.403	0.238	0.358	0.254
1.5	1.286	0.100	0.892	0.046	0.780	0.090	0.659	0.138	0.578	0.168	0.472	0.210	0.403	0.238	0.356	0.255
2	1.282	0.112	0.902	0.048	0.793	0.101	0.674	0.154	0.593	0.188	0.488	0.230	0.419	0.257	0.368	0.280
3	1.219	0.112	0.907	0.047	0.801	0.093	0.684	0.138	0.606	0.164	0.501	0.202	0.429	0.229	0.377	0.248
4	1.194	0.103	0.915	0.046	0.818	0.096	0.704	0.151	0.621	0.189	0.509	0.242	0.438	0.276	0.387	0.301
5	1.189	0.097	0.917	0.050	0.821	0.107	0.708	0.173	0.629	0.220	0.522	0.287	0.452	0.332	0.400	0.366
7.5	1.144	0.087	0.932	0.047	0.851	0.106	0.753	0.180	0.682	0.236	0.582	0.317	0.514	0.373	0.462	0.418
10	1.091	0.077	0.954	0.040	0.899	0.086	0.828	0.151	0.771	0.203	0.686	0.281	0.624	0.337	0.575	0.381

Table 6-12 Median and Standard Deviation of the Natural Log of the Damping Correction Factors for $\xi \geq 2\%$ CEUS Deep Soil Motions.

T	$\xi = 2\%$		$\xi = 7\%$		$\xi = 10\%$		$\xi = 15\%$		$\xi = 20\%$		$\xi = 30\%$		$\xi = 40\%$		$\xi = 50\%$	
(sec)	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$
M 5-6																
0.05	1.274	0.108	0.920	0.047	0.841	0.094	0.759	0.137	0.709	0.165	0.650	0.196	0.608	0.220	0.575	0.240
0.1	1.346	0.122	0.888	0.051	0.780	0.101	0.666	0.153	0.597	0.182	0.508	0.227	0.447	0.258	0.404	0.282
0.2	1.367	0.110	0.870	0.045	0.748	0.091	0.622	0.147	0.540	0.185	0.440	0.230	0.378	0.254	0.333	0.268
0.3	1.250	0.107	0.899	0.056	0.787	0.113	0.658	0.169	0.574	0.200	0.463	0.246	0.392	0.275	0.342	0.294
0.5	1.239	0.132	0.909	0.054	0.812	0.113	0.697	0.174	0.616	0.214	0.506	0.265	0.430	0.294	0.375	0.312
0.8	1.241	0.125	0.904	0.050	0.799	0.101	0.684	0.168	0.607	0.210	0.503	0.267	0.436	0.302	0.387	0.324
1	1.200	0.129	0.925	0.053	0.843	0.111	0.747	0.179	0.679	0.222	0.580	0.277	0.513	0.316	0.464	0.346
1.3	1.215	0.105	0.923	0.053	0.845	0.108	0.760	0.165	0.702	0.202	0.615	0.250	0.553	0.281	0.504	0.303
1.5	1.187	0.119	0.927	0.056	0.847	0.117	0.761	0.180	0.700	0.228	0.618	0.289	0.561	0.328	0.519	0.353
2	1.135	0.110	0.948	0.050	0.888	0.110	0.821	0.177	0.773	0.224	0.705	0.281	0.657	0.314	0.618	0.340
3	1.049	0.055	0.976	0.030	0.945	0.067	0.903	0.115	0.872	0.154	0.826	0.211	0.789	0.253	0.758	0.284
4	1.027	0.050	0.989	0.018	0.978	0.035	0.960	0.065	0.943	0.094	0.910	0.137	0.881	0.172	0.856	0.198
5	1.019	0.036	0.991	0.020	0.980	0.043	0.968	0.066	0.958	0.085	0.939	0.117	0.919	0.145	0.899	0.170
7.5	1.006	0.014	0.996	0.007	0.991	0.018	0.984	0.032	0.978	0.045	0.965	0.068	0.954	0.086	0.942	0.102
10	1.004	0.010	0.997	0.006	0.993	0.015	0.987	0.029	0.982	0.041	0.972	0.061	0.964	0.078	0.956	0.090
M 6-7																
0.05	1.216	0.115	0.910	0.044	0.881	0.080	0.817	0.115	0.776	0.133	0.721	0.162	0.686	0.182	0.662	0.194
0.1	1.309	0.111	0.908	0.050	0.816	0.102	0.718	0.158	0.656	0.192	0.578	0.237	0.529	0.273	0.493	0.302
0.2	1.372	0.116	0.880	0.050	0.762	0.095	0.642	0.143	0.565	0.181	0.469	0.234	0.411	0.268	0.371	0.292
0.3	1.307	0.119	0.890	0.050	0.776	0.101	0.656	0.156	0.577	0.192	0.474	0.238	0.410	0.263	0.366	0.280
0.5	1.314	0.119	0.892	0.056	0.781	0.112	0.660	0.168	0.580	0.199	0.472	0.238	0.403	0.261	0.353	0.280
0.8	1.298	0.119	0.890	0.052	0.777	0.101	0.652	0.153	0.569	0.178	0.462	0.208	0.393	0.232	0.343	0.250
1	1.273	0.118	0.894	0.052	0.784	0.107	0.666	0.166	0.587	0.205	0.481	0.252	0.412	0.278	0.363	0.298
1.3	1.263	0.101	0.900	0.049	0.794	0.102	0.678	0.160	0.601	0.195	0.500	0.236	0.433	0.265	0.384	0.285
1.5	1.227	0.111	0.914	0.048	0.818	0.100	0.709	0.159	0.635	0.197	0.534	0.246	0.464	0.282	0.412	0.311
2	1.203	0.103	0.916	0.048	0.823	0.103	0.720	0.164	0.646	0.205	0.545	0.267	0.476	0.314	0.426	0.352
3	1.167	0.102	0.927	0.047	0.844	0.101	0.749	0.163	0.681	0.206	0.587	0.273	0.523	0.321	0.473	0.362
4	1.137	0.102	0.941	0.046	0.873	0.099	0.791	0.164	0.730	0.213	0.645	0.276	0.585	0.324	0.538	0.363
5	1.117	0.097	0.948	0.047	0.888	0.101	0.814	0.169	0.762	0.219	0.688	0.285	0.634	0.334	0.592	0.371
7.5	1.068	0.078	0.967	0.042	0.926	0.093	0.878	0.151	0.840	0.195	0.785	0.262	0.743	0.306	0.708	0.342
10	1.032	0.052	0.982	0.028	0.961	0.060	0.931	0.103	0.906	0.136	0.865	0.189	0.831	0.229	0.803	0.257
M 7+																
0.05	1.209	0.121	0.939	0.042	0.888	0.076	0.839	0.112	0.808	0.134	0.771	0.155	0.749	0.167	0.733	0.174
0.1	1.288	0.127	0.913	0.050	0.832	0.096	0.756	0.143	0.712	0.168	0.656	0.195	0.623	0.208	0.598	0.220
0.2	1.346	0.124	0.897	0.052	0.798	0.100	0.697	0.154	0.630	0.190	0.545	0.231	0.492	0.255	0.456	0.273
0.3	1.329	0.127	0.896	0.054	0.792	0.109	0.683	0.159	0.613	0.184	0.525	0.213	0.467	0.229	0.426	0.240
0.5	1.324	0.115	0.889	0.049	0.778	0.096	0.666	0.145	0.593	0.177	0.495	0.218	0.430	0.243	0.383	0.258
0.8	1.358	0.124	0.881	0.055	0.760	0.108	0.635	0.155	0.554	0.182	0.448	0.217	0.380	0.238	0.332	0.252
1	1.314	0.117	0.886	0.049	0.769	0.097	0.646	0.145	0.561	0.175	0.453	0.212	0.383	0.231	0.333	0.242
1.3	1.299	0.103	0.884	0.044	0.765	0.092	0.641	0.145	0.560	0.178	0.453	0.217	0.383	0.242	0.333	0.262
1.5	1.306	0.103	0.892	0.049	0.778	0.097	0.654	0.148	0.573	0.181	0.466	0.218	0.398	0.239	0.348	0.257
2	1.267	0.122	0.903	0.050	0.797	0.101	0.680	0.150	0.601	0.181	0.493	0.217	0.421	0.242	0.370	0.264
3	1.246	0.106	0.904	0.047	0.804	0.093	0.688	0.147	0.608	0.183	0.502	0.232	0.433	0.260	0.383	0.280
4	1.214	0.097	0.908	0.047	0.807	0.097	0.692	0.150	0.614	0.183	0.509	0.226	0.440	0.258	0.390	0.279
5	1.187	0.091	0.916	0.046	0.820	0.097	0.709	0.155	0.631	0.196	0.525	0.253	0.454	0.291	0.402	0.319
7.5	1.159	0.090	0.926	0.046	0.842	0.100	0.743	0.168	0.672	0.219	0.572	0.300	0.505	0.355	0.456	0.396
10	1.103	0.077	0.949	0.043	0.887	0.096	0.810	0.160	0.751	0.212	0.665	0.285	0.603	0.340	0.555	0.382

Table 6-13. Median and Standard Deviation of the Natural Log of the Damping Correction Factors for ξ = 1% WUS Rock and Deep Soil Motions.

T	*M* 5-6 R = 0-50 km		*M* 5-6 R = 50-100 km		*M* 6-7 R = 0-50 km		*M* 6-7 R = 50-200 km		*M* 7+ R = 0-50 km		*M* 7+ R = 50-200 km	
(sec)	Median	σ_{lnDCF}	Median	σ_{lnDCF}	Median	σ_{lnDCF}	Median	σ_{lnDCF}	Median	σ_{lnDCF}	Median	σ_{lnDCF}
						WUS Rock						
0.05	1.163	0.160	1.290	0.244	1.135	0.151	1.109	0.120	1.196	0.189	1.108	0.145
0.1	1.325	0.193	1.509	0.185	1.391	0.206	1.464	0.180	1.451	0.218	1.453	0.241
0.2	1.377	0.163	1.555	0.201	1.513	0.185	1.669	0.204	1.528	0.173	1.641	0.220
0.3	1.394	0.124	1.553	0.170	1.506	0.189	1.646	0.209	1.531	0.174	1.658	0.182
0.5	1.389	0.145	1.406	0.169	1.426	0.154	1.600	0.175	1.511	0.200	1.723	0.207
0.8	1.391	0.186	1.439	0.228	1.377	0.178	1.524	0.205	1.511	0.172	1.602	0.193
1	1.317	0.171	1.433	0.224	1.381	0.158	1.562	0.188	1.368	0.168	1.516	0.153
1.3	1.233	0.173	1.307	0.191	1.397	0.144	1.469	0.171	1.403	0.176	1.533	0.208
1.5	1.287	0.192	1.342	0.212	1.369	0.154	1.456	0.216	1.381	0.176	1.513	0.157
2	1.148	0.160	1.218	0.183	1.262	0.156	1.434	0.191	1.346	0.176	1.480	0.179
3	1.167	0.146	1.169	0.177	1.238	0.151	1.326	0.149	1.289	0.144	1.436	0.192
4	1.093	0.122	1.116	0.137	1.224	0.138	1.312	0.169	1.255	0.157	1.316	0.140
5	1.062	0.096	1.106	0.137	1.160	0.125	1.196	0.145	1.204	0.123	1.329	0.151
7.5	1.021	0.045	1.041	0.084	1.097	0.105	1.122	0.115	1.171	0.122	1.226	0.123
10	1.009	0.021	1.017	0.048	1.054	0.073	1.079	0.103	1.132	0.105	1.201	0.130
						WUS Soil						
0.05	1.208	0.218	1.126	0.152	1.173	0.172	1.058	0.082	1.127	0.130	1.030	0.040
0.1	1.387	0.210	1.457	0.198	1.477	0.207	1.316	0.190	1.378	0.207	1.278	0.187
0.2	1.541	0.210	1.557	0.175	1.518	0.190	1.560	0.213	1.527	0.209	1.562	0.199
0.3	1.334	0.143	1.581	0.197	1.504	0.161	1.578	0.206	1.582	0.209	1.615	0.182
0.5	1.407	0.148	1.457	0.167	1.472	0.180	1.619	0.188	1.543	0.193	1.615	0.153
0.8	1.362	0.182	1.466	0.162	1.392	0.157	1.635	0.176	1.521	0.171	1.699	0.160
1	1.412	0.215	1.474	0.169	1.377	0.158	1.586	0.213	1.451	0.192	1.618	0.168
1.3	1.402	0.182	1.458	0.156	1.375	0.142	1.536	0.192	1.429	0.157	1.538	0.172
1.5	1.341	0.167	1.403	0.164	1.383	0.172	1.489	0.173	1.457	0.179	1.547	0.155
2	1.258	0.172	1.266	0.140	1.294	0.143	1.395	0.163	1.405	0.162	1.487	0.167
3	1.147	0.094	1.120	0.106	1.291	0.137	1.315	0.176	1.397	0.163	1.460	0.165
4	1.143	0.146	1.059	0.088	1.250	0.129	1.260	0.201	1.302	0.140	1.394	0.175
5	1.058	0.096	1.047	0.080	1.194	0.123	1.236	0.154	1.261	0.128	1.318	0.145
7.5	1.034	0.081	1.006	0.018	1.129	0.116	1.119	0.117	1.224	0.114	1.241	0.131
10	1.003	0.010	1.004	0.018	1.072	0.087	1.067	0.087	1.182	0.105	1.203	0.147

Table 6-14. Median and Standard Deviation of the Natural Log of the Damping Correction Factors for ξ = 1% CEUS Rock and Deep Soil Motions.

T (sec)	M 5-6 R = 0-50 km		M 5-6 R = 50-100 km		M 6-7 R = 0-50 km		M 6-7 R = 50-200 km		M 7+ R = 0-50 km		M 7+ R = 50-200 km	
	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$	Median	$\sigma_{\ln DCF}$
CEUS Rock												
0.05	1.700	0.152	1.830	0.164	1.673	0.191	1.863	0.131	1.785	0.192	1.818	0.174
0.1	1.481	0.189	1.606	0.216	1.550	0.199	1.740	0.142	1.635	0.205	1.862	0.166
0.2	1.431	0.154	1.589	0.144	1.611	0.161	1.802	0.201	1.664	0.161	1.795	0.173
0.3	1.344	0.100	1.563	0.210	1.466	0.177	1.618	0.185	1.521	0.166	1.710	0.160
0.5	1.348	0.135	1.483	0.218	1.420	0.141	1.576	0.186	1.458	0.181	1.683	0.173
0.8	1.280	0.166	1.357	0.162	1.360	0.185	1.472	0.188	1.457	0.161	1.603	0.174
1	1.253	0.153	1.339	0.206	1.368	0.158	1.504	0.165	1.362	0.158	1.518	0.140
1.3	1.262	0.163	1.255	0.176	1.382	0.152	1.437	0.161	1.422	0.162	1.553	0.161
1.5	1.232	0.165	1.305	0.189	1.353	0.132	1.448	0.194	1.399	0.164	1.542	0.136
2	1.190	0.128	1.220	0.175	1.264	0.141	1.436	0.190	1.410	0.162	1.512	0.159
3	1.110	0.114	1.139	0.147	1.240	0.150	1.301	0.157	1.284	0.122	1.421	0.179
4	1.101	0.114	1.097	0.113	1.231	0.153	1.246	0.142	1.262	0.151	1.320	0.142
5	1.059	0.094	1.062	0.088	1.126	0.105	1.179	0.142	1.223	0.111	1.351	0.145
7.5	1.011	0.038	1.026	0.059	1.060	0.079	1.093	0.090	1.191	0.127	1.233	0.118
10	1.005	0.021	1.008	0.026	1.024	0.035	1.049	0.061	1.096	0.099	1.163	0.112
CEUS Soil												
0.05	1.480	0.155	1.547	0.164	1.385	0.176	1.540	0.170	1.291	0.180	1.591	0.164
0.1	1.542	0.193	1.689	0.148	1.526	0.174	1.709	0.144	1.459	0.197	1.726	0.142
0.2	1.573	0.186	1.672	0.153	1.639	0.172	1.721	0.181	1.552	0.193	1.777	0.158
0.3	1.353	0.145	1.511	0.172	1.508	0.156	1.606	0.190	1.564	0.193	1.690	0.171
0.5	1.358	0.175	1.491	0.216	1.477	0.161	1.633	0.176	1.543	0.177	1.636	0.151
0.8	1.347	0.178	1.439	0.203	1.434	0.143	1.595	0.176	1.561	0.171	1.685	0.195
1	1.284	0.145	1.395	0.213	1.386	0.141	1.546	0.200	1.470	0.175	1.621	0.155
1.3	1.308	0.178	1.395	0.129	1.392	0.129	1.507	0.152	1.449	0.160	1.569	0.156
1.5	1.288	0.183	1.300	0.175	1.345	0.155	1.413	0.173	1.520	0.153	1.539	0.131
2	1.192	0.145	1.240	0.175	1.280	0.141	1.378	0.160	1.429	0.159	1.477	0.180
3	1.063	0.072	1.080	0.086	1.248	0.124	1.277	0.175	1.375	0.143	1.437	0.151
4	1.041	0.073	1.036	0.070	1.187	0.120	1.235	0.181	1.305	0.122	1.363	0.162
5	1.040	0.061	1.022	0.043	1.175	0.131	1.173	0.148	1.269	0.120	1.310	0.138
7.5	1.010	0.022	1.007	0.015	1.105	0.111	1.094	0.113	1.239	0.125	1.237	0.131
10	1.006	0.013	1.006	0.015	1.048	0.070	1.044	0.075	1.155	0.108	1.143	0.111

6.5.4 Database

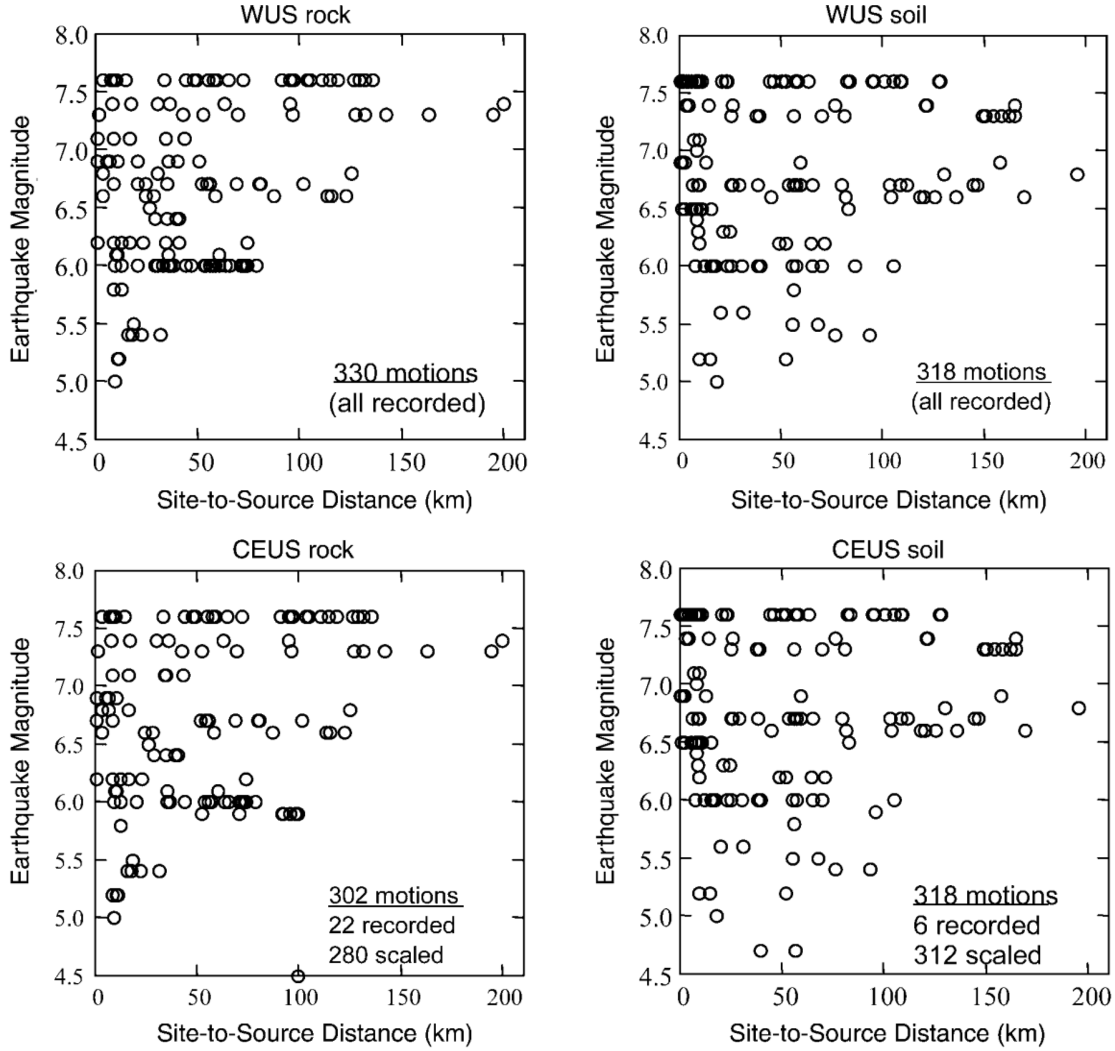


Figure 6-18. Distribution of motions used in the study. Each point on these plots represents the two horizontal components of motions at a site.

6.5.5 *MATLAB Code*

```
% by Kathryn A. Gunberg 6/30/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Cameron and Green damping correction factors, 2007
% Note: for border line cases: M6, M7 and Rrup = 50, use both sets of DCF
% and take a bound of the resulting spectra.
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% T     = Period
% M     = Moment Magnitude
% G     = Region: 1 for WUS, 0 for CEUS
% Rrup  = Closest distance to rupture plane (km)
% S     = Soil category: 0 for rock, 1 for soil
% D     = % Damping Required (1, 2, 7, 10 15, 20, 30, 40, or 50%)
% ---------------------------------------------------------------------------
% Output
% DCF   = damping correction factor
% sigma = logarithmic standard deviation of spectral period prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [DCF, sigma] = CG_2007(T, M, G, Rrup, S, D)
period   = [.05 0.1 0.2 0.3 0.5 0.8 1   1.3 1.5 2   3   4   5   7.5 10];
i   = find(abs((period - T)) < 0.0001); % Identify the period index
if D == 1
    j = 1;
    if G == 1
        if S == 0
            if M < 6
                if Rrup < 50
                    DCF  = [1.163   1.325   1.377   1.394   1.389   1.391   1.317   1.233...
                            1.287   1.148   1.167   1.093   1.062   1.021   1.009];
                    sig  = [0.160   0.193   0.163   0.124   0.145   0.186   0.171   0.173...
                            0.192   0.160   0.146   0.122   0.096   0.045   0.021];
                else
                    DCF  = [1.290   1.509   1.555   1.553   1.406   1.439   1.433   1.307...
                            1.342   1.218   1.169   1.116   1.106   1.041   1.017];
                    sig  = [0.244   0.185   0.201   0.170   0.169   0.228   0.224   0.191...
                            0.212   0.183   0.177   0.137   0.137   0.084   0.048];
                end
            elseif M < 7
                if Rrup < 50
                    DCF  = [1.135   1.391   1.513   1.506   1.426   1.377   1.381   1.397...
                            1.369   1.262   1.238   1.224   1.160   1.097   1.054];
                    sig  = [0.151   0.206   0.185   0.189   0.154   0.178   0.158   0.144...
                            0.154   0.156   0.151   0.138   0.125   0.105   0.073];
                else
                    DCF  = [1.109   1.464   1.669   1.646   1.600   1.524   1.562   1.469...
                            1.456   1.434   1.326   1.312   1.196   1.122   1.079];
                    sig  = [0.120   0.180   0.204   0.209   0.175   0.205   0.188   0.171...
                            0.216   0.191   0.149   0.169   0.145   0.115   0.103];
                end
            else
                if Rrup < 50
                    DCF  = [1.196   1.451   1.528   1.531   1.511   1.511   1.368   1.403...
                            1.381   1.346   1.289   1.255   1.204   1.171   1.132];
                    sig  = [0.189   0.218   0.173   0.174   0.200   0.172   0.168   0.176...
                            0.176   0.176   0.144   0.157   0.123   0.122   0.105];
                else
                    DCF  = [1.108   1.453   1.641   1.658   1.723   1.602   1.516   1.533...
                            1.513   1.480   1.436   1.316   1.329   1.226   1.201];
                    sig  = [0.145   0.241   0.220   0.182   0.207   0.193   0.153   0.208...
                            0.157   0.179   0.192   0.140   0.151   0.123   0.130];
                end
            end
        else
            if M < 6
```

```
            if Rrup < 50
                DCF  = [1.208   1.387   1.541   1.334   1.407   1.362   1.412   1.402...
                        1.341   1.258   1.147   1.143   1.058   1.034   1.003];
                sig  = [0.218   0.210   0.210   0.143   0.148   0.182   0.215   0.182...
                        0.167   0.172   0.094   0.146   0.096   0.081   0.010];
            else
                DCF  = [1.126   1.457   1.557   1.581   1.457   1.466   1.474   1.458...
                        1.403   1.266   1.120   1.059   1.047   1.006   1.004];
                sig  = [0.152   0.198   0.175   0.197   0.167   0.162   0.169   0.156...
                        0.164   0.140   0.106   0.088   0.080   0.018   0.018];
            end
        elseif M < 7
            if Rrup < 50
                DCF  = [1.173   1.477   1.518   1.504   1.472   1.392   1.377   1.375...
                        1.383   1.294   1.291   1.250   1.194   1.129   1.072];
                sig  = [0.172   0.207   0.190   0.161   0.180   0.157   0.158   0.142...
                        0.172   0.143   0.137   0.129   0.123   0.116   0.087];
            else
                DCF  = [1.058   1.316   1.560   1.578   1.619   1.635   1.586   1.536...
                        1.489   1.395   1.315   1.260   1.236   1.119   1.067];
                sig  = [0.082   0.190   0.213   0.206   0.188   0.176   0.213   0.192...
                        0.173   0.163   0.176   0.201   0.154   0.117   0.087];
            end
        else
            if Rrup < 50
                DCF  = [1.127   1.378   1.527   1.582   1.543   1.521   1.451   1.429...
                        1.457   1.405   1.397   1.302   1.261   1.224   1.182];
                sig  = [0.130   0.207   0.209   0.209   0.193   0.171   0.192   0.157...
                        0.179   0.162   0.163   0.140   0.128   0.114   0.105];
            else
                DCF  = [1.030   1.278   1.562   1.615   1.615   1.699   1.618   1.538...
                        1.547   1.487   1.460   1.394   1.318   1.241   1.203];
                sig  = [0.040   0.187   0.199   0.182   0.153   0.160   0.168   0.172...
                        0.155   0.167   0.165   0.175   0.145   0.131   0.147];
            end
        end
    end
else
    if S == 0
        if M < 6
            if Rrup < 50
                DCF  = [1.700   1.481   1.431   1.344   1.348   1.280   1.253   1.262...
                        1.232   1.190   1.110   1.101   1.059   1.011   1.005];
                sig  = [0.152   0.189   0.154   0.100   0.135   0.166   0.153   0.163...
                        0.165   0.128   0.114   0.114   0.094   0.038   0.021];
            else
                DCF  = [1.830   1.606   1.589   1.563   1.483   1.357   1.339   1.255...
                        1.305   1.220   1.139   1.097   1.062   1.026   1.008];
                sig  = [0.164   0.216   0.144   0.210   0.218   0.162   0.206   0.176...
                        0.189   0.175   0.147   0.113   0.088   0.059   0.026];
            end
        elseif M < 7
            if Rrup < 50
                DCF  = [1.673   1.550   1.611   1.466   1.420   1.360   1.368   1.382...
                        1.353   1.264   1.240   1.231   1.126   1.060   1.024];
                sig  = [0.191   0.199   0.161   0.177   0.141   0.185   0.158   0.152...
                        0.132   0.141   0.150   0.153   0.105   0.079   0.035];
            else
                DCF  = [1.863   1.740   1.802   1.618   1.576   1.472   1.504   1.437...
                        1.448   1.436   1.301   1.246   1.179   1.093   1.049];
                sig  = [0.131   0.142   0.201   0.185   0.186   0.188   0.165   0.161...
                        0.194   0.190   0.157   0.142   0.142   0.090   0.061];
            end
        else
            if Rrup < 50
                DCF  = [1.785   1.635   1.664   1.521   1.458   1.457   1.362   1.422...
                        1.399   1.410   1.284   1.262   1.223   1.191   1.096];
                sig  = [0.192   0.205   0.161   0.166   0.181   0.161   0.158   0.162...
                        0.164   0.162   0.122   0.151   0.111   0.127   0.099];
            else
                DCF  = [1.818   1.862   1.795   1.710   1.683   1.603   1.518   1.553...
```

```
                    1.542   1.512   1.421   1.320   1.351   1.233   1.163];
                sig  = [0.174   0.166   0.173   0.160   0.173   0.174   0.140   0.161...
                        0.136   0.159   0.179   0.142   0.145   0.118   0.112];
            end
        end
    else
        if M < 6
            if Rrup < 50
                DCF  = [1.480   1.542   1.573   1.353   1.358   1.347   1.284   1.308...
                        1.288   1.192   1.063   1.041   1.040   1.010   1.006];
                sig  = [0.155   0.193   0.186   0.145   0.175   0.178   0.145   0.178...
                        0.183   0.145   0.072   0.073   0.061   0.022   0.013];
            else
                DCF  = [1.547   1.689   1.672   1.511   1.491   1.439   1.395   1.395...
                        1.300   1.240   1.080   1.036   1.022   1.007   1.006];
                sig  = [0.164   0.148   0.153   0.172   0.216   0.203   0.213   0.129...
                        0.175   0.175   0.086   0.070   0.043   0.015   0.015];
            end
        elseif M < 7
            if Rrup < 50
                DCF  = [1.385   1.526   1.639   1.508   1.477   1.434   1.386   1.392...
                        1.345   1.280   1.248   1.187   1.175   1.105   1.048];
                sig  = [0.176   0.174   0.172   0.156   0.161   0.143   0.141   0.129...
                        0.155   0.141   0.124   0.120   0.131   0.111   0.070];
            else
                DCF  = [1.540   1.709   1.721   1.606   1.633   1.595   1.546   1.507...
                        1.413   1.378   1.277   1.235   1.173   1.094   1.044];
                sig  = [0.170   0.144   0.181   0.190   0.176   0.176   0.200   0.152...
                        0.173   0.160   0.175   0.181   0.148   0.113   0.075];
            end
        else
            if Rrup < 50
                DCF  = [1.291   1.459   1.552   1.564   1.543   1.561   1.470   1.449...
                        1.520   1.429   1.375   1.305   1.269   1.239   1.155];
                sig  = [0.180   0.197   0.193   0.193   0.177   0.171   0.175   0.160...
                        0.153   0.159   0.143   0.122   0.120   0.125   0.108];
            else
                DCF  = [1.591   1.726   1.777   1.690   1.636   1.685   1.621   1.569...
                        1.539   1.477   1.437   1.363   1.310   1.237   1.143];
                sig  = [0.164   0.142   0.158   0.171   0.151   0.195   0.155   0.156...
                        0.131   0.180   0.151   0.162   0.138   0.131   0.111];
            end
        end
    end
end
else
    damp     = [2   7   10  15  20  30  40  50];
    j        = find(abs((damp - D)) < 0.0001);   % Identify the %damping index
    if G == 1
        if S == 0
            if M < 6
                DCF  = [1.111   1.223   1.280   1.302   1.232   1.248   1.230   1.163...
                        1.189   1.121   1.114   1.073   1.059   1.022   1.010;
                        0.961   0.921   0.889   0.884   0.907   0.906   0.915   0.934...
                        0.935   0.945   0.954   0.960   0.968   0.989   0.995;
                        0.919   0.838   0.776   0.767   0.807   0.805   0.825   0.860...
                        0.865   0.883   0.909   0.915   0.931   0.975   0.987;
                        0.876   0.748   0.649   0.641   0.692   0.697   0.724   0.775...
                        0.781   0.810   0.852   0.856   0.883   0.953   0.974;
                        0.848   0.691   0.563   0.558   0.611   0.624   0.652   0.715...
                        0.722   0.757   0.808   0.816   0.845   0.935   0.962;
                        0.808   0.613   0.457   0.448   0.500   0.521   0.555   0.626...
                        0.643   0.684   0.747   0.760   0.791   0.903   0.941;
                        0.778   0.560   0.391   0.378   0.429   0.451   0.487   0.559...
                        0.585   0.635   0.701   0.720   0.751   0.876   0.922;
                        0.754   0.519   0.342   0.328   0.377   0.399   0.437   0.507...
                        0.539   0.594   0.664   0.688   0.722   0.852   0.906];
                sig  = [0.122   0.131   0.118   0.100   0.100   0.128   0.133   0.119...
                        0.132   0.116   0.114   0.091   0.085   0.048   0.027;
                        0.053   0.054   0.052   0.042   0.044   0.055   0.055   0.051...
                        0.054   0.054   0.056   0.050   0.048   0.022   0.013;
```

```
            0.110   0.111   0.110   0.085   0.089   0.116   0.117   0.105...
            0.111   0.114   0.113   0.111   0.102   0.051   0.030;
            0.162   0.170   0.175   0.126   0.142   0.181   0.180   0.163...
            0.182   0.185   0.185   0.194   0.174   0.096   0.057;
            0.196   0.207   0.219   0.148   0.179   0.222   0.227   0.205...
            0.230   0.235   0.239   0.249   0.232   0.135   0.083;
            0.240   0.266   0.279   0.179   0.232   0.282   0.284   0.264...
            0.290   0.305   0.305   0.328   0.315   0.196   0.126;
            0.266   0.307   0.313   0.206   0.264   0.329   0.328   0.310...
            0.331   0.347   0.355   0.383   0.372   0.242   0.161;
            0.286   0.339   0.339   0.223   0.288   0.365   0.361   0.348...
            0.366   0.382   0.396   0.426   0.414   0.279   0.190];
elseif M < 7
    DCF  = [1.060   1.220   1.328   1.322   1.289   1.253   1.268   1.260...
            1.249   1.195   1.174   1.171   1.118   1.074   1.045;
            0.981   0.934   0.886   0.884   0.894   0.901   0.896   0.900...
            0.906   0.921   0.927   0.924   0.943   0.965   0.977;
            0.961   0.871   0.778   0.770   0.783   0.793   0.786   0.799...
            0.808   0.835   0.843   0.841   0.877   0.921   0.946;
            0.938   0.806   0.662   0.650   0.664   0.675   0.665   0.687...
            0.700   0.739   0.744   0.749   0.797   0.863   0.906;
            0.922   0.762   0.588   0.572   0.583   0.592   0.584   0.610...
            0.627   0.671   0.675   0.685   0.734   0.815   0.874;
            0.898   0.701   0.494   0.471   0.472   0.480   0.476   0.506...
            0.528   0.572   0.579   0.595   0.648   0.742   0.823;
            0.879   0.654   0.434   0.406   0.398   0.406   0.405   0.436...
            0.460   0.505   0.516   0.535   0.590   0.690   0.780;
            0.863   0.617   0.389   0.359   0.346   0.353   0.354   0.384...
            0.408   0.455   0.469   0.490   0.545   0.650   0.743];
    sig  = [0.078   0.123   0.125   0.121   0.111   0.125   0.116   0.106...
            0.122   0.120   0.104   0.107   0.094   0.078   0.062;
            0.031   0.048   0.050   0.047   0.052   0.054   0.054   0.049...
            0.052   0.054   0.050   0.056   0.047   0.040   0.033;
            0.065   0.096   0.102   0.089   0.103   0.110   0.109   0.098...
            0.099   0.111   0.107   0.118   0.097   0.089   0.074;
            0.098   0.147   0.157   0.132   0.145   0.160   0.164   0.149...
            0.149   0.173   0.181   0.190   0.158   0.153   0.125;
            0.116   0.180   0.191   0.159   0.173   0.192   0.197   0.184...
            0.179   0.217   0.233   0.245   0.210   0.204   0.166;
            0.140   0.230   0.240   0.196   0.211   0.234   0.235   0.230...
            0.217   0.280   0.306   0.325   0.289   0.278   0.227;
            0.160   0.269   0.272   0.219   0.237   0.264   0.258   0.263...
            0.247   0.320   0.351   0.377   0.347   0.335   0.275;
            0.176   0.298   0.298   0.235   0.254   0.287   0.278   0.287...
            0.272   0.349   0.386   0.417   0.392   0.376   0.315];
else
    DCF  = [1.071   1.236   1.309   1.325   1.349   1.328   1.260   1.280...
            1.273   1.255   1.227   1.187   1.176   1.136   1.115;
            0.977   0.934   0.900   0.888   0.883   0.883   0.900   0.892...
            0.900   0.901   0.909   0.916   0.920   0.933   0.942;
            0.953   0.871   0.803   0.780   0.774   0.766   0.793   0.777...
            0.792   0.798   0.812   0.823   0.829   0.853   0.874;
            0.928   0.811   0.706   0.665   0.660   0.649   0.676   0.657...
            0.672   0.686   0.698   0.715   0.722   0.757   0.788;
            0.911   0.773   0.643   0.588   0.589   0.570   0.597   0.580...
            0.594   0.613   0.620   0.640   0.647   0.686   0.722;
            0.886   0.718   0.558   0.494   0.494   0.468   0.492   0.480...
            0.494   0.514   0.519   0.536   0.544   0.585   0.627;
            0.869   0.677   0.500   0.433   0.430   0.401   0.423   0.416...
            0.428   0.448   0.453   0.467   0.475   0.515   0.562;
            0.854   0.646   0.458   0.390   0.385   0.354   0.374   0.369...
            0.379   0.399   0.404   0.417   0.424   0.462   0.511];
    sig  = [0.098   0.147   0.134   0.113   0.131   0.120   0.108   0.126...
            0.113   0.124   0.122   0.103   0.102   0.089   0.085;
            0.037   0.057   0.059   0.053   0.048   0.051   0.047   0.050...
            0.044   0.051   0.051   0.047   0.049   0.049   0.046;
            0.075   0.114   0.114   0.103   0.092   0.100   0.098   0.099...
            0.089   0.099   0.102   0.098   0.101   0.106   0.101;
            0.109   0.170   0.173   0.161   0.141   0.149   0.149   0.144...
            0.138   0.148   0.157   0.159   0.162   0.177   0.173;
            0.128   0.204   0.213   0.199   0.172   0.184   0.181   0.175...
```

```
                0.169   0.178   0.187   0.205   0.205   0.230   0.232;
                0.156   0.257   0.269   0.244   0.217   0.231   0.224   0.212...
                0.209   0.227   0.222   0.267   0.270   0.312   0.321;
                0.173   0.297   0.313   0.276   0.245   0.262   0.250   0.236...
                0.240   0.263   0.250   0.307   0.313   0.373   0.384;
                0.189   0.327   0.349   0.303   0.264   0.284   0.269   0.255...
                0.260   0.292   0.270   0.333   0.345   0.421   0.437];
    end
else
    if M < 6
        DCF  = [1.088   1.236   1.322   1.255   1.260   1.250   1.266   1.261...
                1.227   1.164   1.086   1.065   1.035   1.012   1.002;
                0.976   0.925   0.885   0.899   0.903   0.903   0.907   0.905...
                0.910   0.933   0.962   0.973   0.986   0.995   0.998;
                0.953   0.846   0.768   0.786   0.795   0.793   0.810   0.806...
                0.812   0.856   0.920   0.944   0.969   0.988   0.996;
                0.929   0.762   0.646   0.657   0.672   0.675   0.706   0.697...
                0.704   0.769   0.864   0.910   0.945   0.978   0.992;
                0.911   0.706   0.572   0.572   0.587   0.596   0.634   0.626...
                0.634   0.708   0.820   0.885   0.926   0.972   0.989;
                0.881   0.629   0.479   0.465   0.477   0.491   0.536   0.534...
                0.545   0.626   0.755   0.843   0.899   0.961   0.981;
                0.855   0.573   0.418   0.395   0.402   0.423   0.468   0.472...
                0.483   0.566   0.707   0.807   0.874   0.948   0.973;
                0.832   0.532   0.373   0.344   0.348   0.374   0.417   0.426...
                0.438   0.522   0.669   0.777   0.850   0.937   0.966];
        sig  = [0.110   0.130   0.124   0.118   0.106   0.108   0.119   0.106...
                0.115   0.108   0.068   0.086   0.059   0.035   0.010;
                0.032   0.052   0.044   0.051   0.051   0.051   0.050   0.047...
                0.049   0.051   0.034   0.040   0.026   0.014   0.006;
                0.061   0.104   0.088   0.103   0.104   0.105   0.097   0.095...
                0.102   0.105   0.071   0.079   0.056   0.032   0.014;
                0.092   0.154   0.137   0.156   0.163   0.155   0.144   0.145...
                0.156   0.165   0.125   0.116   0.095   0.056   0.023;
                0.113   0.187   0.170   0.186   0.200   0.186   0.181   0.173...
                0.189   0.210   0.165   0.136   0.122   0.069   0.029;
                0.144   0.236   0.212   0.224   0.236   0.228   0.233   0.207...
                0.238   0.266   0.223   0.176   0.151   0.093   0.041;
                0.168   0.273   0.243   0.250   0.260   0.254   0.265   0.233...
                0.272   0.303   0.269   0.209   0.175   0.114   0.053;
                0.185   0.299   0.260   0.269   0.278   0.272   0.291   0.252...
                0.300   0.329   0.302   0.235   0.195   0.130   0.063];
    elseif M < 7
        DCF  = [1.061   1.206   1.302   1.309   1.311   1.300   1.281   1.266...
                1.256   1.211   1.190   1.167   1.143   1.082   1.049;
                0.982   0.938   0.893   0.889   0.890   0.887   0.896   0.896...
                0.901   0.912   0.920   0.928   0.936   0.961   0.974;
                0.964   0.876   0.786   0.776   0.775   0.770   0.787   0.789...
                0.798   0.815   0.831   0.847   0.866   0.914   0.942;
                0.947   0.812   0.674   0.659   0.652   0.645   0.670   0.670...
                0.683   0.705   0.731   0.753   0.781   0.851   0.899;
                0.935   0.770   0.603   0.583   0.569   0.564   0.590   0.591...
                0.605   0.630   0.661   0.685   0.719   0.802   0.865;
                0.918   0.714   0.516   0.487   0.462   0.462   0.481   0.485...
                0.500   0.526   0.564   0.593   0.632   0.728   0.807;
                0.905   0.674   0.461   0.424   0.393   0.395   0.411   0.416...
                0.431   0.456   0.497   0.531   0.569   0.675   0.764;
                0.893   0.643   0.422   0.379   0.344   0.346   0.362   0.367...
                0.380   0.404   0.446   0.483   0.522   0.633   0.728];
        sig  = [0.089   0.131   0.132   0.123   0.123   0.122   0.127   0.114...
                0.115   0.104   0.102   0.114   0.095   0.077   0.062;
                0.029   0.056   0.052   0.049   0.053   0.050   0.055   0.047...
                0.047   0.048   0.048   0.051   0.045   0.041   0.034;
                0.059   0.114   0.101   0.096   0.103   0.098   0.112   0.094...
                0.099   0.102   0.101   0.106   0.096   0.090   0.074;
                0.088   0.173   0.151   0.151   0.159   0.149   0.166   0.143...
                0.152   0.161   0.162   0.164   0.165   0.157   0.125;
                0.108   0.211   0.193   0.187   0.197   0.176   0.200   0.170...
                0.183   0.198   0.204   0.205   0.215   0.205   0.167;
                0.131   0.266   0.251   0.232   0.244   0.207   0.246   0.201...
                0.222   0.248   0.262   0.267   0.283   0.272   0.232;
```

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                0.147   0.307   0.290   0.266   0.272   0.225   0.269   0.221...
                0.245   0.282   0.301   0.311   0.333   0.321   0.278;
                0.159   0.339   0.320   0.290   0.292   0.236   0.281   0.236...
                0.266   0.309   0.335   0.349   0.372   0.359   0.313];
        else
            DCF  = [1.040   1.167   1.299   1.322   1.326   1.342   1.311   1.286...
                1.294   1.266   1.270   1.216   1.186   1.153   1.129;
                0.989   0.956   0.908   0.897   0.891   0.884   0.888   0.887...
                0.893   0.897   0.903   0.910   0.916   0.930   0.942;
                0.977   0.914   0.819   0.800   0.782   0.769   0.769   0.770...
                0.782   0.791   0.803   0.811   0.824   0.849   0.873;
                0.964   0.872   0.730   0.701   0.673   0.645   0.640   0.643...
                0.659   0.677   0.693   0.700   0.715   0.750   0.786;
                0.955   0.846   0.672   0.635   0.602   0.563   0.556   0.559...
                0.576   0.597   0.616   0.622   0.637   0.677   0.722;
                0.943   0.810   0.601   0.551   0.506   0.457   0.448   0.453...
                0.471   0.492   0.515   0.518   0.529   0.573   0.628;
                0.934   0.785   0.558   0.498   0.442   0.388   0.381   0.385...
                0.402   0.422   0.445   0.449   0.456   0.503   0.561;
                0.926   0.764   0.525   0.458   0.395   0.340   0.333   0.338...
                0.353   0.372   0.393   0.398   0.403   0.451   0.509];
            sig  = [0.065   0.117   0.127   0.123   0.114   0.117   0.121   0.108...
                0.115   0.111   0.114   0.103   0.093   0.084   0.088;
                0.021   0.047   0.052   0.050   0.052   0.051   0.048   0.043...
                0.046   0.049   0.051   0.045   0.043   0.041   0.043;
                0.044   0.097   0.102   0.094   0.101   0.100   0.095   0.089...
                0.093   0.098   0.100   0.093   0.091   0.086   0.092;
                0.068   0.143   0.153   0.139   0.148   0.149   0.141   0.141...
                0.141   0.145   0.150   0.144   0.149   0.145   0.154;
                0.085   0.168   0.184   0.169   0.178   0.182   0.168   0.173...
                0.171   0.177   0.184   0.180   0.187   0.190   0.198;
                0.101   0.203   0.226   0.203   0.211   0.219   0.199   0.213...
                0.204   0.222   0.234   0.223   0.237   0.260   0.266;
                0.110   0.223   0.258   0.226   0.227   0.242   0.217   0.234...
                0.227   0.251   0.266   0.252   0.269   0.306   0.318;
                0.117   0.240   0.283   0.246   0.241   0.258   0.231   0.250...
                0.245   0.269   0.290   0.275   0.295   0.344   0.358];
        end
    end
else
    if S == 0
        if M < 6
            DCF  = [1.394   1.312   1.305   1.275   1.241   1.203   1.183   1.163...
                1.176   1.135   1.084   1.067   1.041   1.013   1.005;
                0.889   0.895   0.885   0.899   0.908   0.919   0.921   0.934...
                0.942   0.942   0.958   0.967   0.979   0.993   0.997;
                0.785   0.790   0.770   0.794   0.818   0.832   0.836   0.858...
                0.875   0.883   0.910   0.926   0.952   0.982   0.993;
                0.680   0.676   0.646   0.673   0.711   0.728   0.739   0.773...
                0.795   0.816   0.855   0.881   0.916   0.966   0.987;
                0.607   0.601   0.561   0.591   0.634   0.654   0.673   0.714...
                0.741   0.768   0.817   0.848   0.890   0.953   0.980;
                0.519   0.502   0.452   0.480   0.523   0.556   0.580   0.630...
                0.663   0.700   0.761   0.795   0.846   0.932   0.968;
                0.465   0.437   0.381   0.407   0.449   0.489   0.517   0.567...
                0.604   0.652   0.718   0.756   0.813   0.911   0.956;
                0.426   0.390   0.329   0.356   0.395   0.438   0.469   0.518...
                0.557   0.614   0.684   0.726   0.787   0.892   0.945];
            sig  = [0.106   0.132   0.109   0.118   0.118   0.118   0.129   0.115...
                0.123   0.103   0.093   0.078   0.065   0.037   0.017;
                0.056   0.049   0.052   0.054   0.050   0.054   0.059   0.052...
                0.052   0.048   0.048   0.042   0.034   0.023   0.010;
                0.100   0.100   0.109   0.103   0.099   0.110   0.113   0.117...
                0.111   0.101   0.104   0.096   0.078   0.055   0.021;
                0.139   0.149   0.176   0.151   0.160   0.172   0.170   0.181...
                0.177   0.167   0.175   0.155   0.132   0.102   0.040;
                0.173   0.183   0.224   0.187   0.204   0.219   0.213   0.223...
                0.214   0.212   0.227   0.198   0.169   0.132   0.058;
                0.212   0.235   0.286   0.230   0.263   0.279   0.276   0.281...
                0.270   0.274   0.300   0.266   0.234   0.174   0.090;
                0.237   0.273   0.326   0.263   0.302   0.328   0.319   0.320...
```

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            0.309   0.310   0.355   0.320   0.278   0.210   0.119;
            0.256   0.300   0.350   0.290   0.331   0.366   0.355   0.350...
            0.341   0.338   0.395   0.359   0.314   0.240   0.137];
    elseif M < 7
        DCF  = [1.398   1.336   1.395   1.307   1.284   1.249   1.252   1.245...
            1.247   1.210   1.176   1.158   1.104   1.054   1.025;
            0.882   0.898   0.871   0.888   0.897   0.907   0.903   0.903...
            0.904   0.923   0.927   0.929   0.948   0.971   0.986;
            0.770   0.796   0.752   0.777   0.787   0.807   0.804   0.804...
            0.805   0.836   0.847   0.849   0.887   0.933   0.969;
            0.665   0.692   0.632   0.664   0.670   0.695   0.690   0.692...
            0.697   0.736   0.752   0.758   0.812   0.879   0.943;
            0.602   0.623   0.555   0.588   0.589   0.615   0.611   0.616...
            0.623   0.663   0.683   0.693   0.753   0.837   0.921;
            0.519   0.536   0.457   0.489   0.477   0.506   0.507   0.513...
            0.521   0.562   0.583   0.601   0.668   0.773   0.880;
            0.465   0.478   0.395   0.422   0.406   0.433   0.436   0.442...
            0.452   0.491   0.516   0.540   0.607   0.727   0.844;
            0.427   0.434   0.351   0.374   0.356   0.378   0.383   0.389...
            0.401   0.438   0.468   0.494   0.563   0.690   0.812];
        sig  = [0.110   0.118   0.121   0.118   0.118   0.123   0.119   0.103...
            0.114   0.117   0.104   0.103   0.091   0.062   0.037;
            0.057   0.050   0.054   0.047   0.054   0.049   0.059   0.051...
            0.047   0.054   0.047   0.053   0.046   0.033   0.022;
            0.105   0.095   0.106   0.094   0.108   0.100   0.114   0.103...
            0.096   0.108   0.099   0.114   0.098   0.077   0.049;
            0.138   0.133   0.158   0.136   0.158   0.156   0.173   0.165...
            0.150   0.170   0.166   0.183   0.160   0.139   0.087;
            0.151   0.160   0.193   0.166   0.186   0.190   0.210   0.204...
            0.190   0.218   0.214   0.233   0.208   0.185   0.118;
            0.169   0.188   0.238   0.206   0.223   0.233   0.252   0.253...
            0.241   0.283   0.281   0.307   0.283   0.256   0.169;
            0.178   0.208   0.264   0.232   0.244   0.263   0.280   0.287...
            0.276   0.329   0.329   0.359   0.342   0.307   0.213;
            0.184   0.227   0.287   0.241   0.264   0.286   0.300   0.311...
            0.302   0.363   0.365   0.399   0.385   0.349   0.249];
    else
        DCF  = [1.410   1.384   1.384   1.323   1.314   1.306   1.258   1.293...
            1.286   1.282   1.219   1.194   1.189   1.144   1.091;
            0.875   0.881   0.886   0.901   0.895   0.895   0.901   0.889...
            0.892   0.902   0.907   0.915   0.917   0.932   0.954;
            0.757   0.770   0.778   0.800   0.789   0.788   0.795   0.772...
            0.780   0.793   0.801   0.818   0.821   0.851   0.899;
            0.641   0.657   0.667   0.688   0.677   0.670   0.679   0.651...
            0.659   0.674   0.684   0.704   0.708   0.753   0.828;
            0.569   0.588   0.597   0.612   0.603   0.590   0.601   0.572...
            0.578   0.593   0.606   0.621   0.629   0.682   0.771;
            0.483   0.506   0.506   0.514   0.510   0.485   0.498   0.468...
            0.472   0.488   0.501   0.509   0.522   0.582   0.686;
            0.433   0.455   0.448   0.451   0.448   0.419   0.430   0.403...
            0.403   0.419   0.429   0.438   0.452   0.514   0.624;
            0.397   0.418   0.406   0.407   0.401   0.372   0.382   0.358...
            0.356   0.368   0.377   0.387   0.400   0.462   0.575];
        sig  = [0.123   0.129   0.119   0.112   0.125   0.120   0.103   0.112...
            0.100   0.112   0.112   0.103   0.097   0.087   0.077;
            0.050   0.055   0.049   0.054   0.051   0.056   0.050   0.048...
            0.046   0.048   0.047   0.046   0.050   0.047   0.040;
            0.093   0.103   0.105   0.106   0.101   0.109   0.102   0.095...
            0.090   0.101   0.093   0.096   0.107   0.106   0.086;
            0.128   0.153   0.163   0.159   0.149   0.163   0.152   0.141...
            0.138   0.154   0.138   0.151   0.173   0.180   0.151;
            0.143   0.175   0.199   0.194   0.178   0.197   0.183   0.172...
            0.168   0.188   0.164   0.189   0.220   0.236   0.203;
            0.159   0.197   0.247   0.235   0.211   0.243   0.227   0.214...
            0.210   0.230   0.202   0.242   0.287   0.317   0.281;
            0.164   0.220   0.279   0.264   0.230   0.281   0.261   0.238...
            0.238   0.257   0.229   0.276   0.332   0.373   0.337;
            0.166   0.238   0.306   0.286   0.248   0.308   0.281   0.254...
            0.255   0.280   0.248   0.301   0.366   0.418   0.381];
    end
else
```

```
if M < 6
    DCF  = [1.274   1.346   1.367   1.250   1.239   1.241   1.200   1.215...
            1.187   1.135   1.049   1.027   1.019   1.006   1.004;
            0.920   0.888   0.870   0.899   0.909   0.904   0.925   0.923...
            0.927   0.948   0.976   0.989   0.991   0.996   0.997;
            0.841   0.780   0.748   0.787   0.812   0.799   0.843   0.845...
            0.847   0.888   0.945   0.978   0.980   0.991   0.993;
            0.759   0.666   0.622   0.658   0.697   0.684   0.747   0.760...
            0.761   0.821   0.903   0.960   0.968   0.984   0.987;
            0.709   0.597   0.540   0.574   0.616   0.607   0.679   0.702...
            0.700   0.773   0.872   0.943   0.958   0.978   0.982;
            0.650   0.508   0.440   0.463   0.506   0.503   0.580   0.615...
            0.618   0.705   0.826   0.910   0.939   0.965   0.972;
            0.608   0.447   0.378   0.392   0.430   0.436   0.513   0.553...
            0.561   0.657   0.789   0.881   0.919   0.954   0.964;
            0.575   0.404   0.333   0.342   0.375   0.387   0.464   0.504...
            0.519   0.618   0.758   0.856   0.899   0.942   0.956];
    sig  = [0.108   0.122   0.110   0.107   0.132   0.125   0.129   0.105...
            0.119   0.110   0.055   0.050   0.036   0.014   0.010;
            0.047   0.051   0.045   0.056   0.054   0.050   0.053   0.053...
            0.056   0.050   0.030   0.018   0.020   0.007   0.006;
            0.094   0.101   0.091   0.113   0.113   0.101   0.111   0.108...
            0.117   0.110   0.067   0.035   0.043   0.018   0.015;
            0.137   0.153   0.147   0.169   0.174   0.168   0.179   0.165...
            0.180   0.177   0.115   0.065   0.066   0.032   0.029;
            0.165   0.182   0.185   0.200   0.214   0.210   0.222   0.202...
            0.228   0.224   0.154   0.094   0.085   0.045   0.041;
            0.196   0.227   0.230   0.246   0.265   0.267   0.277   0.250...
            0.289   0.281   0.211   0.137   0.117   0.068   0.061;
            0.220   0.258   0.254   0.275   0.294   0.302   0.316   0.281...
            0.328   0.314   0.253   0.172   0.145   0.086   0.078;
            0.240   0.282   0.268   0.294   0.312   0.324   0.346   0.303...
            0.353   0.340   0.284   0.198   0.170   0.102   0.090];
elseif M < 7
    DCF  = [1.216   1.309   1.372   1.307   1.314   1.298   1.273   1.263...
            1.227   1.203   1.167   1.137   1.117   1.068   1.032;
            0.910   0.908   0.880   0.890   0.892   0.890   0.894   0.900...
            0.914   0.916   0.927   0.941   0.948   0.967   0.982;
            0.881   0.816   0.762   0.776   0.781   0.777   0.784   0.794...
            0.818   0.823   0.844   0.873   0.888   0.926   0.961;
            0.817   0.718   0.642   0.656   0.660   0.652   0.666   0.678...
            0.709   0.720   0.749   0.791   0.814   0.878   0.931;
            0.776   0.656   0.565   0.577   0.580   0.569   0.587   0.601...
            0.635   0.646   0.681   0.730   0.762   0.840   0.906;
            0.721   0.578   0.469   0.474   0.472   0.462   0.481   0.500...
            0.534   0.545   0.587   0.645   0.688   0.785   0.865;
            0.686   0.529   0.411   0.410   0.403   0.393   0.412   0.433...
            0.464   0.476   0.523   0.585   0.634   0.743   0.831;
            0.662   0.493   0.371   0.366   0.353   0.343   0.363   0.384...
            0.412   0.426   0.473   0.538   0.592   0.708   0.803];
    sig  = [0.115   0.111   0.116   0.119   0.119   0.119   0.118   0.101...
            0.111   0.103   0.102   0.102   0.097   0.078   0.052;
            0.044   0.050   0.050   0.050   0.056   0.052   0.052   0.049...
            0.048   0.048   0.047   0.046   0.047   0.042   0.028;
            0.080   0.102   0.095   0.101   0.112   0.101   0.107   0.102...
            0.100   0.103   0.101   0.099   0.101   0.093   0.060;
            0.115   0.158   0.143   0.156   0.168   0.153   0.166   0.160...
            0.159   0.164   0.163   0.164   0.169   0.151   0.103;
            0.133   0.192   0.181   0.192   0.199   0.178   0.205   0.195...
            0.197   0.205   0.206   0.213   0.219   0.195   0.136;
            0.162   0.237   0.234   0.238   0.238   0.208   0.252   0.236...
            0.246   0.267   0.273   0.276   0.285   0.262   0.189;
            0.182   0.273   0.268   0.263   0.261   0.232   0.278   0.265...
            0.282   0.314   0.321   0.324   0.334   0.306   0.229;
            0.194   0.302   0.292   0.280   0.280   0.250   0.298   0.285...
            0.311   0.352   0.362   0.363   0.371   0.342   0.257];
else
    DCF  = [1.209   1.288   1.346   1.329   1.324   1.358   1.314   1.299...
            1.306   1.267   1.246   1.214   1.187   1.159   1.103;
            0.939   0.913   0.897   0.896   0.889   0.881   0.886   0.884...
            0.892   0.903   0.904   0.908   0.916   0.926   0.949;
```

```
                        0.888   0.832   0.798   0.792   0.778   0.760   0.769   0.765...
                        0.778   0.797   0.804   0.807   0.820   0.842   0.887;
                        0.839   0.756   0.697   0.683   0.666   0.635   0.646   0.641...
                        0.654   0.680   0.688   0.692   0.709   0.743   0.810;
                        0.808   0.712   0.630   0.613   0.593   0.554   0.561   0.560...
                        0.573   0.601   0.608   0.614   0.631   0.672   0.751;
                        0.771   0.656   0.545   0.525   0.495   0.448   0.453   0.453...
                        0.466   0.493   0.502   0.509   0.525   0.572   0.665;
                        0.749   0.623   0.492   0.467   0.430   0.380   0.383   0.383...
                        0.398   0.421   0.433   0.440   0.454   0.505   0.603;
                        0.733   0.598   0.456   0.426   0.383   0.332   0.333   0.333...
                        0.348   0.370   0.383   0.390   0.402   0.456   0.555];
                sig  = [0.121   0.127   0.124   0.127   0.115   0.124   0.117   0.103...
                        0.103   0.122   0.106   0.097   0.091   0.090   0.077;
                        0.042   0.050   0.052   0.054   0.049   0.055   0.049   0.044...
                        0.049   0.050   0.047   0.047   0.046   0.046   0.043;
                        0.076   0.096   0.100   0.109   0.096   0.108   0.097   0.092...
                        0.097   0.101   0.093   0.097   0.097   0.100   0.096;
                        0.112   0.143   0.154   0.159   0.145   0.155   0.145   0.145...
                        0.148   0.150   0.147   0.150   0.155   0.168   0.160;
                        0.134   0.168   0.190   0.184   0.177   0.182   0.175   0.178...
                        0.181   0.181   0.183   0.183   0.196   0.219   0.212;
                        0.155   0.195   0.231   0.213   0.218   0.217   0.212   0.217...
                        0.218   0.217   0.232   0.226   0.253   0.300   0.285;
                        0.167   0.208   0.255   0.229   0.243   0.238   0.231   0.242...
                        0.239   0.242   0.260   0.258   0.291   0.355   0.340;
                        0.174   0.220   0.273   0.240   0.258   0.252   0.242   0.262...
                        0.257   0.264   0.280   0.279   0.319   0.396   0.382];
            end
        end
    end
end
DCF     = DCF(j,i);
sigma   = sig(j,i);
```

6.6 Duration (Bracketed and Effective): Lee and Green – 2009

6.6.1 References

Lee, Jongwon (2009). Engineering Characterization of Earthquake Ground Motions, PhD dissertation, University of Michigan.

Lee, J. and Green, R.A. (2011). Predictive Equations for the Braketed and Effective Durations of Earthquake Ground Motions, *in preparation*.

6.6.2 Abstract

Using 324 three-component ground motion records from active seismic regions and 310 three-component ground motion records (both recorded and scaled) for stable continental regions, empirical models for duration parameters were developed. The model predicts bracketed duration ($D_{bracket}$) and effective duration (D_{eff}). The model is applicable for either shallow crustal earthquakes in active plate margins (i.e. WUS) or shallow stable continental regions (i.e. CEUS) for earthquakes between M5.0 and M7.6 and distances up to 200 km (up to 100 km for M5-6 earthquakes). The model is not applicable to subduction zone earthquakes.

6.6.3 Attenuation Relationship

The duration is a function of:

- D_{type} – Duration type: 1 for $D_{bracket}$, 2 for D_{eff}
- **M** – Moment magnitude
- G – Region: 1 for WUS, 0 for CEUS
- R_{rup} – Closest distance to rupture plane (km)
- S – Site category: 0 for rock, 1 for soil

$$D = \left\{\exp\left(c_1 + c_2(M-6) + c_3 R_{rup} + S\left[s_1 + s_2 R_{rup}\right]\right) - 1\right\} \cdot p\left(D > 0 | M, R_{rup}, S\right)$$

where:

$$p\left(D > 0 | M, R_{rup}, S\right) = probabilty\ of\ D > 0\ given\ M, R_{rup}, and\ S = \frac{1}{1 + e^{\beta_1 + \beta_2 M + \beta_3 R_{rup}}}$$

Note that the proabilty term is calculated separately from the rest of the equation in MATLAB code.

Standard Error

$$\sigma_{tot} = \sqrt{\sigma^2 + \tau^2}$$

Coefficients

Table 6-15. Regression coefficients and errors. (Note: Errors valid for ln(D+1).)

CEUS

T	c_1	c_2	c_3	s_1	s_2	τ	σ	σ_{tot}
$D_{bracket}$	2.67	0.75	-0.0058	-0.16	0.0021	0.43	0.51	0.67
D_{eff}	2.03	0.99	-0.0066	-0.18	0.0043	0.32	0.45	0.55

WUS

T	c_1	c_2	c_3	s_1	s_2	τ	σ	σ_{tot}
$D_{bracket}$	2.04	0.95	-0.022	0.074	0.0045	0.38	0.53	0.65
D_{eff}	1.49	1.04	-0.014	0.14	0.0020	0.36	0.42	0.55

Table 6-16. Regression coefficients.

CEUS

T	Site	β_1	β_2	β_3
$D_{bracket}$	Rock	9.47	-2.28	0.042
	Soil	4.19	-1.32	0.025
D_{eff}	Rock	9.12	-1.95	0.039
	Soil	4.24	-1.21	0.025

WUS

T	c_1	β_1	β_2	β_3
$D_{bracket}$	Rock	4.11	-1.24	0.058
	Soil	-0.39	-0.56	0.039
D_{eff}	Rock	8.60	-1.83	0.099
	Soil	8.71	-1.76	0.052

6.6.4 Calibration Plots

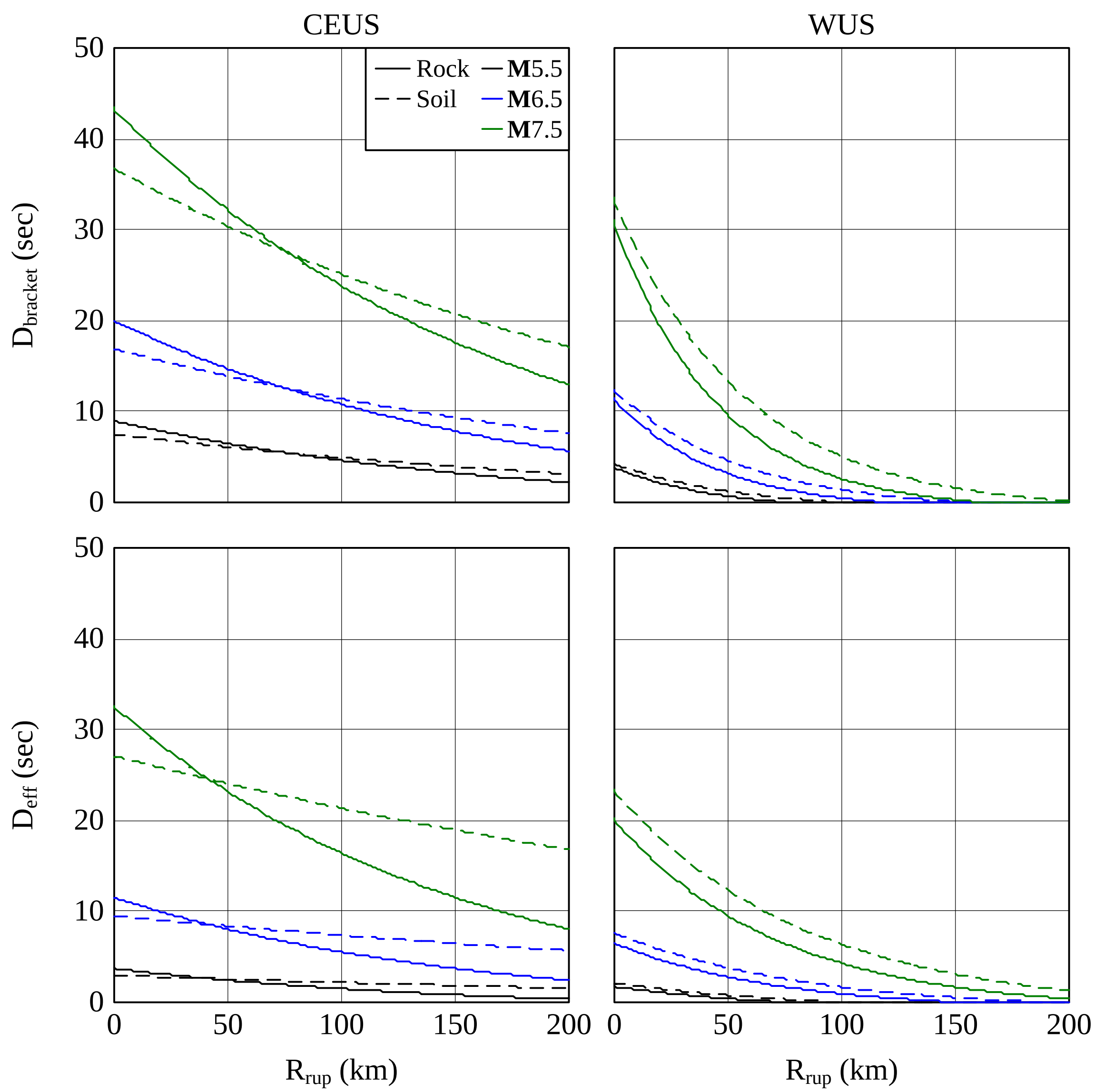


Figure 6-19. Non-zero bracketed and effective duration as a function of distance for given parameters.

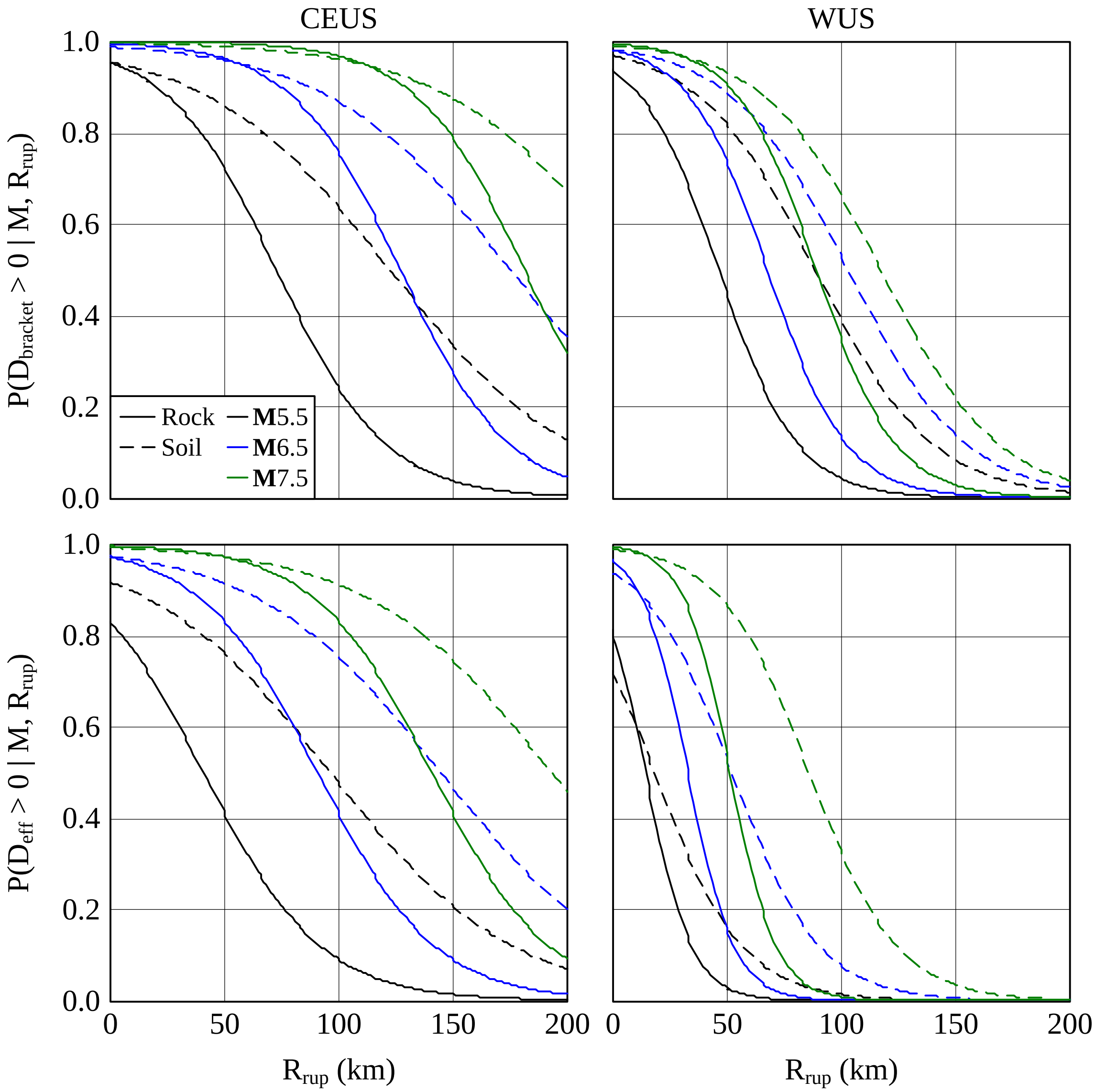


Figure 6-20. Probability that duration is greater than zero as a function of distance.

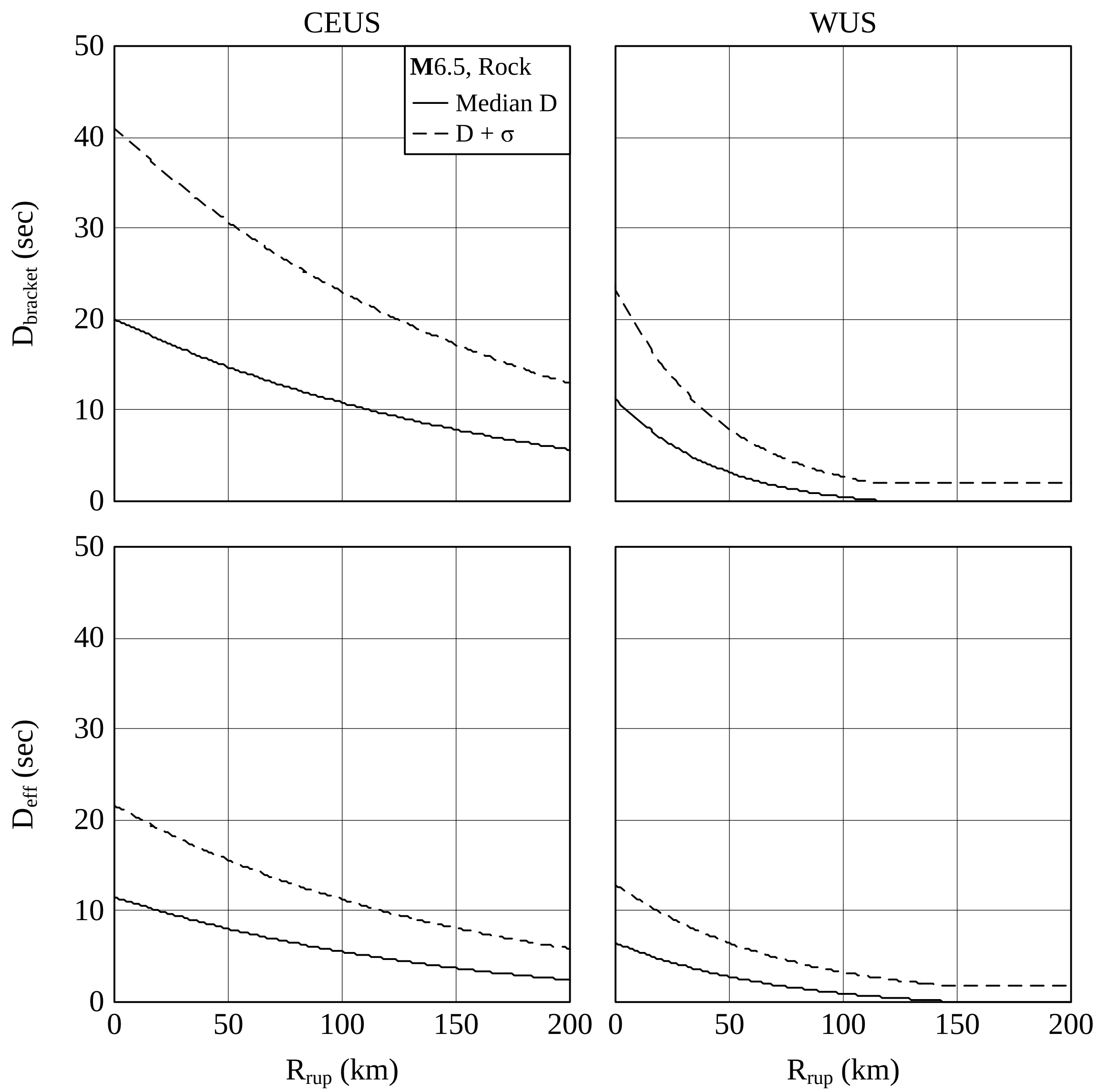


Figure 6-21. Example of application of median non-zero bracketed and effective duration plus one standard deviation.

6.6.5 Database

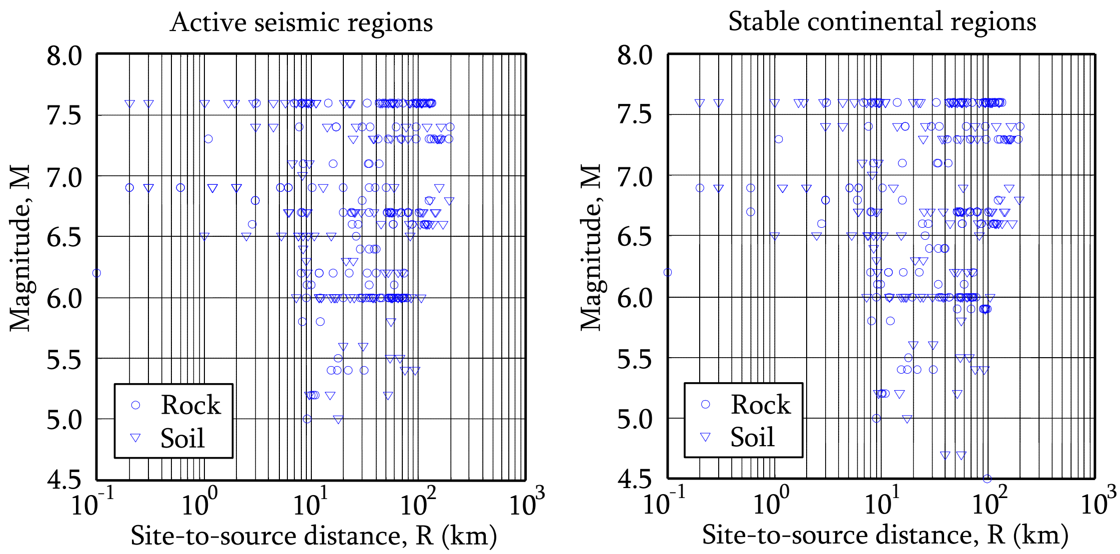


Figure 6-22. Earthquake magnitude and site-to-source distance distributions of the strong ground motion data set.

6.6.6 MATLAB Code

```
% by Kathryn A. Gunberg 8/4/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Lee and Green bracketed/effective duration equation, 2009
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% D     = Duration: 1 for bracketed, 2 for effective
% M     = Moment Magnitude
% G     = Region: 1 for WUS, 0 for CEUS
% Rrup  = Closest distance to rupture plane (km)
% S     = Soil category: 0 for rock, 1 for soil
% --------------------------------------------------------------------------
% Output
% Dbe  = Significant duration (sec)
% sigma = logarithmic standard deviation of Dsig prediction
% P     = Probability of 0 duration
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Dbe, sigma, P] = LG_2009_Dbe(D, M, G, Rrup, S)
if G == 0
    c1   = [2.67    2.03];
    c2   = [0.75    0.99];
    c3   = [-0.0058 -0.0066];
    s1   = [-0.16   -0.18];
    s2   = [0.0021  0.0043];
    tau  = [0.43    0.32];
    sig  = [0.51    0.45];
    sigt = [0.67    0.55];
    if S == 0
        b1   = [9.47    9.12];
        b2   = [-2.28   -1.95];
        b3   = [0.042   0.039];
    else
        b1   = [4.19    4.24];
        b2   = [-1.32   -1.21];
        b3   = [0.025   0.025];
    end
else
    c1   = [2.04    1.49];
    c2   = [0.95    1.04];
    c3   = [-0.022  -0.014];
    s1   = [0.074   0.14];
    s2   = [0.0045  0.0020];
    tau  = [0.38    0.36];
    sig  = [0.53    0.42];
    sigt = [0.65    0.55];
    if S == 0
        b1   = [4.11    8.60];
        b2   = [-1.24   -1.83];
        b3   = [0.058   0.099];
    else
        b1   = [-0.39   8.71];
        b2   = [-0.56   -1.76];
        b3   = [0.039   0.052];
    end
end
Dbe = max(exp(c1(D) + c2(D)*(M-6) + c3(D)*Rrup + S*(s1(D) + s2(D)*Rrup))-1,0);
sigma = sigt(D);
P = 1/(1 + exp(b1(D) + M*b2(D) + Rrup*b3(D)));
```

6.7 Duration (Significant): Lee and Green – 2009

6.7.1 References

Lee, Jongwon (2009). Engineering Characterization of Earthquake Ground Motions, PhD dissertation, University of Michigan.

Lee, J. and Green, R.A. (2011). Predictive Equations for the Significant Duration of Earthquake Ground Motions, *in preparation*.

6.7.2 Abstract

Using 324 three-component ground motion records from active seismic regions and 310 three-component ground motion records (both recorded and scaled) for stable continental regions, empirical models for duration parameters were developed. The model predicts significant durations (D_{sig}), $D_{5\text{-}75}$ and $D_{5\text{-}95}$. The model is applicable for either shallow crustal earthquakes in active plate margins (i.e. WUS) or shallow stable continental regions (i.e. CEUS) for earthquakes between M5.0 and M7.6 and distances up to 200 km (up to 100 km for M5-6 earthquakes). The model is not applicable to subduction zone earthquakes.

6.7.3 Attenuation Relationship

The duration is a function of:

D_{type}	– Duration type: 1 for $D_{5\text{-}75}$, 2 for $D_{5\text{-}95}$
M	– Moment magnitude
G	– Region: 1 for WUS, 0 for CEUS
R_{rup}	– Closest distance to rupture plane (km)
S	– Site category: 0 for rock, 1 for soil

$$D_{sig} = c_1 + c_2 \exp(M - 6) + c_3 R_{rup} + S\left[s_1 + s_2(M - 6) + s_3 R_{rup}\right]$$

Standard Error

$$\sigma_{tot_{\ln D_{sig}}} = \sqrt{\sigma^2 + \tau^2}$$

Coefficients

Table 6-17. Regression coefficients and errors.

CEUS

T	c_1	c_2	c_3	s_1	s_2	s_3	τ	σ	σ_{tot}
$D_{5\text{-}75}$	0.0	2.23	0.10	-0.72	-0.19	-0.0140	0.46	0.35	0.58
$D_{5\text{-}95}$	2.5	4.21	0.14	-0.98	-0.45	-0.0071	0.37	0.32	0.49

WUS

T	c_1	c_2	c_3	s_1	s_2	s_3	τ	σ	σ_{tot}
$D_{5\text{-}75}$	0.0	1.86	0.06	0.22	0.0	0.0000	0.28	0.37	0.46
$D_{5\text{-}95}$	1.5	3.22	0.11	2.01	0.8	-0.0097	0.26	0.28	0.38

6.7.4 *Calibration Plots*

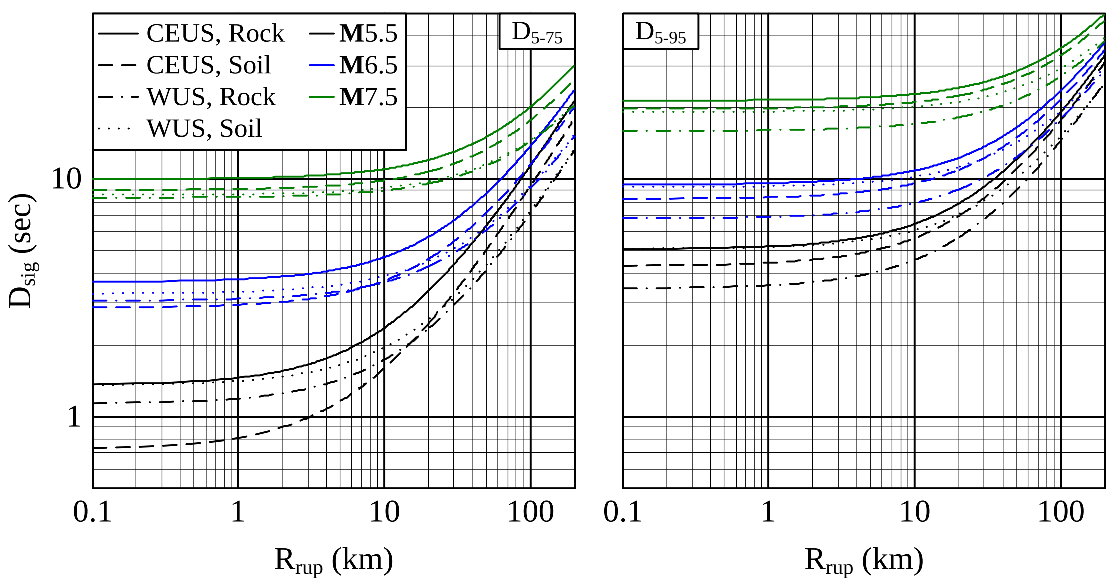


Figure 6-23. Significant duration as a function of distance for given parameters.

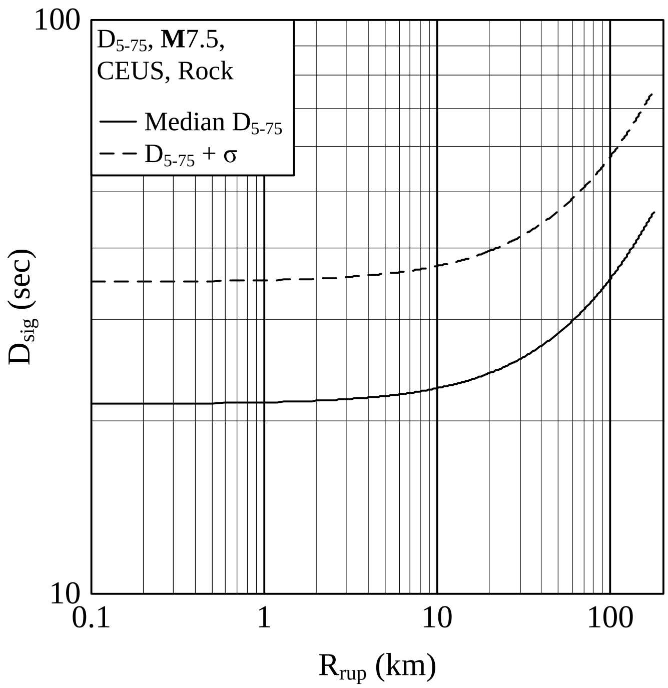


Figure 6-24. Example of application of median significant duration plus one standard deviation.

6.7.5 Database

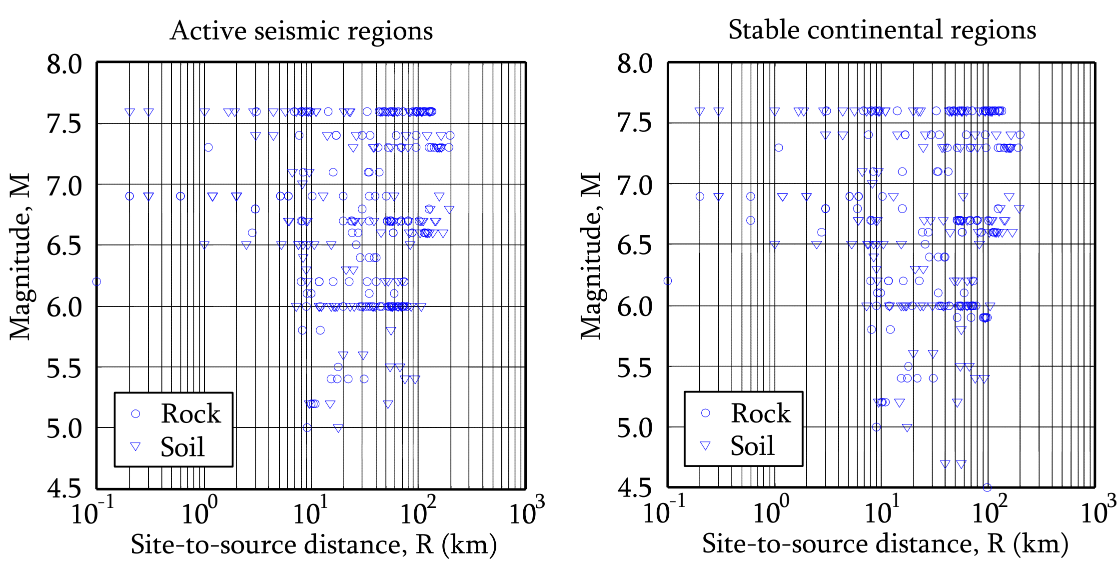


Figure 6-25. Earthquake magnitude and site-to-source distance distributions of the strong ground motion data set.

6.7.6 MATLAB Code

```
% by Kathryn A. Gunberg 8/4/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Lee and Green significant duration equation, 2009
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% D     = Significant duration: 1 for D5-75, 2 for D5-95
% M     = Moment Magnitude
% G     = Region: 1 for WUS, 0 for CEUS
% Rrup  = Closest distance to rupture plane (km)
% S     = Soil category: 0 for rock, 1 for soil
% --------------------------------------------------------------------------
% Output
% Dsig  = Significant duration (sec)
% sigma = logarithmic standard deviation of Dsig prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Dsig, sigma] = LG_2009_Dsig(D, M, G, Rrup, S)
if G == 0
    c1   = [0.0     2.5];
    c2   = [2.23    4.21];
    c3   = [0.10    0.14];
    s1   = [-0.72   -0.98];
    s2   = [-0.19   -0.45];
    s3   = [-0.0140 -0.0071];
    tau  = [0.46    0.37];
    sig  = [0.35    0.32];
    sigt = [0.58    0.49];
else
    c1   = [0.0     1.5];
    c2   = [1.86    3.22];
    c3   = [0.06    0.11];
    s1   = [0.22    2.01];
    s2   = [0.0     0.8];
    s3   = [0.0000  -0.0097];
    tau  = [0.28    0.26];
    sig  = [0.37    0.28];
    sigt = [0.46    0.38];
end
Dsig = c1(D) + c2(D)*exp(M-6) + c3(D)*Rrup + S*(s1(D) + s2(D)*(M-6) + s3(D)*Rrup);
sigma = sigt(D);
```

6.8 Equivalent Number of Stress & Strain Cycles: Lee and Green – 2009

6.8.1 References

Lee, Jongwon (2009). Engineering Characterization of Earthquake Ground Motions, PhD dissertation, University of Michigan.

Lee, J. and Green, R.A. (2011). Predictive Equations for the Number of Equivalent Stress and Strain Cycles for Earthquake Ground Motions, *in preparation*.

6.8.2 Abstract

Using 324 three-component ground motion records from active seismic regions and 310 three-component ground motion records (both recorded and scaled) for stable continental regions, empirical models for duration parameters were developed. The model predicts the equivalent number of stress ($n_{eq\tau}$) and strain ($n_{eq\gamma}$) cycles. The model is applicable for either shallow crustal earthquakes in active plate margins (i.e. WUS) or shallow stable continental regions (i.e. CEUS) for earthquakes between M5.0 and M7.6 and distances up to 200 km (up to 100 km for M5-6 earthquakes). The model is not applicable to subduction zone earthquakes.

6.8.3 Attenuation Relationship

The equivalent number of stress/strain cycles is a function of:

- n – Model parameter, 0.0, 0.1, 0.2, 0.3 0.4, or 0.5 for stress, enter -1 for strain
- **M** – Moment magnitude
- G – Region: 1 for WUS, 0 for CEUS
- R_{rup} – Closest distance to rupture plane (km)
- z – Depth in soil profile (m)

$$\ln(n_{eq}) = \exp(c_1 z) + c_2 R_{rup}{}^{c_3} + c_4 M + c_5$$

Standard Error

$$\sigma_{tot} = \sqrt{\sigma^2 + \tau^2}$$

Coefficients

Table 6-18. Regression coefficients and errors.

CEUS

T	c_1	c_2	c_3	c_4	c_5	τ	σ	σ_{tot}
0.0	-0.0211	2.111	0.120	0.005	-1.80	0.36	0.51	0.62
0.1	-0.0214	2.266	0.113	0.018	-2.03	0.36	0.50	0.62
0.2	-0.0219	2.415	0.107	0.042	-2.29	0.36	0.49	0.61
0.3	-0.0209	2.150	0.120	0.040	-1.99	0.36	0.48	0.60
0.4	-0.0190	1.857	0.136	0.050	-1.77	0.34	0.48	0.59
0.5	-0.0171	1.760	0.141	0.055	-1.69	0.34	0.48	0.59
Strain	-0.020	0.80	0.22	0.19	-1.30	0.26	0.47	0.54

WUS

T	c_1	c_2	c_3	c_4	c_5	τ	σ	σ_{tot}
0.0	-0.0123	1.820	0.120	0.074	-2.02	0.30	0.45	0.54
0.1	-0.0116	2.042	0.108	0.116	-2.47	0.31	0.42	0.52
0.2	-0.0112	2.083	0.107	0.104	-2.43	0.32	0.41	0.52
0.3	-0.0104	1.904	0.117	0.107	-2.27	0.30	0.41	0.51
0.4	-0.0101	1.664	0.131	0.122	-2.11	0.30	0.40	0.50
0.5	-0.0107	1.370	0.150	0.154	-1.98	0.30	0.40	0.50
Strain	-0.0099	0.67	0.21	0.28	-1.79	0.24	0.41	0.48

6.8.4 Calibration Plots

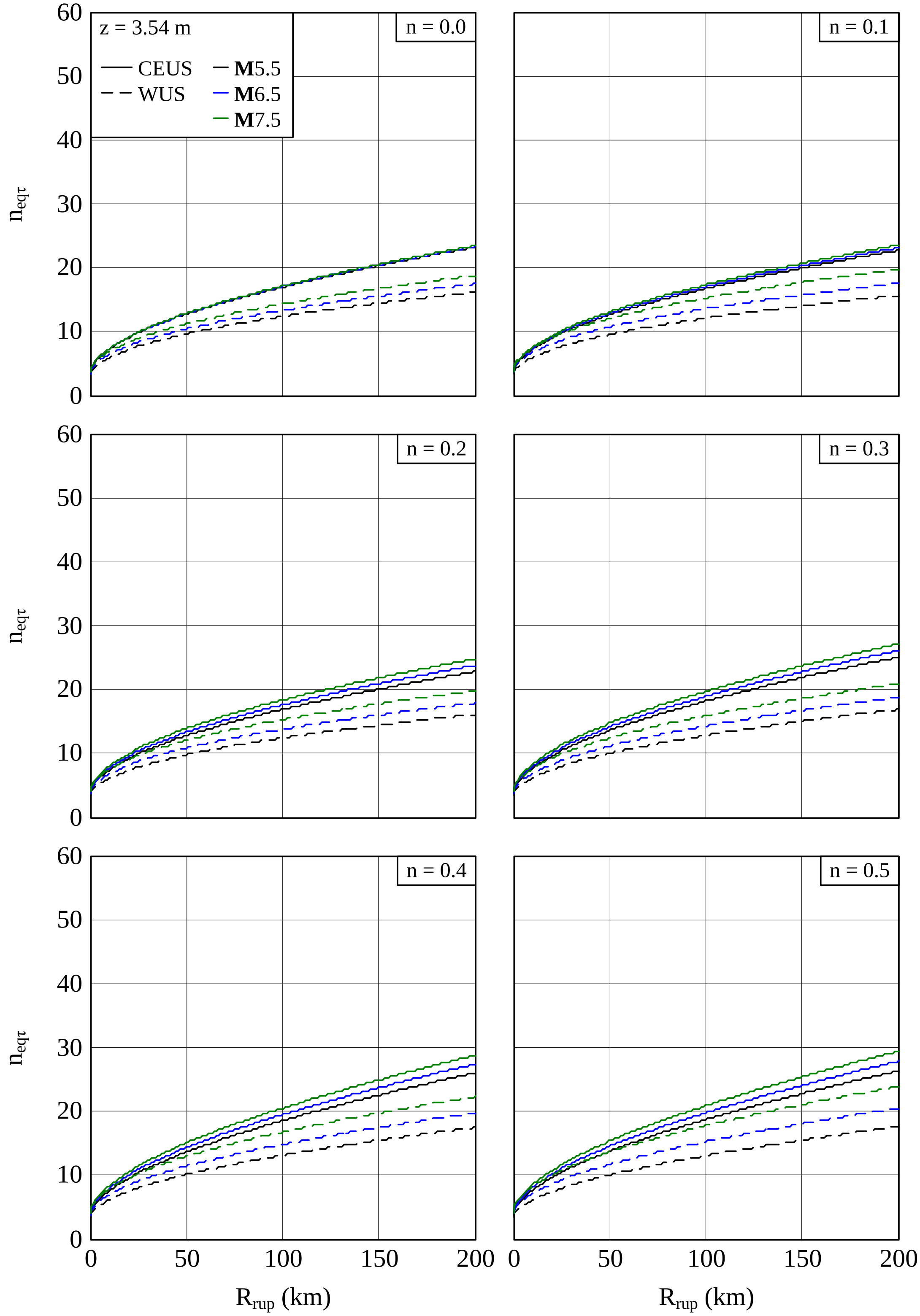
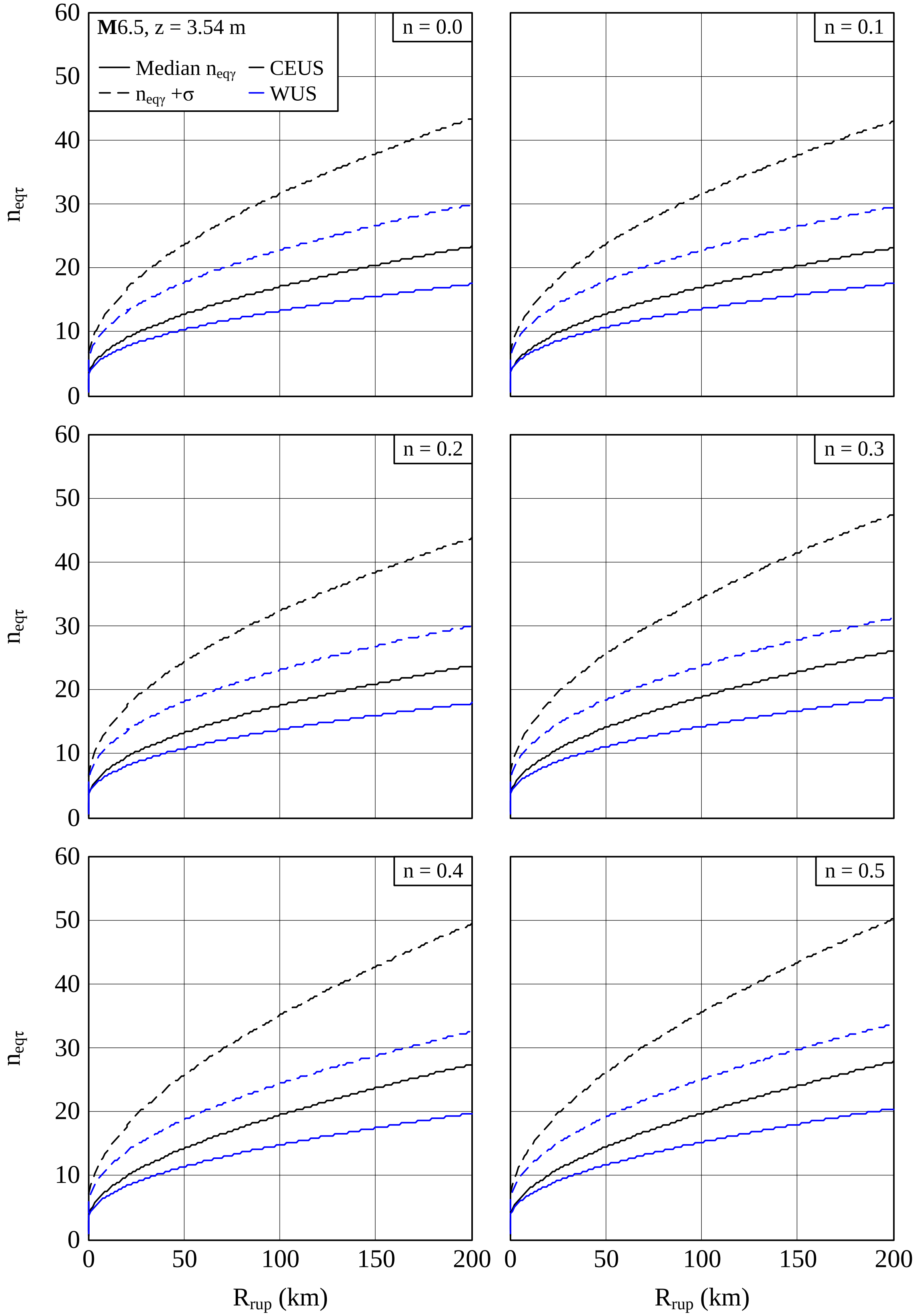


Figure 6-26. Number of equivalent stress cycles as a function of distance for given parameters.



M6.5, z = 3.54 m
Median $n_{eq\gamma}$
$n_{eq\gamma}$ +σ
CEUS
WUS
n = 0.0
n = 0.1
n = 0.2
n = 0.3
n = 0.4
n = 0.5
$n_{eq\tau}$
R_{rup} (km)

Figure 6-27. Example of application of number of equivalent stress cycles plus one standard deviation.

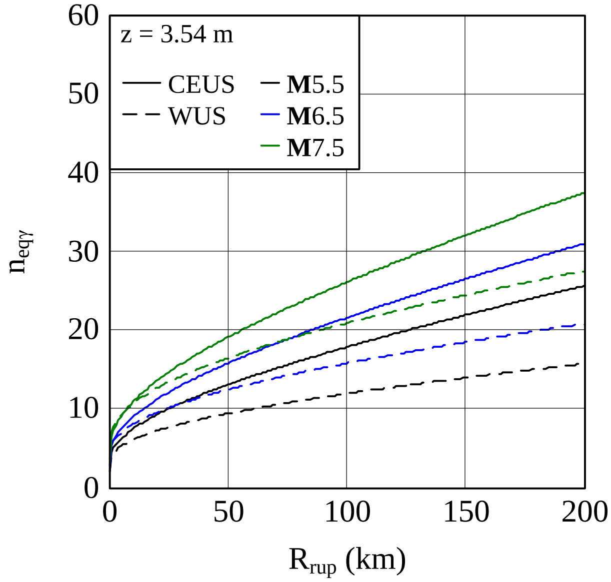


Figure 6-28. Number of equivalent strain cycles as a function of distance for given parameters.

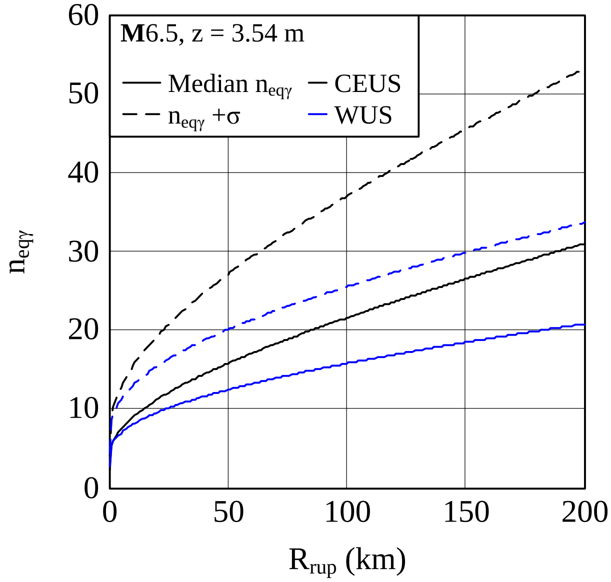


Figure 6-29. Example of application of number of equivalent strain cycles plus one standard deviation.

6.8.5 Database

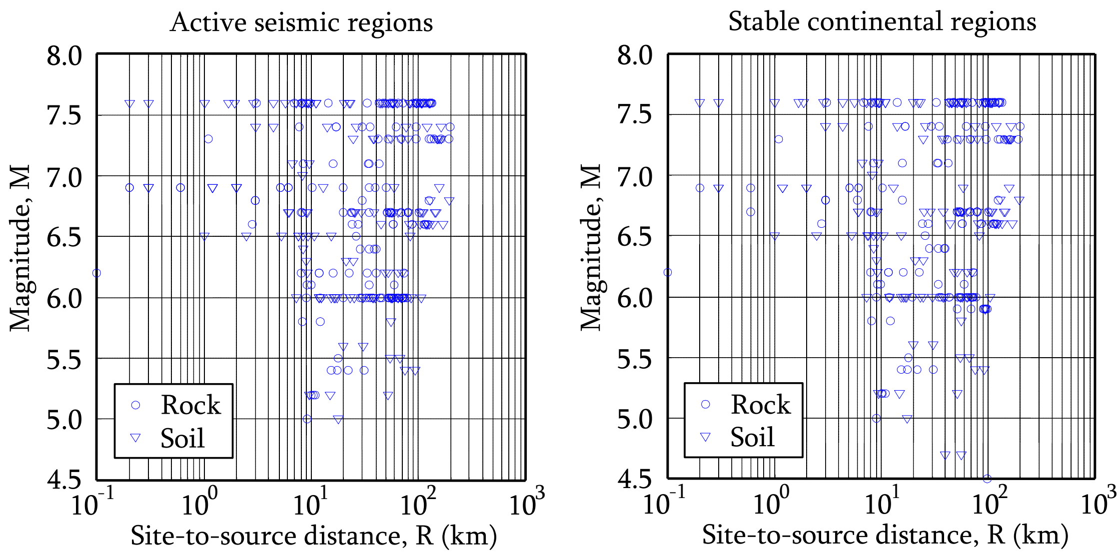


Figure 6-30. Earthquake magnitude and site-to-source distance distributions of the strong ground motion data set.

6.8.6 MATLAB Code

```
% by Kathryn A. Gunberg 8/4/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Lee and Green equivalent number of cycles equation, 2009
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% n     = Model parameter, 0.0, 0.1, 0.2, 0.3 0.4, or 0.5 for stress,
%         enter -1 for strain
% M     = Moment Magnitude
% G     = Region: 1 for WUS, 0 for CEUS
% Rrup  = Closest distance to rupture plane (km)
% z     = Depth (m)
% -------------------------------------------------------------------------
% Output
% neq   = Number of equivalent stress or strain cycles
% sigma = logarithmic standard deviation of neq prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [neq, sigma] = LG_2009_neq(n, M, G, Rrup, z)
MP   = [0.0 0.1 0.2 0.3 0.4 0.5 -1];
if G == 0
    c1   = [-0.0211 -0.0214 -0.0219 -0.0209 -0.0190 -0.0171 -0.020];
    c2   = [2.111   2.266   2.415   2.150   1.857   1.760   0.80];
    c3   = [0.120   0.113   0.107   0.120   0.136   0.141   0.22];
    c4   = [0.005   0.018   0.042   0.040   0.050   0.055   0.19];
    c5   = [-1.80   -2.03   -2.29   -1.99   -1.77   -1.69   -1.30];
    tau  = [0.36    0.36    0.36    0.36    0.34    0.34    0.26];
    sig  = [0.51    0.50    0.49    0.48    0.48    0.48    0.47];
    sigt = [0.62    0.62    0.61    0.60    0.59    0.59    0.54];
else
    c1   = [-0.0123 -0.0116 -0.0112 -0.0104 -0.0101 -0.0107 -0.0099];
    c2   = [1.820   2.042   2.083   1.904   1.664   1.370   0.67];
    c3   = [0.120   0.108   0.107   0.117   0.131   0.150   0.21];
    c4   = [0.074   0.116   0.104   0.107   0.122   0.154   0.28];
    c5   = [-2.02   -2.47   -2.43   -2.27   -2.11   -1.98   -1.79];
    tau  = [0.30    0.31    0.32    0.30    0.30    0.30    0.24];
    sig  = [0.45    0.42    0.41    0.41    0.40    0.40    0.41];
    sigt = [0.54    0.52    0.52    0.51    0.50    0.50    0.48];
end
i = find(MP == n);
neq = exp(exp(c1(i)*z) + c2(i)*Rrup^c3(i) + c4(i)*M + c5(i));
sigma = sigt(i);
```

6.9 Duration (Significant, Bracketed and Uniform): Bommer, Stafford and Alarcón – 2009

6.9.1 References

Bommer, J. J., P. J. Stafford, and J. E. Alarcón (2009). Empirical Equations for the Prediction of the Significant, Bracketed, and Uniform Duration of Earthquake Ground Motion, *Bulletin of the Seismological Society of America* **99**(6), 3217-3233.

6.9.2 Abstract

Using records from the Next Generation Attenuation flatfile, empirical models for duration parameters were developed. The model predicts significant duration (D_{SR}), bracketed duration (D_{BA}) and uniform duration (D_{UA}). The model is applicable for shallow crustal earthquakes in active plate margins for earthquakes between M4.8 and M7.9 and distances up to 100 km (up to 100 km for M5-6 earthquakes).

6.9.3 Attenuation Relationship

The duration is a function of:

D_{type} – Duration type:
- 1 for D_{SR}; threashold: 5-75% of Arias intensity
- 2 for D_{SR}; threashold: 5-95% of Arias Intensity
- 3 for D_{BA}; threashold: 0.025g
- 4 for D_{BA}; threashold: 0.050g
- 5 for D_{BA}; threashold: 0.100g
- 6 for D_{UA}; threashold: 0.025g
- 7 for D_{UA}; threashold: 0.050g
- 8 for D_{UA}; threashold: 0.100g

M – Moment magnitude
Z_{TOR} – Depth to top of rupture plane (km)
F – Fault type: 1 for reverse and reverse/oblique, 0 for normal and strike-slip
R_{rup} – Closest distance to rupture plane (km)
V_{S30} – Shear wave velocity (m/s) averaged over top 30 m
arb – Error: 0 for error from geometric mean of horizontal components, 1 for arbitrary

$$\ln(D_{SR}) = c_0 + m_1 M + (r_1 + r_2 M)\ln\sqrt{{R_{rup}}^2 + {h_1}^2} + v_1 \ln V_{S30} + z_1 Z_{TOR}$$

$$\ln(D_{BA}) = c_0 + m_1 M + r_1 \ln\sqrt{{R_{rup}}^2 + {h_1}^2} + v_1 \ln V_{S30} + f_1 F_{rv}$$

$$\ln(D_{UA}) = c_0 + m_1 M + r_1 \ln\sqrt{{R_{rup}}^2 + {h_1}^2} + v_1 \ln V_{S30} + f_1 F_{rv}$$

Coefficients

Table 6-19. Significant duration coefficients.

Parameter	D_{SR} (5-75%)	D_{SR} (5-75%)
c_0	-5.6298	-2.2393
m_1	1.2619	0.9368
r_1	2.0063	1.5686
r_2	-0.252	-0.1953
h_1	2.3316	2.5
v_1	-0.2900	-0.3478
z_1	-0.0522	-0.0365
$\sigma_{T,ARB}$	0.5564	0.4748
$\sigma_{T,GM}$	0.5289	0.4616

Table 6-20. Bracketed duration coefficients.

Parameter	D_{BA} (0.025g)	D_{BA} (0.050g)	D_{BA} (0.100g)
c_0	9.6688	3.0982	0.6342
m_1	1.3798	1.6885	1.7122
r_1	-3.1204	-2.2715	-2.7126
h_1	46.3141	19.3897	11.1824
v_1	-0.6247	-0.7994	-0.5269
f_1	0.1730	0.1450	0.1486
$\sigma_{T,ARB}$	1.2271	1.5165	1.8809
$\sigma_{T,GM}$	1.1425	1.3940	1.7351

Table 6-21. Uniform duration coefficients.

Parameter	D_{UA} (0.025g)	D_{UA} (0.050g)	D_{UA} (0.100g)
c_0	5.5325	3.6260	0.6011
m_1	1.5598	1.5675	1.5360
r_1	-2.6156	-2.5499	-2.6030
h_1	22.5475	12.6151	7.7907
v_1	-0.9392	-0.9929	-0.7645
f_1	0.2275	0.2070	0.2902
$\sigma_{T,ARB}$	1.2840	1.4272	1.5733
$\sigma_{T,GM}$	1.2410	1.3694	1.5058

6.9.4 *Calibration Plots*

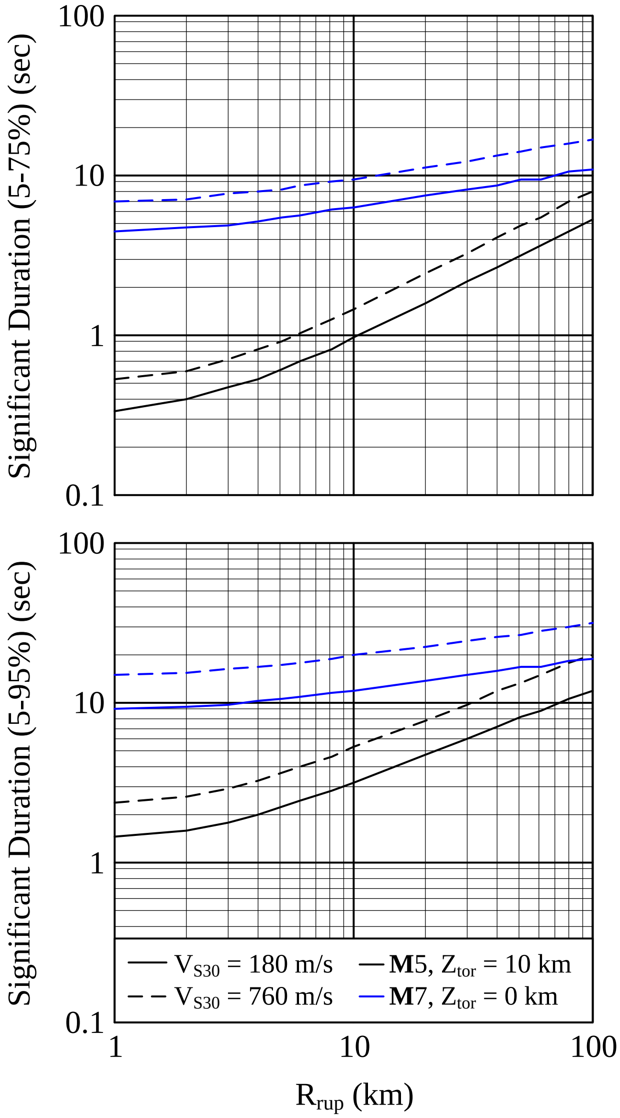


Figure 6-31. Signficant duration as a function of distances for various conditions.

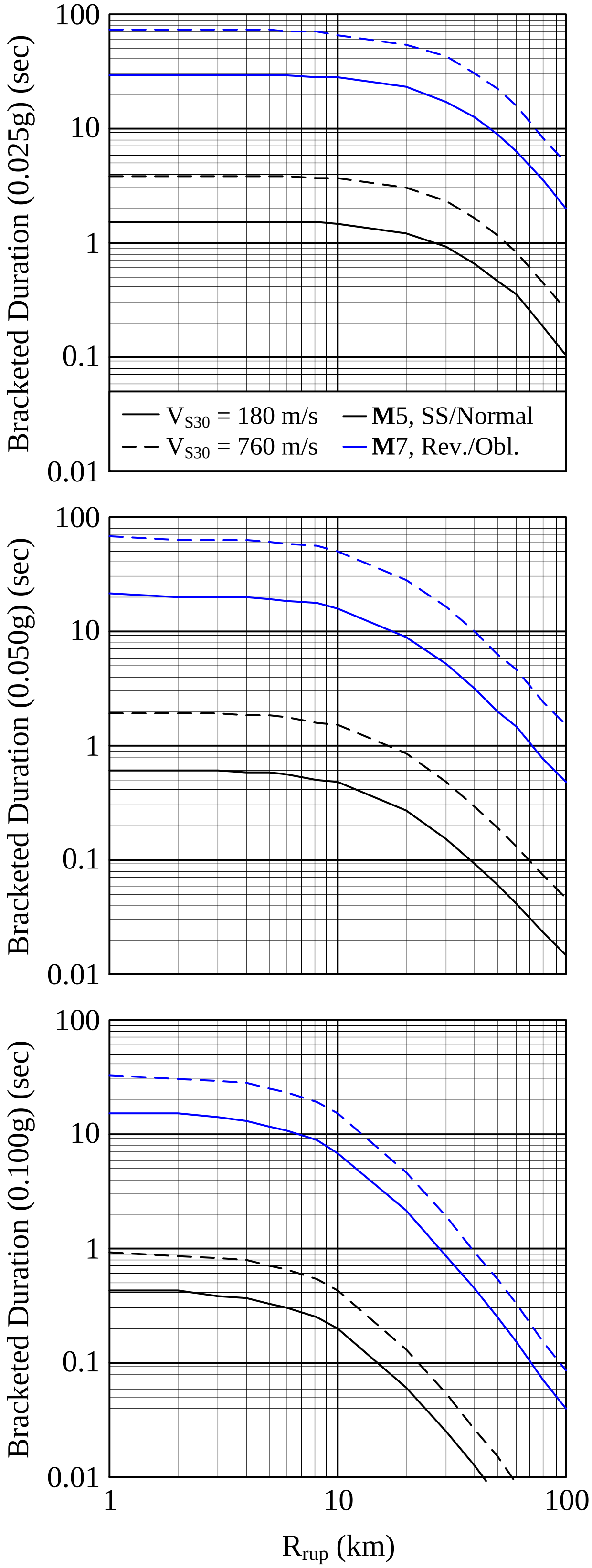


Figure 6-32. Bracketed duration as a function of distances for various conditions.

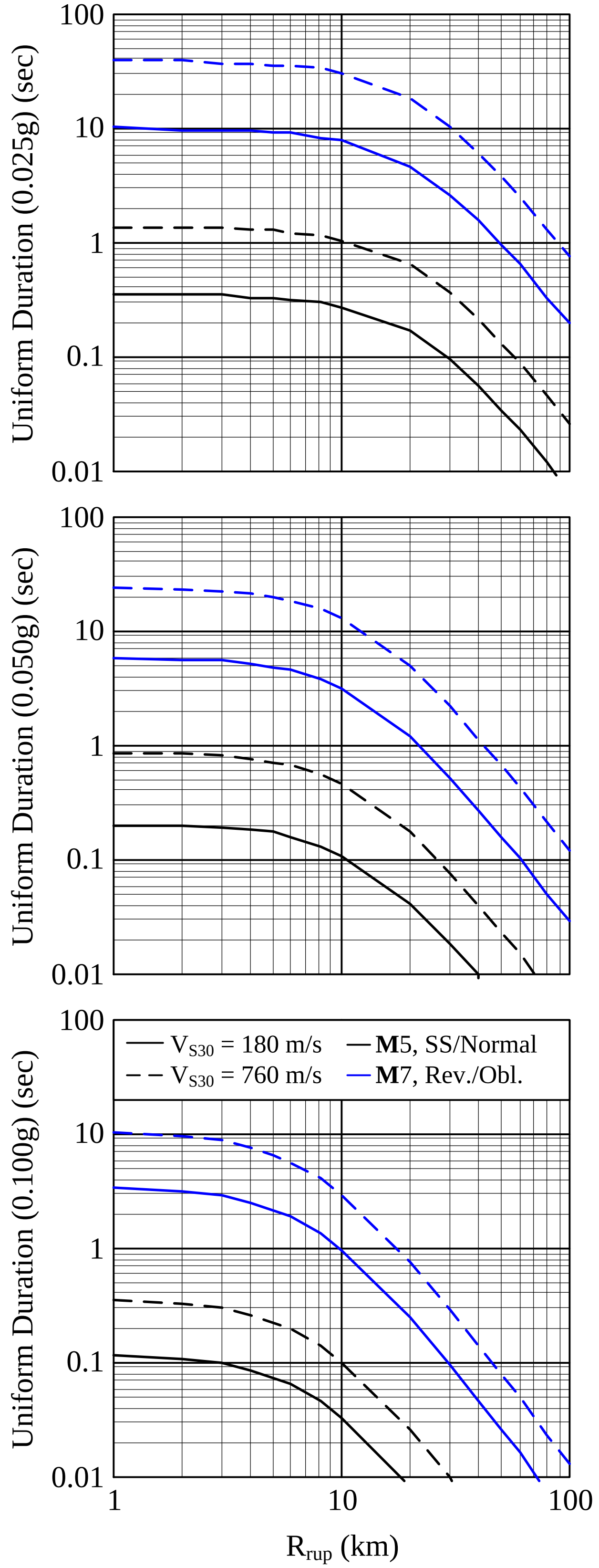


Figure 6-33. Uniform duration as a function of distances for various conditions.

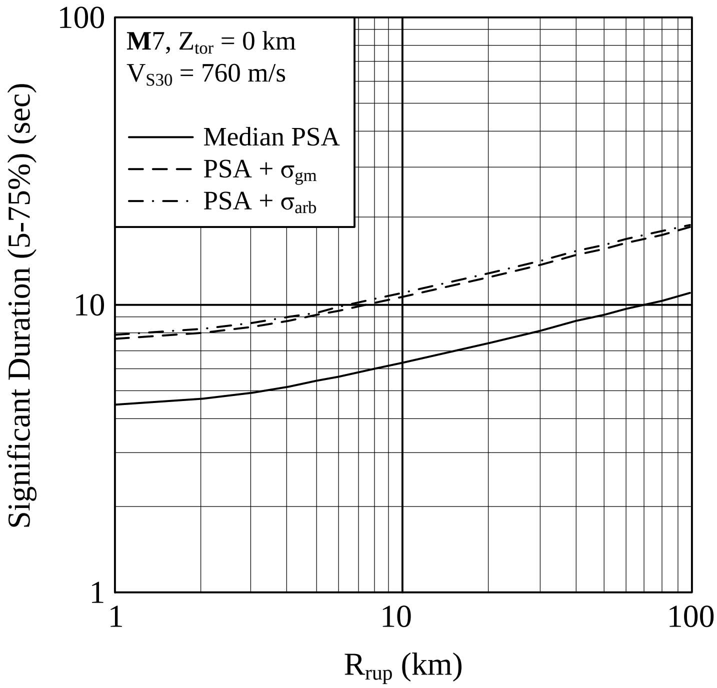


Figure 6-34. Example of application of duration plus one standard deviation.

6.9.5 Database

Table 6-22. Sizes of datasets used for the derivation of the empirical predictive models for different measures of duration.

	D_{SR} (5-75%)	D_{SR} (5-75%)	D_{BA} (0.025g)	D_{BA} (0.050g)	D_{BA} (0.100g)	D_{UA} (0.025g)	D_{UA} (0.050g)	D_{UA} (0.100g)
Eqs	114	114	112	104	95	112	104	95
Recs	2406	2406	1918	1454	853	1918	1456	854
Comps	4812	4812	3699	2681	1471	3706	2699	1487
Pairs	2406	2406	1795	1271	652	1797	1272	657

Eqs, number of earthquakes contributing records; Recs, number of records contributing components; Comps, number of components used; and Paris, number of records with two nonzero durations on both horizontal components.

6.9.6 MATLAB Code

```
% by Kathryn A. Gunberg 8/4/2009
% Virginia Tech
% kgunberg@vt.edu
%
% Bommer et al. significant/bracketed/uniform duration equation, 2009
%
% Note: all inputs and outputs are scalars (i.e., 1x1 matrix)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input Variables
% D     = Duration type:
%           1 for D_SR; threashold:  5-75% of Arias intensity
%           2 for D_SR; threashold:  5-95% of Arias Intensity
%           3 for D_BA; threashold:  0.025g
%           4 for D_BA; threashold:  0.050g
%           5 for D_BA; threashold:  0.100g
%           6 for D_UA; threashold:  0.025g
%           7 for D_UA; threashold:  0.050g
%           8 for D_UA; threashold:  0.100g
% M     = Moment Magnitude
% Ztor  = Depth to top of rupture plane (km)
% F     = Fault type: 1 for reverse and reverse/oblique, 0 for normal and strike-slip
% Rrup  = Closest distance to rupture surface (km)
% Vs30  = Shear wave velocity (m/s) averaged over top 30 m
% arb   = Error type: 1 for arbitrary, 0 for geometric mean
% -------------------------------------------------------------------------
% Output
% Dsbu  = Significant, Bracketed or Uniform duration (sec)
% sigma = logarithmic standard deviation of Dsbu prediction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Dsbu, sigma] = BSA_2009_Dsbu(D, M, Ztor, F, Rrup, Vs30, arb)
c        = [-5.6298 -2.2393 9.6688  3.0982  0.6342  5.5325  3.6260  0.6011];
m        = [1.2619  0.9368  1.3798  1.6885  1.7122  1.5598  1.5675  1.5360];
r1       = [2.0063  1.5686  -3.1204 -2.2715 -2.7126 -2.6156 -2.5499 -2.6030];
r2       = [-0.252  -0.1953 0       0       0       0       0       0];
h        = [2.3316  2.5 46.3141 19.3897 11.1824 22.5475 12.6151 7.7907];
v        = [-0.2900 -0.3478 -0.6247 -0.7994 -0.5269 -0.9392 -0.9929 -0.7645];
z        = [-0.0522 -0.0365 0       0       0       0       0       0];
f        = [0       0       0.1730  0.1450  0.1486  0.2275  0.2070  0.2902];
s_arb    = [0.5564  0.4748  1.2271  1.5165  1.8809  1.2840  1.4272  1.5733];
s_gm     = [0.5289  0.4616  1.1425  1.3940  1.7351  1.2410  1.3694  1.5058];
Dsbu = exp(c(D)+m(D)*M+(r1(D)+r2(D)*M)*log(sqrt(Rrup^2+h(D)^2))+v(D)*log(Vs30)+z(D)*Ztor+f(D)*F);
if arb == 1
    sigma = s_arb(D);
else
    sigma = s_gm(D);
end
```