PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Adjusting Ground-Motion Intensity Measures to a Reference Site for which V_{S30} = 3000 m/sec

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PEER Report No. 2015/06
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ABSTRACT

Adjustment factors that can used to convert ground-motion intensity measures at sites with V_{S30} = 760 m/sec and V_{S30} = 2000 m/sec to a reference rock site, defined as one with V_{S30} = 3000 m/sec, are provided as tables: (1) for moment magnitudes from 2 to 8; (2) rupture distances from 2 km to 1200 km; (3) response spectra at periods from 0.01 sec to 10.0 sec; and (4) peak acceleration and peak velocity. Ten velocity models used in ground-motion studies in central and eastern North America with V_{S30} values very close to 760 m/sec were considered, and adjustment factors are provided for two of those models that effectively span the range of models; in addition, for the convenience of the user, adjustment factors are provide for an average of a representative set of models with V_{S30} = 760 m/sec. For models with this velocity, adjustment factors are provided for four values of the diminution parameter κ, ranging from 0.005 sec to 0.030 sec. The adjustment factors are based on stochastic-method simulations of ground motion.

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1 Introduction

The ground-motion intensity measures (GMIMs) used in the PEER NGA-East project were derived from recordings obtained from sites with a large range of V_{S30} values (the parameter used to characterize site amplification). The distribution of V_{S30} from the 18 November 2014 version of the NGA-East flatfile [Goulet et al. 2014] is shown in Figure 1. The figure is given in two parts: the left graph shows the distribution for all sites, and the right graph shows the distribution for sites somewhat subjectively defined as being in southeastern (SE) Canada and northeastern (NE) U.S. (north of New York City, New York, and east of St. Louis, Missouri). The latter graph was made because the fundamental interest in this report is to derive adjustment factors to modify the observed GMIMs to a reference rock site condition, defined by Hashash et al. [2014] as a hard rock site with V_{S30} = 3000 m/sec. Hard rock sites are more likely to be found in glaciated regions such as SE Canada and NE U.S. than elsewhere. This is confirmed by Figure 1, in which it is clear that most of the sites in the NGA-East database correspond to stiff soil/soft rock conditions, whereas the distribution of V_{S30} in SE Canada and NE U.S. is quite different, with a number of sites corresponding to hard rock (V_{S30} = 2000 m/sec). Although most, if not all, of the V_{S30} = 2000 m/sec assignments are estimated from factors such as local site geology, topographic slopes, or type of terrain, and are not based on measurements, the value of V_{S30} = 2000 m/sec serves as a proxy for sites that would be classified as being on hard rock.

It is of interest that no sites in the NGA-East database have V_{S30} values greater than 2000 m/sec. Therefore, the reference hard-rock condition is an idealization that does not exist or is rare in reality. The observations used by Hashash et al. [2014] to derive the reference-rock condition of 3000 m/sec were largely from measurements in boreholes at depths below the surface, where the velocities were not influenced by weathering layers and sedimentary overburden; thus they do not correspond to actual values of V_{S30} that would have been obtained from those sites. In spite of the absence of sites with V_{S30} = 3000 m/sec, the simulations in the NGA-East project are for a site condition of V_{S30} = 3000 m/sec. The choice of such a high value was motivated by not wanting site-specific amplifications to be significantly influenced by the material beneath any local sedimentary layers. In other words, input motions could be taken as those on the surface of the reference rock and then propagated through a site-specific velocity profile placed on top of the reference rock velocity profile.

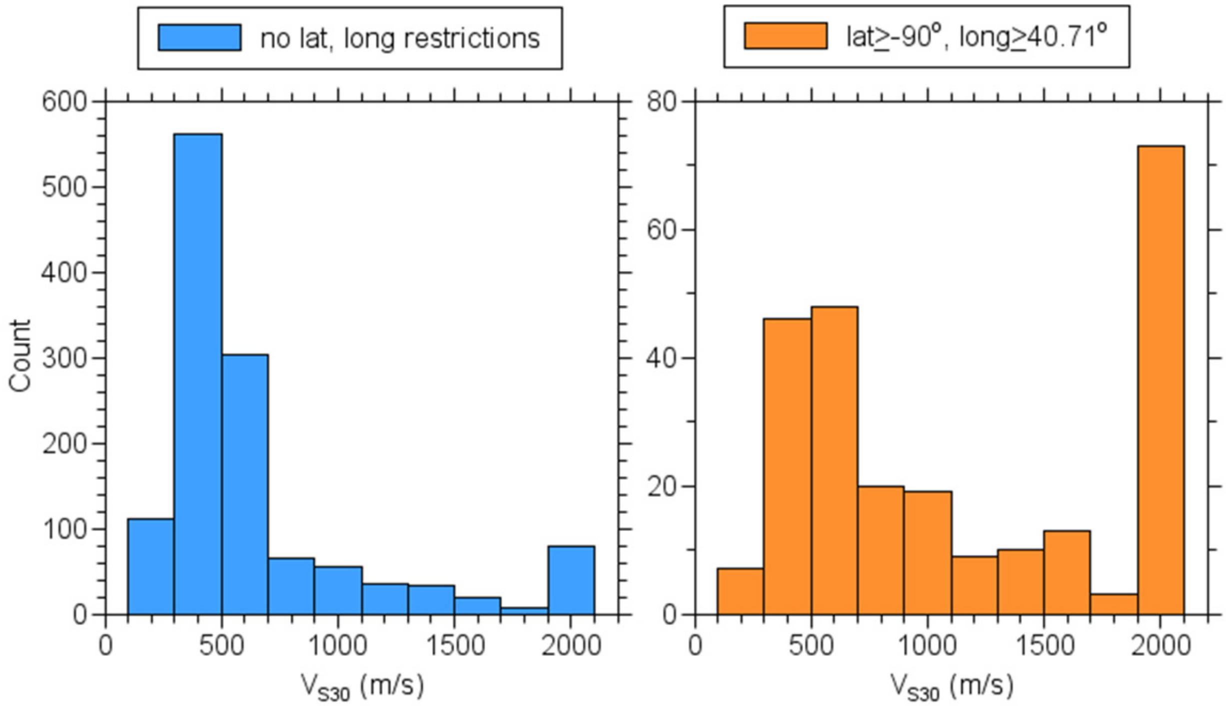

Figure 1 **Histograms of V_{S30} values in the NGA-East flatfile. The left graph includes all sites, whereas the right graph is the subset of sites east of St. Louis, Missouri, and north of New York City, New York (this is a rough way of choosing sites in northeastern U.S. and southeastern Canada).**

In view of the dominance of sites in the NGA-East database with V_{S30} values less than 2000 m/sec, it is useful to adjust recorded motions to a reference-rock condition. This is useful for comparisons of simulations and observations. The adjustments in this report are developed for three types of GMIMs: 5%-damped pseudo-absolute response spectral acceleration (PSA), peak ground velocity (PGV), and peak ground acceleration (PGA). The method for adjusting observed motions to the reference-rock condition is straightforward. There are three steps to the method:

1. Adjust observed GMIMs to an intermediate reference condition (usually $V_{S30} = 2000$ m/sec) using the site function that appears in ground-motion prediction equations (GMPEs). The function most commonly used is $\ln GMIM \approx c \ln\left(V_{S30}/V_{REF}\right)$; the coefficient c could come from studies such as those of Hollenback et al. [2015], regressing data in the NGA-East flatfile, or from other studies such as described by Stewart et al. [2012], in which amplifications from the PEER NGA-West2 GMPEs are adjusted based on residuals of the NGA-East data relative to the NGA-West2 GMPEs, or even from the NGA-West2 GMPEs, assuming the stiff soil/soft rock site responses are similar in eastern and western North America;

2. Simulate GMIMs for many magnitudes (**M**), distances (R_{RUP}, the closest distance to the rupture surface), and oscillator periods (T), one set of simulations using crustal amplifications for Fourier spectra obtained from models for which

V_{S30} = 760 m/sec, and a second set of simulations for crustal amplifications with V_{S30} = 3000 m/sec; and

3. Form the ratios of the GMIMs for the two sets of amplifications. These ratios are the second set of adjustment factors to be applied to motions, the first set being discussed in step 1. The second set of adjustments is given here as tables, rather than as equations that are a function of magnitude, distance, and oscillator period. As will be discussed, the adjustment ratios are relatively constant for certain ranges of **M**, R_{RUP}, and T.

In this report, I discuss the crustal amplifications for the two values of V_{S30} (760 m/sec and 3000 m/sec) and then the ratios of GMIMs needed for step 2 (adjusting the GMIM values from sites with V_{S30} = 760 m/sec to those with V_{S30} = 3000 m/sec). Included in the section on the crustal amplifications is a discussion of the velocity profiles used for the amplifications. In addition to the ratios of GMIMs for V_{S30} = 3000 m/sec divided by GMIMs for V_{S30} = 760 m/sec, I also show GMIM ratios for V_{S30} = 3000 m/sec divided by the GMIM for V_{S30} = 2000 m/sec, because many of stations in the NGA-East flatfile have been assigned V_{S30} = 2000 m/sec (as an aside, I would think that this argues for the reference velocity for NGA-East being 2000 m/sec, not 3000 m/sec).

2 CRUSTAL AMPLIFICATIONS FOR SITES WITH V_{S30} = 760 m/sec

2.1 VELOCITY PROFILES FOR SITES WITH V_{S30} = 760 M/SEC

I was provided with six profiles for which V_{S30} = 760 m/sec. From here on, I sometimes refer to these sites as BC sites, named after the boundary between the National Earthquake Hazards Reduction Program [NEHRP] sites classes B and C (Chapter 3) [BSSC 2004]. Three profiles came from Walter Silva (S), and the other three came from Youssef Hashash and Joseph Harmon (HH). These models [note: I use "profiles" and "models" interchangeably] were guided by databases of velocity profiles. Sites with the same value of V_{S30} can be underlain by quite different velocity profiles; the multiplicity of profiles for each author is intended to include a range of those velocity-depth functions. The HH models have velocities of 3 km/sec within 100 m or so of the surface.

I was initially skeptical that such high velocities could occur at shallow depths, but a number of the models in Beresnev and Atkinson [1997] have velocities close to or greater than 3000 m/sec within 50 m of the surface. In addition, I used the BC site condition velocity model from Frankel et al. [1996] (Fea96). This model, derived by me and in collaboration with Art Frankel, replaces a western U.S. model that I used in 1986 with a model having a linear gradient in the upper 200 m with a slope such that V_{S30} = 760 m/sec. These seven models are not from measurements at specific sites but are intended to represent generic sites. In addition to those seven models, I used velocity models based on measurements at three sites for which V_{S30} was close to 760 m/sec: HAIL, Harrisburg, IL, V_{S30} = 765 m/sec, from Odum et al. [2010]; HATCH, Baxley, Georgia, Georgia Power Co., V_{S30} = 762 m/sec, from J. C. Chin [*Personal Communication]*; and OTT, Ottawa, Ontario, V_{S30} = 755 m/sec, from Beresnev and Atkinson [1997]. The velocity profiles for the ten models are shown in Figures 2 and 3; the figures differ only in the maximum depth for each figure.

As is obvious from Figures 2 and 3, even though each model has a V_{S30} very close to 760 m/sec, the models differ significantly in detail. The models range from those represented by continuous functions of depth (e.g., Fea96) to those with large jumps in velocity at discrete interfaces (e.g., S760t), as well as a combination of these two characteristics (e.g., HH1000).

Because the simulations need velocity profiles extending to depths of at least 8 km, I had to merge the shallow profiles with deeper profiles. I did this by plotting the nine models that did not extend to 8 km (three Silva, three HH, HAIL, HATCH, and OTT) along with three shear-wave profiles extending to a depth of 8 km that I had available. These deeper profiles are the one from Fea96, and the Boore and Joyner [1997] (BJ97) generic rock and very hard rock profiles. The combined velocity models, which were used in the calculations of crustal amplifications, are shown in Figures 4 and 5 for different maximum depths. In those figures, I have not distinguished between the original shallow models and the extended models, but the legends include the maximum depths of each shallow model.

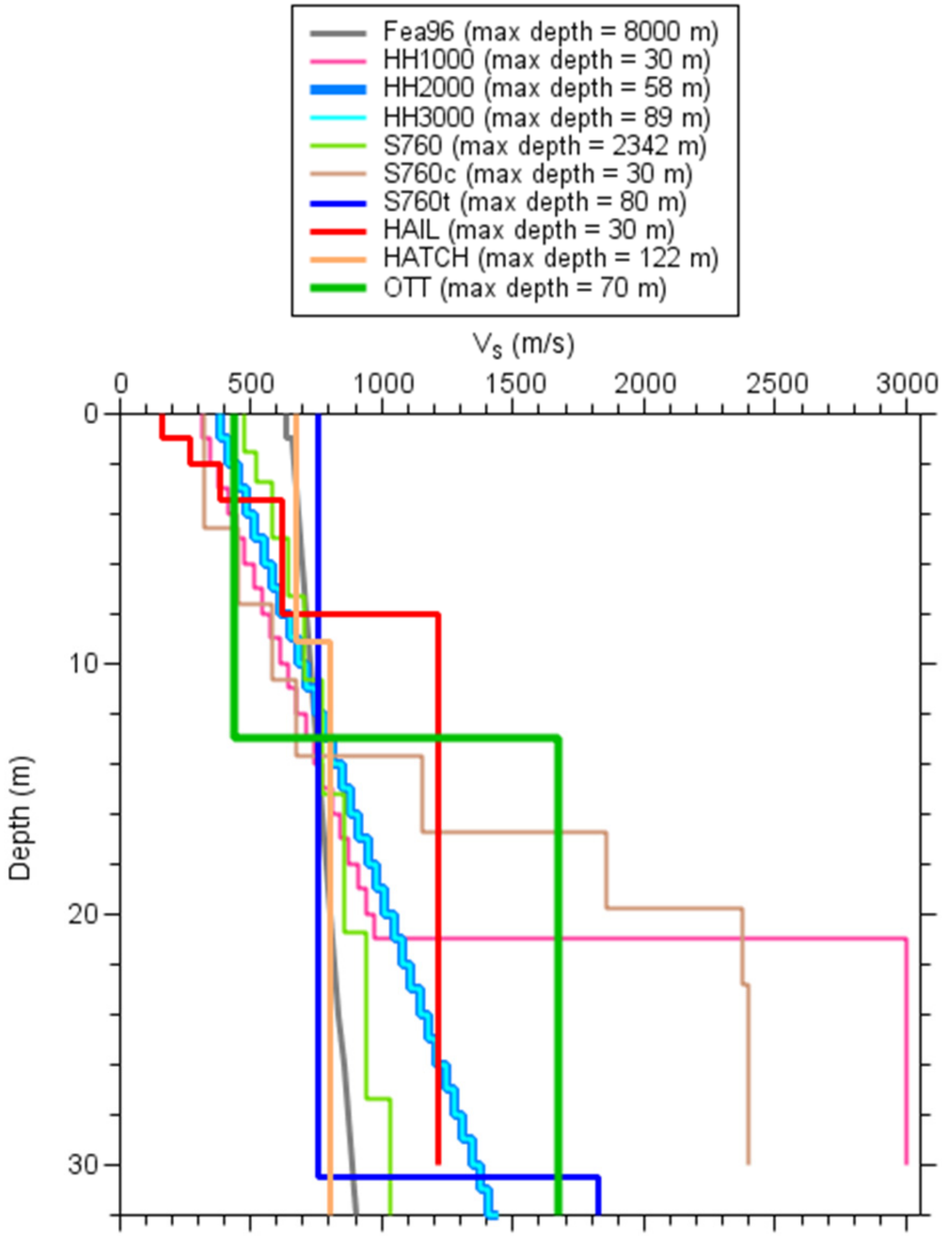

Figure 2 **Models with V_{S30} = 760 m/sec (Fea96=Frankel et al.; HH=Hashash and Harmon; S=Silva—see text for details). Some of the models extend below 32 m. The lowest depth of 32 m was chosen so that near-surface details can be seen.**

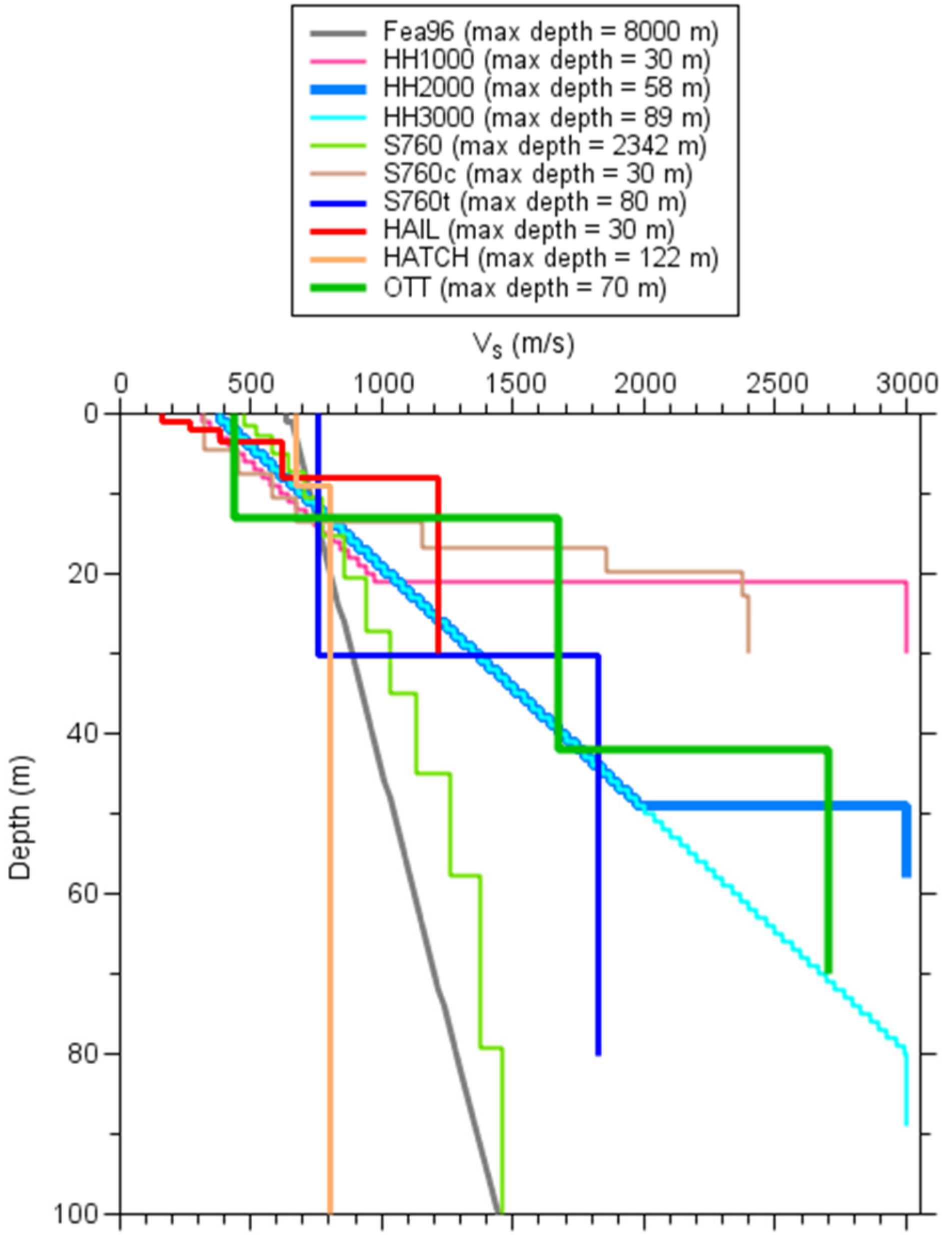

Figure 3 **Models with V_{S30} = 760 m/sec; see caption to Figure 2 for explanation of model abbreviations. Some of the models extend below 100 m. The lowest depth of 100 m was chosen so that details deeper than the 32 m used in the previous figure can be seen.**

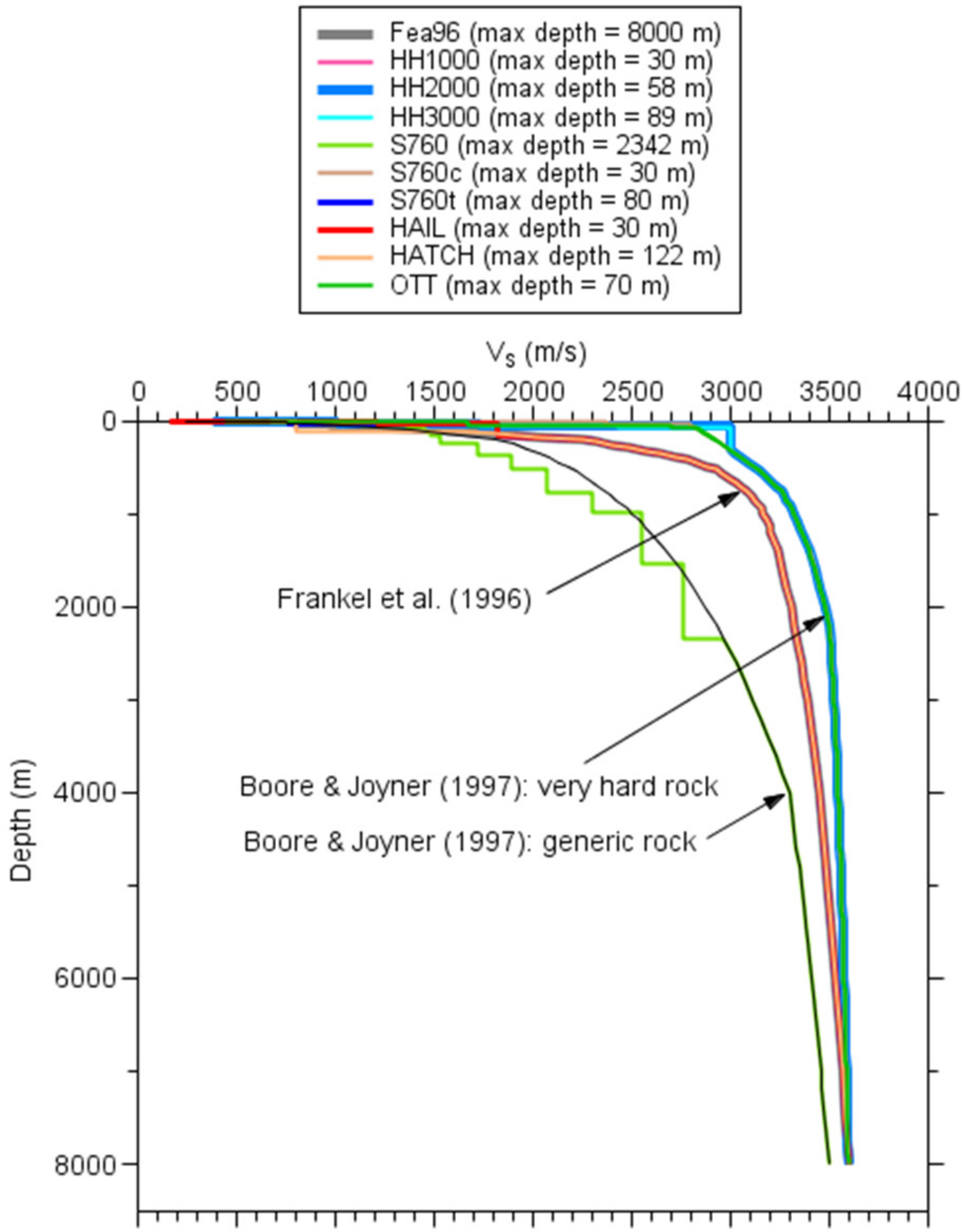

Figure 4 **Combined profiles; see caption to Figure 2 for explanation of model abbreviations. The maximum depth for the plot is 8500 m. The main purpose of this figure is to show the three profiles on to which the shallow profiles were merged.**

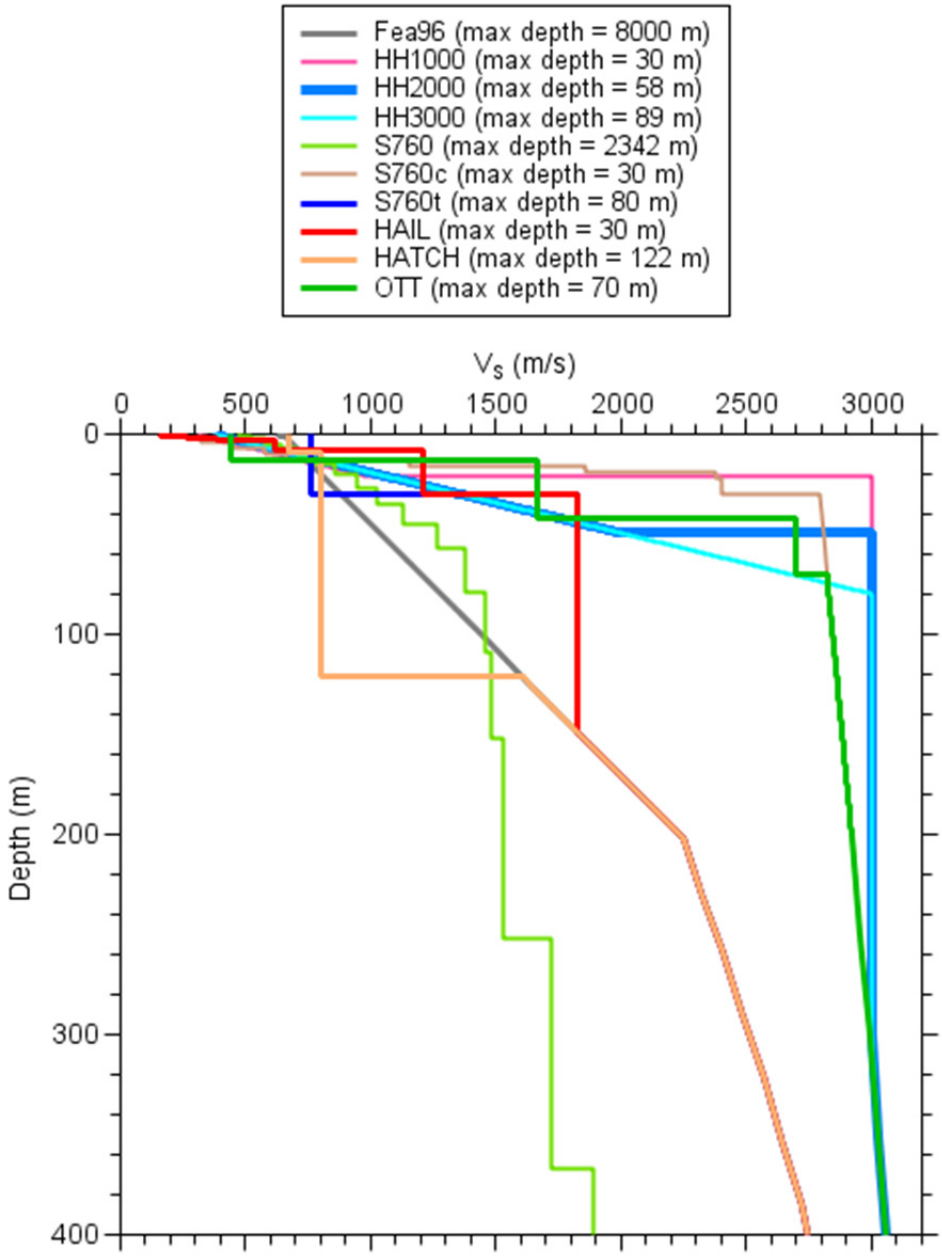

Figure 5 **Combined profiles; see caption to Figure 2 for explanation of model abbreviations. The maximum depth of 400 m was chosen to show model details between those shown in Figure 4 and Figure 3.**

2.2 AMPLIFICATIONS FOR SITES WITH V_{S30} = 760 M/SEC

I computed the square-root impedance (SRI) amplifications for each of the profiles, using the method described in Boore [2013]. The amplifications were computed assuming a source density and velocity of 2.8 g/cc and 3.7 km/sec, assuming a vertical angle of incidence and no attenuation (see Boore and Thompson [2015]). I also computed full resonant amplifications for two Silva models, a gradient model (S760) and a model with a large change in velocity at a single interface (S760t); see Figure 3. All amplifications assume linear response. The amplifications assume no attenuation, but to show the effect of attenuation, curves have been added for two models in which the diminution operator $\exp(-\pi\kappa f)$ has been applied, with $\kappa = 0.02$ sec. The results are shown in Figures 6 and 7 (where Figure 7 shows the subset of models from Figure 6 that were used in computing BC-to-reference rock adjustment factors described later).

Here are some comments on the amplifications shown in Figure 6:

1. The SRI amplifications all come together at a frequency corresponding to a quarter wavelength for 30 m, since each model has the same or almost the same V_{S30};
2. The amplifications at lower frequencies are controlled by the deeper parts of the profiles, and since there are three deeper profiles, the amplifications for the ten shallow models merge into one of three amplification curves;
3. At higher frequencies the amplifications are controlled by the shallow parts of the models, which can have significant variations—but the diminution operator will reduce the importance of these high frequencies when computing PSA at short periods; and
4. The full resonant amplifications are in reasonable agreement with both the gradient and step models (the underprediction of the resonant peaks for the step model is a well-known limitation of the SRI method (see Boore [2013]).

Although I could compute BC-to-reference rock (V_{S30} = 3000 m/sec) adjustment factors for each of the BC models, I decided to compute adjustment factors for five models: Fea96, OTT, HH1000, HH3000, and a subjectively chosen weighted average of the amplifications, labeled as “Average BC Model” in Figures 6 and 7. The average BC model is the geometric mean of the amplifications for Fea96, HH1000, HH3000, and OTT; these models were chosen subjectively to incorporate both gradient and step models (in particular, that for OTT—till over glaciated rock). The crustal amplifications for the Fea96, OTT, and Average BC models are given in Table 1. The OTT model corresponds to one that might be encountered in glaciated regions, with a layer of glacial till on top of bedrock for which glaciation has removed any weathered layer. Such a site would be quite different than BC sites in other parts of the central and eastern North America (CENA). On the other hand, Figure 1 shows that most of the data in the NGA-East flatfile have a V_{S30} distribution that is quite different than those in NE U.S. and SE Canada; therefore, BC-to-reference rock adjustment factors for a BC model more representative of those sites is probably more useful for the NGA-East project. For this reason most of the results discussed in this report used the Fea96 model for the BC crustal amplifications. A comparison between the adjustment factors for the Fea96, OTT, HH1000, HH3000, and Average BC models is given in a later section.

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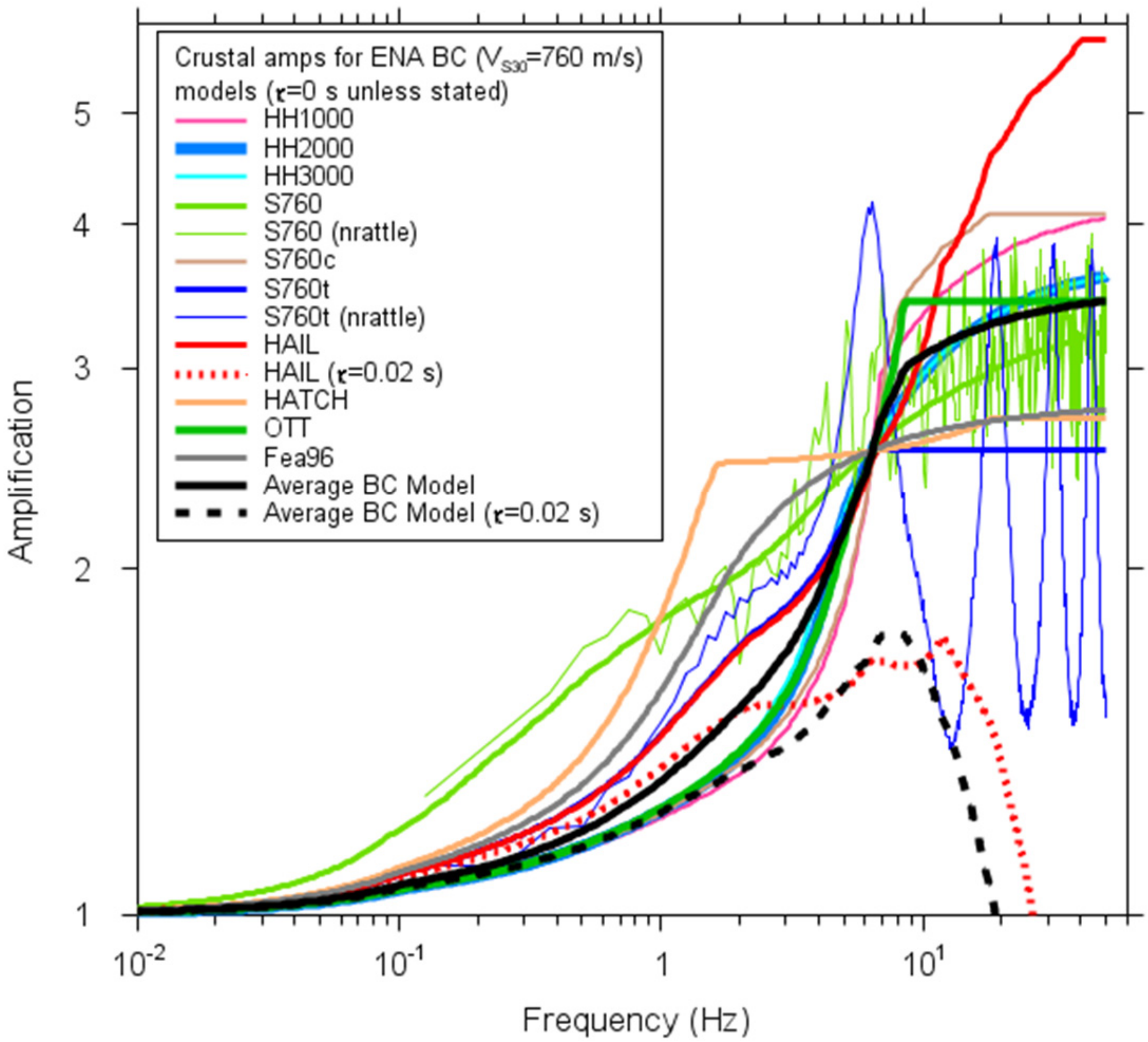

Figure 6 **Amplifications from the square-root-impedance method [Boore 2013] assuming an angle of incidence of 0 degrees; also shown are full-resonant amplifications (using the program *nrattle*) for two of the Silva profiles (one gradient-like and one step-like), assuming *SH* waves with a 30 degree angle of incidence. The effect of applying a kappa operator with κ = 0.02 sec is also shown for two of the profiles. The Fea96 amplifications used a newer velocity-density relation than used to obtain the densities in Table A6 of Frankel et al. [1996] (Fea96), and therefore the amplifications shown in the figure are slightly different than those in Table A5 of Fea96.**

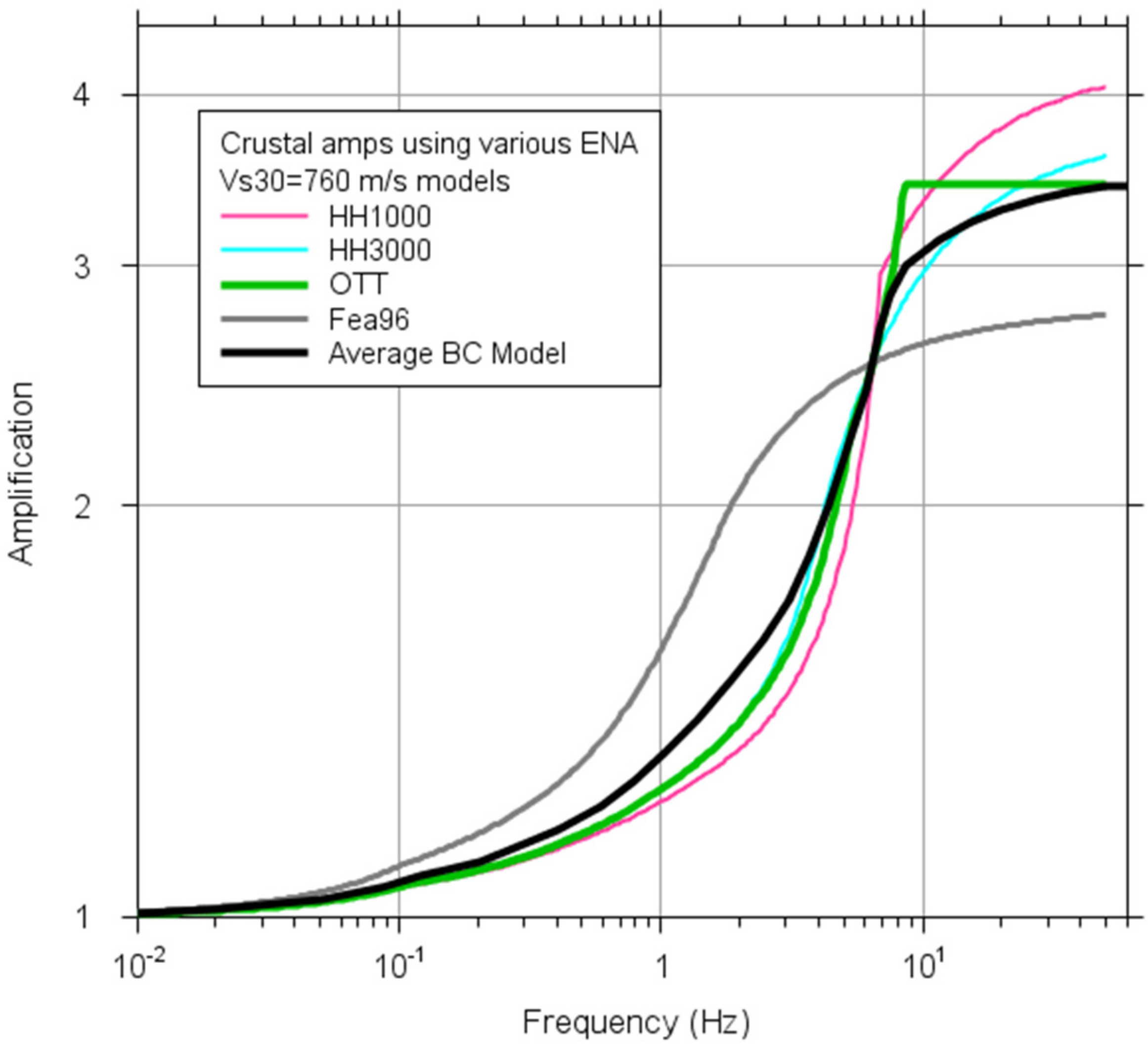

Figure 7 **The subset of crustal amplifications shown in Figure 6 that are used in computing the adjustment factors to go from sites with V_{S30} = 760 m/sec to those with V_{S30} = 3000 m/sec.**

Table 1 Crustal amplifications for three models with V_{S30} close to 760 m/sec*.

F :Fea96	A:Fea96	F:Average	A:Average	F:OTT	A:OTT
0.005	1.000	0.001	1.001	0.010	1.009
0.010	1.019	0.007	1.004	0.030	1.014
0.022	1.031	0.020	1.011	0.060	1.031
0.053	1.054	0.051	1.029	0.111	1.056
0.120	1.104	0.085	1.051	0.195	1.081
0.223	1.167	0.121	1.070	0.377	1.123
0.362	1.234	0.203	1.098	0.635	1.175
0.541	1.321	0.401	1.155	1.027	1.245
0.789	1.450	0.586	1.205	1.575	1.328
1.179	1.667	0.789	1.256	2.294	1.437
1.657	1.928	1.035	1.316	3.105	1.573
2.273	2.135	1.395	1.395	3.786	1.731
3.156	2.314	1.879	1.493	4.617	1.974
4.772	2.470	2.465	1.597	5.233	2.250
8.149	2.595	3.062	1.705	6.057	2.430
15.522	2.677	3.702	1.837	6.937	2.745
32.987	2.736	4.356	1.998	7.863	3.086
59.130	2.761	5.266	2.240	8.459	3.436
76.330	2.761	6.031	2.429	42.663	3.436
—	—	6.542	2.581	—	—
—	—	6.907	2.704	—	—
—	—	7.447	2.852	—	—
—	—	8.580	3.000	—	—
—	—	11.562	3.134	—	—
—	—	15.163	3.226	—	—
—	—	19.886	3.296	—	—
—	—	26.798	3.354	—	—
—	—	36.112	3.397	—	—
—	—	50.000	3.432	—	—
—	—	100.000	3.432	—	—

*F,A are frequencies and amplifications for each model. The frequencies are model dependent; they were chosen to give a good approximation of the amplifications shown in Figure 6, but using a smaller number of frequencies.

3 CRUSTAL AMPLIFICATIONS FOR SITES WITH V_{S30} = 2000 M/SEC and V_{S30} = 3000 M/SEC

3.1 VELOCITY PROFILES FOR SITES WITH V_{S30} = 2000 AND V_{S30} = 3000 M/SEC

The velocity profiles used for the crustal amplifications are based on the very hard rock profile of Boore and Joyner [1997]. For V_{S30} = 3000 m/sec, the top 300 m of the Boore and Joyner profile was replaced by a layer with a velocity of 3000 m/sec (see Boore and Thompson [2015]). For V_{S30} = 2000 m/sec, the top 30 m of the profile had a shear-wave velocity of 2000 m/sec; this was underlain by material with a linear gradient, joining the standard profile at a depth of 300 m. The velocity models are shown in Figure 8. Figure 9(a), from Boore and Thompson [2015], compares the V_{S30} = 3000 m/sec model used here with a different model having the same V_{S30}.

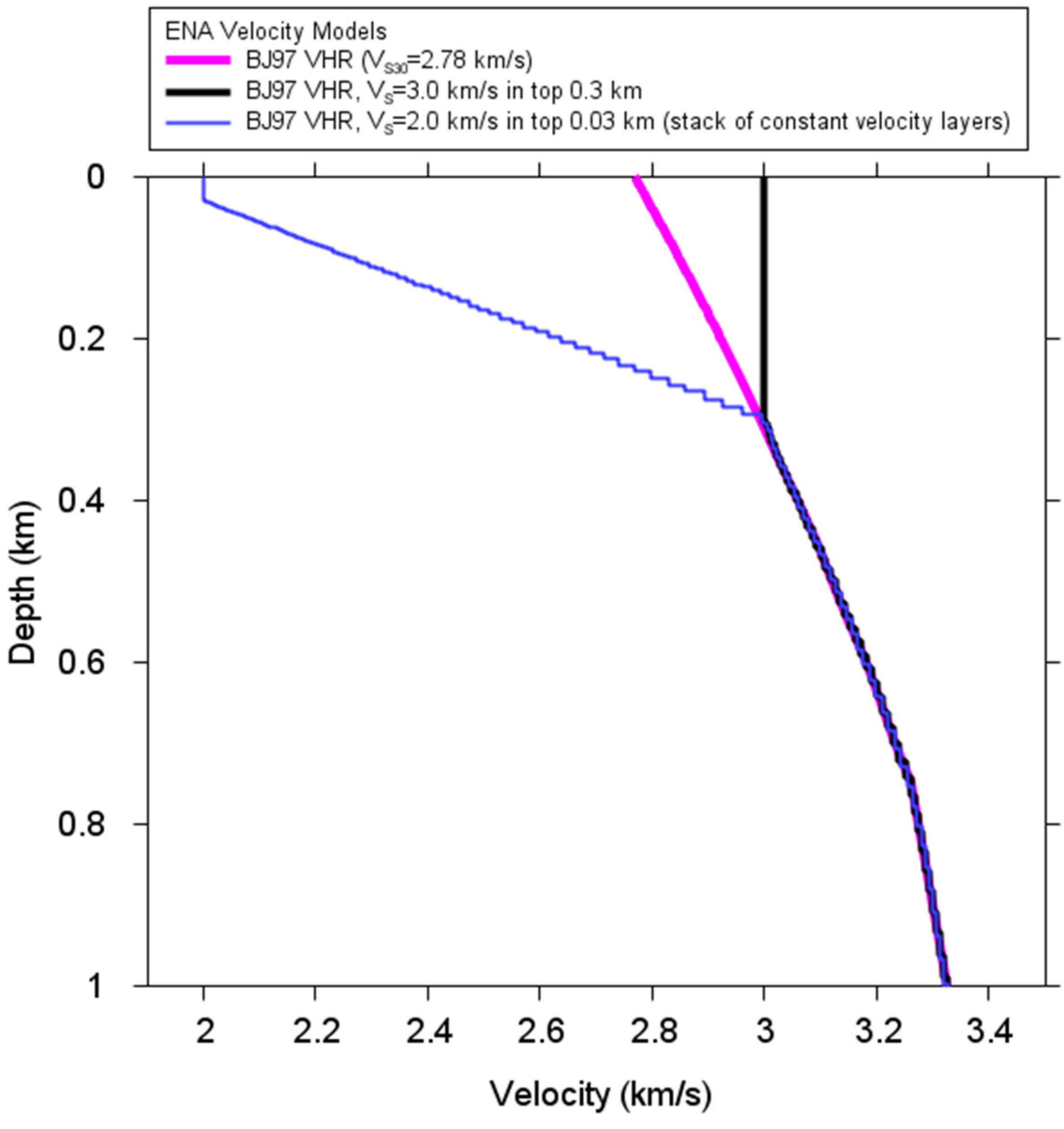

Figure 8 **The Boore and Joyner [1997] (BJ97) very hard rock (VHR) velocity profile and the modifications to that profile such that V_{S30} = 2000 m/sec and V_{S30} = 3000 m/sec. The modified profiles were used to compute the crustal amplifications used in the simulations in this report.**

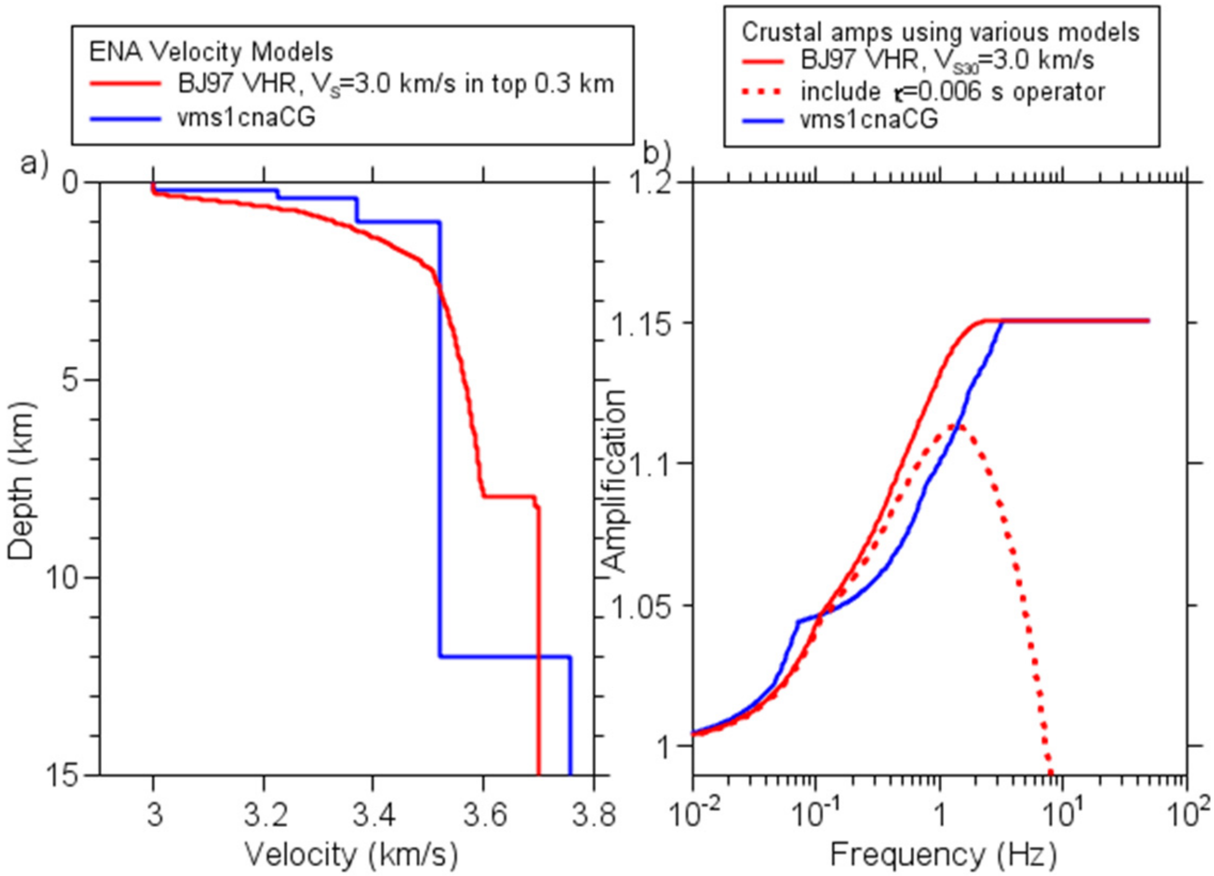

Figure 9 **(a) Velocity models for a modification of the Boore and Joyner [1997] very hard rock (VHR) site in eastern North America (ENA); see Boore and Thompson [2015] for an explanation of the models. The BJ97 model ended at 8 km, without the step shown in the left graph; the step is due to the velocity near the source being 3.7 km/sec, rather than 3.6 km/sec; and (b) amplifications for the two models, without and with the κ attenuation operator for the modified BJ97 model. (Modified from Boore and Thompson [2015].)**

3.2 AMPLIFICATIONS FOR SITES WITH V_{S30} = 3000 M/SEC

The amplifications were computed using the same method and assumptions as those for sites with V_{S30} = 760 m/sec, with the results shown in Figure 9(b). In spite of the detailed differences in the two velocity models, the crustal amplifications for the two models are similar, and, more importantly, they are small.

4 COMPARISON OF CRUSTAL AMPLIFICATIONS FOR SITES WITH V_{S30} = 760 M/SEC, V_{S30} = 2000 M/SEC, and V_{S30} = 3000 M/SEC

The crustal amplifications for the three site conditions, without and with attenuation, are compared in Figure 10. Note that the combined amplification and diminution for sites with V_{S30} = 760 m/sec is greater than for higher velocity sites except at high frequencies, where the decrease due to the diminution operator overwhelms the amplification. This has an impact on the BC-to-reference rock adjustment factors (defined as the ground motion intensity measure for a reference rock site divided by on for a BC site), which tend to become greater than unity at short periods as κ increases and **M** decreases, as will be seen in the next section.

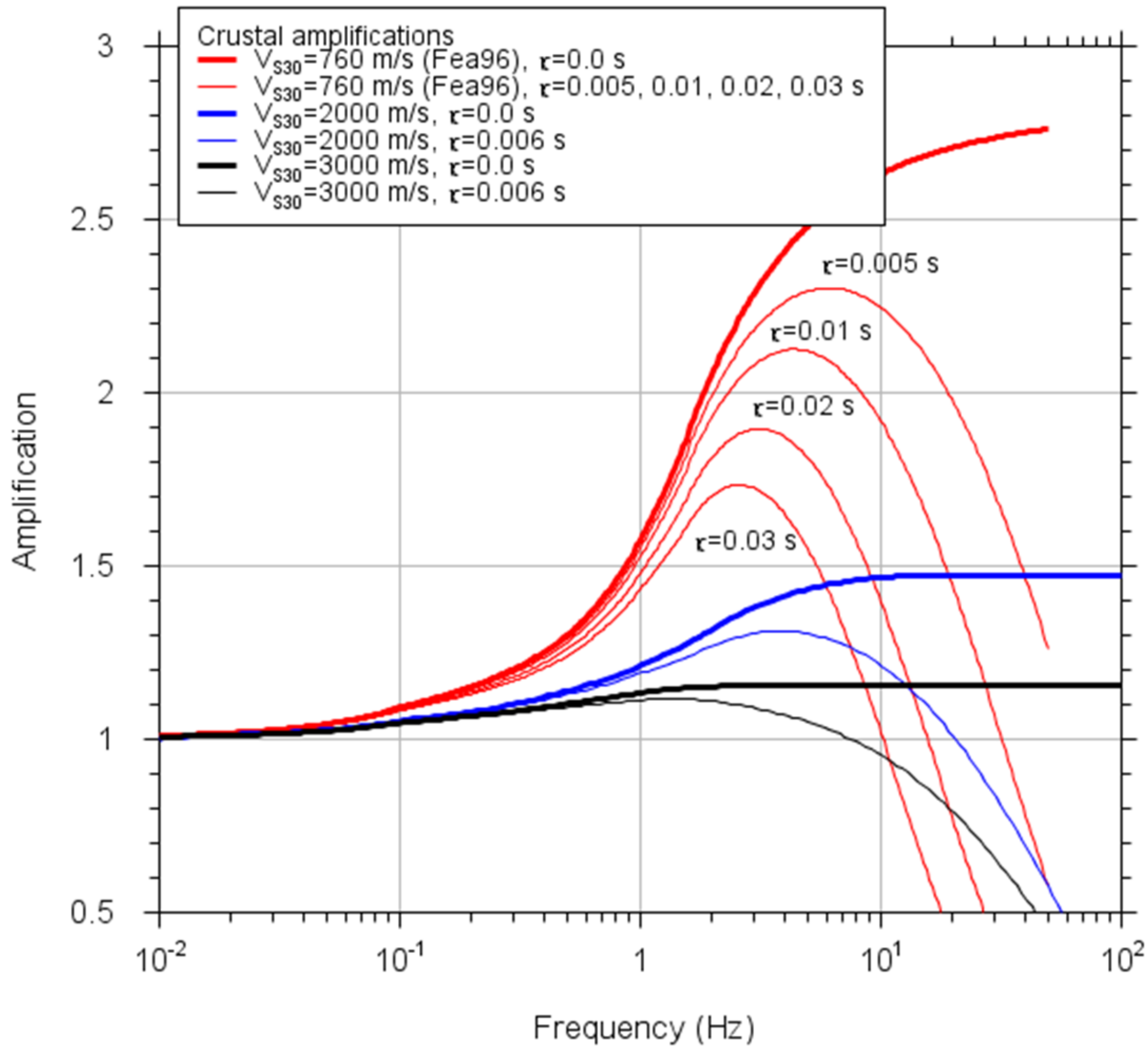

Figure 10 **Crustal amplifications for the three site conditions used in this report. The thin lines show the combined effect of the amplifications and kappa diminution operators [** $\exp(-\pi\kappa f)$ **].**

5 COMPUTATION OF BC-TO-REFERENCE ROCK ADJUSTMENT FACTORS

The BC-to-reference rock adjustment factor (*BC2RRAF*) is defined as

$$BC2RRAF = \frac{Y(V_{S30} = 3000 \text{ m/sec})}{Y(V_{S30} = 760 \text{ m/sec})} \tag{1}$$

where Y is a GMIM for the indicated site condition. I defined the ratio with the BC GMIM in the denominator so that the adjustment of an observed motion is given by a multiplication of the observed motion, adjusted to the BC condition, by *BC2RRAF*. I computed Y and *BC2RRAF*s for two very different path attenuation models: Atkinson [2004] (A04), with a steep decay of $1/R^{1.3}$ within the first 70 km, an increase going as $R^{0.2}$ from 70 to 140 km, followed by a $1/R^{0.5}$ decay, and the Boatwright and Seekins [2011] (BS11) model, with $1/R^{1.0}$ $1\big/R^{1.0}$ within the first 50 km, followed by $1/R^{0.5}$. The $Q(f)$ models differ for A04 and BS11. The Boore and Thompson [2015] path durations were used. The point-source stochastic method program *tmrs_loop_rv_drvr*, part of the SMSIM suite of programs [Boore 2005], was used for the simulations. Other model parameters are contained in the SMSIM parameter files (these files are in the electronic appendix to this report). The Boore and Thompson [2015] finite-fault adjustment factor for earthquakes in stable continental regions was used in the computations. Also in the electronic appendix are files containing tables of the adjustment factors. Interpolation of these tables can be used to obtain the adjustment factors for non-tabulated periods, magnitudes, and distances.

5.1 ADJUSTMENTS OF GMIMS FOR SITES WITH V_{S30} = 2000 M/SEC TO THOSE WITH V_{S30} = 3000 M/SEC

Before showing the *BC2RRAF*s, I first discuss the adjustment factors from a site with $V_{S30} = 2000$ m/sec to one with $V_{S30} = 3000$ m/sec. This uses Equation (1), but with Y in the denominator computed for a $V_{S30} = 2000$ m/sec crustal amplification. For both site conditions, the Campbell et al. [2014] reference value of 0.006 sec for κ was used in the simulations. The results are shown in Figure 11, where the adjustment factors are plotted against distance, with different GMIMs in each graph. As seen there, the adjustment factors are quite similar for the two attenuation models (A04 and BS11). Figure 11 also includes the ratio of the Fourier amplitude spectra (FAS) for the two crustal amplification models. Because the models only differ in the amplifications, and thus the FAS ratios are the same as the ratios of the crustal amplifications themselves, they are not a function of magnitude or distance. Table 2 compiles these FAS ratios; because the possible use of this table, and subsequent ones for BC-to-reference rock, is as a simple substitute for the **M-** and R_{RUP}-dependent adjustment factors based on the stochastic method simulations in converting response spectra from on-site condition to another, the FAS ratios are tabulated versus period rather than frequency.

The FAS ratios and the adjustment factors are in good agreement for the larger magnitudes and for distances within some distance that depends on the period of the GMIM. The differences between the adjustment factors and the FAS ratios is understandable in terms of the combined effect of the frequency response of an oscillator (in particular, the fact that an oscillator can have a response at a frequency for which the ground motion itself has little or no energy), the magnitude- and frequency-dependent source spectral shape, the frequency-dependent amplification and diminution, and the distance- and magnitude-dependent path attenuation. A different way of showing the adjustments factors is given in Figure 12, where the adjustment factors are a function of period for a suite of magnitudes and two distances. Only the Boatwright and Seekins [2011] (BS11) attenuation model was used for the adjustment factors shown in this figure. This again shows the good comparison between the FAS ratios and the adjustment factors, particularly for the larger magnitudes (but note that at larger distances, Figure 11 shows that the short-period adjustment factors diverge significantly from the FAS ratio for the larger magnitudes).

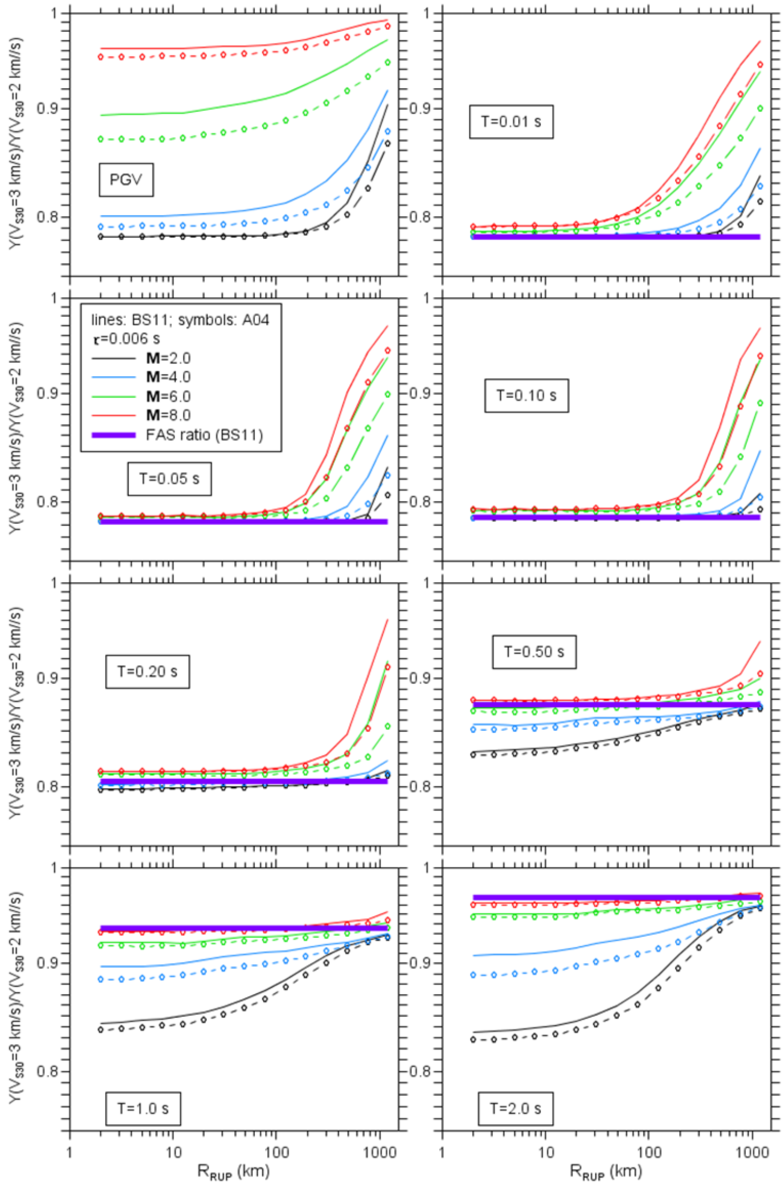

Figure 11 **Ratios of PSA as a function of distance for V_{S30} = 3000 m/sec and V_{S30} = 2000 m/sec for the Atkinson [2004] (A04) and Boatwright and Seekins [2011] (BS11) attenuation models. Also shown are ratios of Fourier acceleration spectra (FAS) (no FAS ratio is shown for PGV). Each graph is for a single measure of ground motion (5%-damped PSA at the indicated periods and PGV) and a range of moment magnitudes (M). κ = 0.006 sec for all ratios.**

Table 2 **Ratio of Fourier amplitude spectra (FAS). FAS for a site with V_{S30} = 3000 m/sec divided by the FAS of a site with V_{S30} = 2000 m/sec. κ = 0.006 sec for both sites.**

T (sec)	ratio (3kps/2kps)
0.010	0.782
0.020	0.782
0.025	0.782
0.030	0.782
0.040	0.782
0.050	0.782
0.075	0.783
0.100	0.786
0.150	0.795
0.200	0.805
0.250	0.816
0.300	0.827
0.400	0.852
0.500	0.877
0.750	0.918
1.000	0.936
1.500	0.956
2.000	0.970
3.000	0.980
4.000	0.985
5.000	0.988
7.500	0.991
10.000	0.994

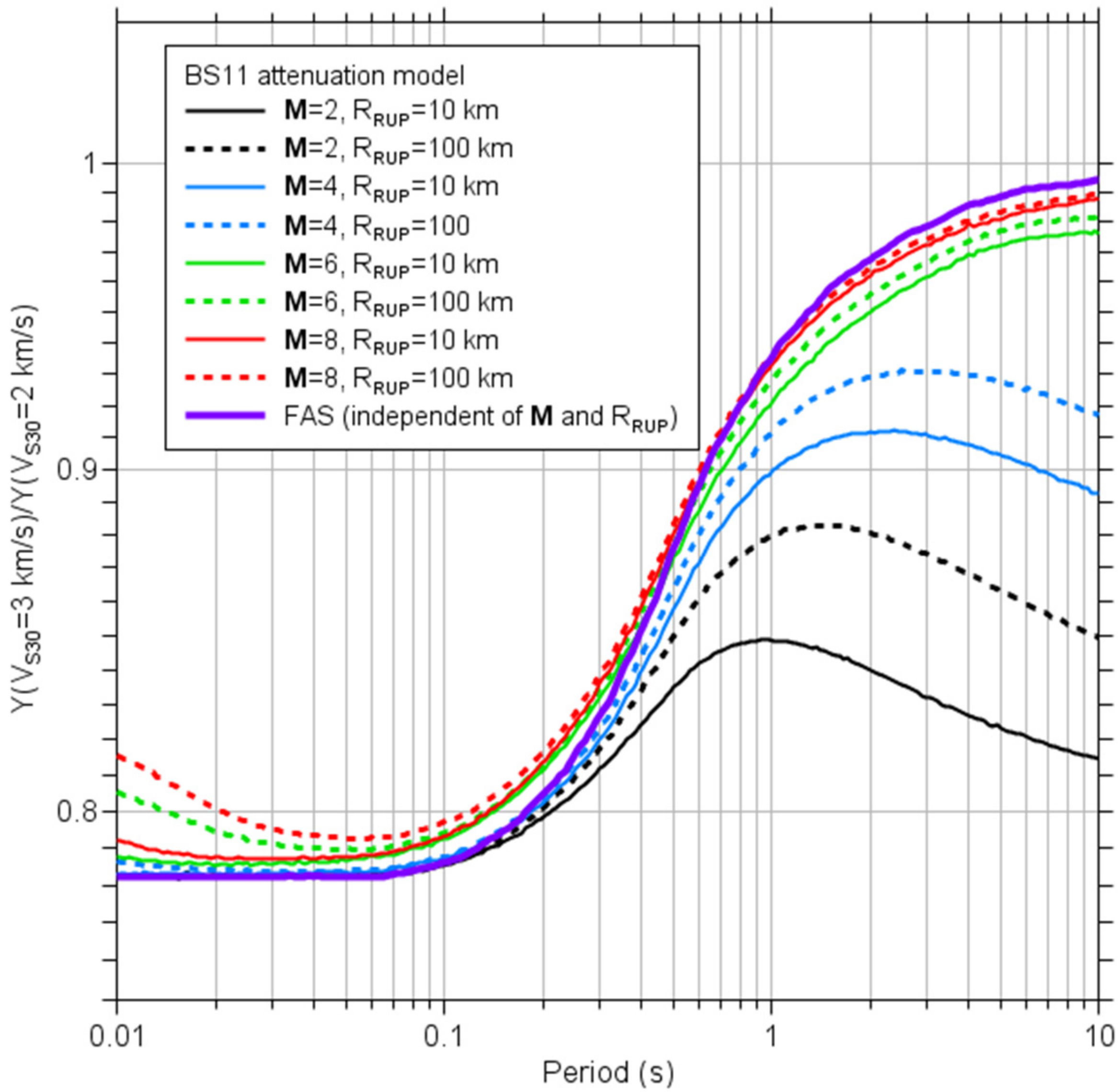

Figure 12 **Ratios of PSA for V_{S30} = 3000 m/sec and V_{S30} = 2000 m/sec as a function of period, for distances of 10 km and 100 km. The Boatwright and Seekins [2011] (BS11) attenuation model and a diminution operator with κ = 0.006 sec was used for the both site conditions. Also shown are ratios of Fourier acceleration spectra (FAS).**

5.2 ADJUSTMENTS OF GMIMS FOR SITES WITH V_{S30} = 760 M/SEC TO THOSE WITH V_{S30} = 3000 M/SEC

There is uncertainty about what value to use for κ for the V_{S30} = 760 m/sec model. Frankel et al. [1996] assumed 0.01 sec, Silva et al. [1999] and Atkinson and Boore [2006] used 0.02 sec, Darragh et al. [2015] found 0.005 sec from inverting data, and Yenier and Atkinson [2015] used 0.025 sec. As will be seen in the *BC2RRAF* plots, the conversion factor from a BC condition to a very hard rock condition can be quite sensitive to the choice of κ for short period motions at close distances. For this report, I show ratios for κ equal to 0.005, 0.01, 0.02, and 0.03 sec. The *BC2RRAF* plots for these values of κ are shown in Figures 13, 14, 15, and 16 as a function of distance, for the Fea96 BC model. As in the previous section, the figures show that the *BC2RRAF*s are not sensitive to the attenuation model (A04 and BS11), and that the factors are in reasonable agreement with the FAS ratios for larger magnitudes and closer distances, particularly for longer period motions. (The FAS ratios for the Fea96 model are given in Table 3.) Direct comparisons of the *BC2RRAF*s, for the BS11 attenuation model, are shown in Figure 17 (to avoid clutter, the results for $\kappa = 0.005$ sec are not shown in that figure). It is not surprising that the short-period adjustment factors are quite sensitive to κ. The question of what κ to use is beyond the scope of this report. I have tried to find BC sites in central and eastern U.S. and Canada with measured ground motions, with no success. But this was prior to the compilation of the NGA-East database, and it could be that such recordings are now available. I suspect that the κ to be used at a BC site similar to OTT will be smaller than those for BC sites that have a less rapid increase velocities at shallow depths than at OTT.

A comparison of the *BC2RRAF*s as a function of period is shown in Figures 18, 19, 20, and 21, one figure per κ. Each figure shows the *BC2RRAF*s for two distances and a suite of magnitudes. Unlike the previous figures, each of these figures uses the same *y*-axis scale for ease of inter-comparison.

Here I summarize a few observations from Figures 13 through 21:

1. The ratios for very small **M** are quite different than for those from larger **M**;
2. In general, the ratios are similar for the two path attenuation models;
3. Ignoring $\mathbf{M} = 2$, the ratios are somewhat insensitive to **M** and R_{RUP}, except for short periods and larger distances. This is good news, as it suggests that a simple period-dependent adjustment factor can be used for a wide range of **M** and R_{RUP}; and
4. The ratios for short-period motions are very sensitive to the value of κ. For example, the *BC2RRAF*s for $\mathbf{M} = 6$ for $\kappa = 0.005$ sec and 0.03 sec differ by a factors of 2.1 and 1.1 for $T = 0.1$ sec and $T = 1.0$ sec, respectively, for distances out to several hundred km.

Table 3 **Ratio of Fourier amplitude spectra (FAS): FAS for a site with V_{S30} = 3000 m/sec and κ = 0.006 sec divided by the FAS of a site with V_{S30} = 760 m/sec for the modified Frankel et al. [1996] (Fea) model and four values of κ.**

T (sec)	ratio (3kps/Fea; κ = 0.005 sec)	ratio (3kps/Fea; κ = 0.01 sec)	ratio (3kps/Fea; κ = 0.02 sec)	ratio (3kps/Fea; κ = 0.03 sec)
0.010	0.304	1.465	33.893	784.310
0.020	0.357	0.784	3.771	18.140
0.025	0.370	0.694	2.438	8.565
0.030	0.379	0.639	1.822	5.193
0.040	0.393	0.582	1.276	2.798
0.050	0.402	0.550	1.030	1.931
0.075	0.416	0.513	0.780	1.186
0.100	0.426	0.499	0.683	0.935
0.150	0.444	0.493	0.608	0.749
0.200	0.457	0.495	0.579	0.677
0.250	0.475	0.506	0.573	0.650
0.300	0.489	0.515	0.572	0.635
0.400	0.524	0.545	0.589	0.638
0.500	0.560	0.578	0.615	0.655
0.750	0.651	0.665	0.693	0.723
1.000	0.720	0.732	0.755	0.779
1.500	0.800	0.808	0.825	0.843
2.000	0.845	0.851	0.865	0.878
3.000	0.886	0.891	0.901	0.910
4.000	0.907	0.911	0.918	0.925
5.000	0.922	0.925	0.930	0.936
7.500	0.945	0.947	0.951	0.955
10.000	0.958	0.959	0.962	0.965

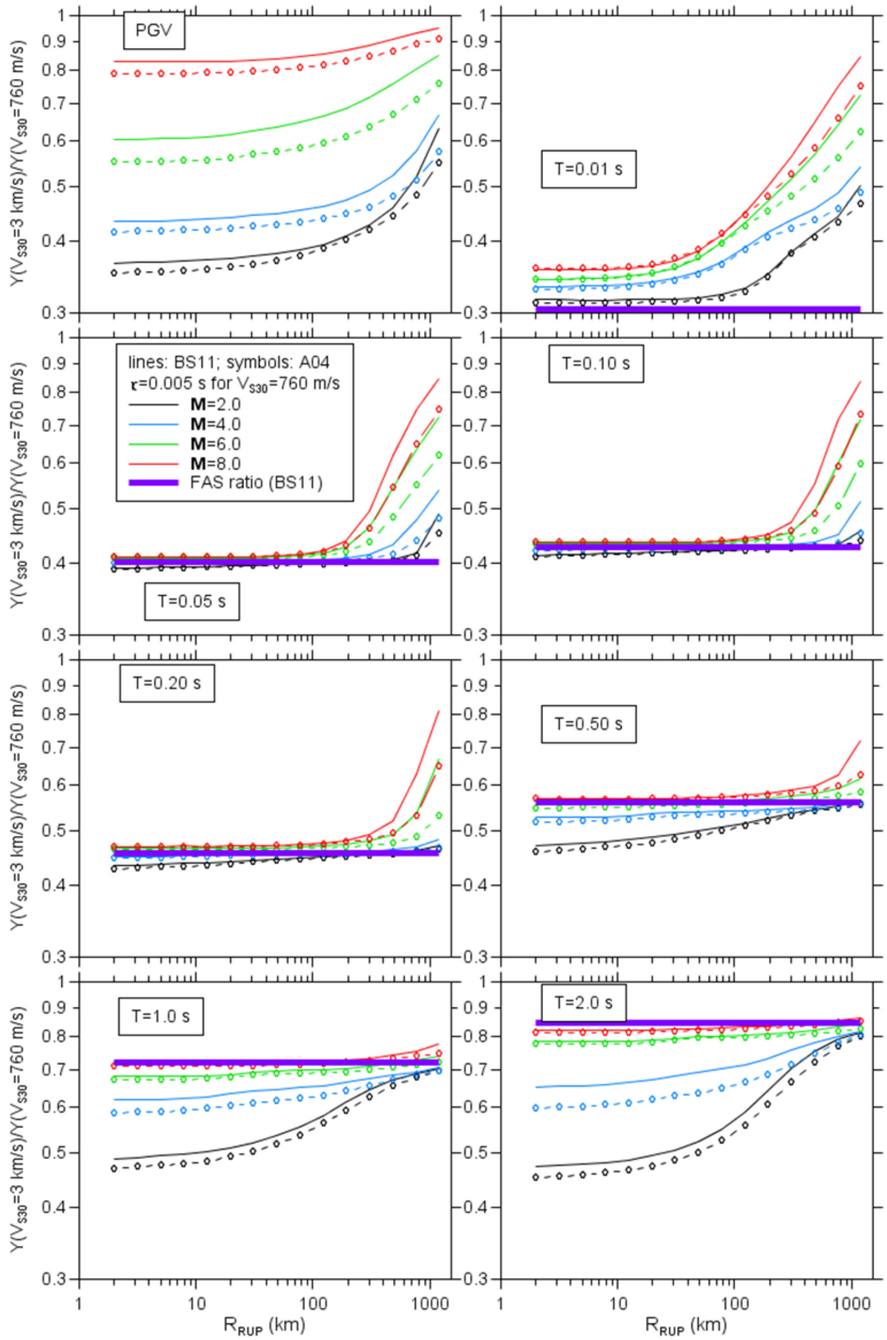

Figure 13 Ratios of PSA as a function of distance for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec for the Atkinson [2004] (A04) and Boatwright and Seekins [2011] (BS11) attenuation models. Also shown are ratios of Fourier acceleration spectra (FAS) (no FAS ratio is shown for PGV). Each graph is for a single measure of ground motion (5%-damped PSA at the indicated periods and PGV) and a range of moment magnitudes (M). κ = 0.006 sec for V_{S30} = 3000 m/sec and κ = 0.005 sec for V_{S30} = 760 m/sec. The modified Frankel et al. [1996] model was used for the V_{S30} = 760 m/sec crustal amplifications.

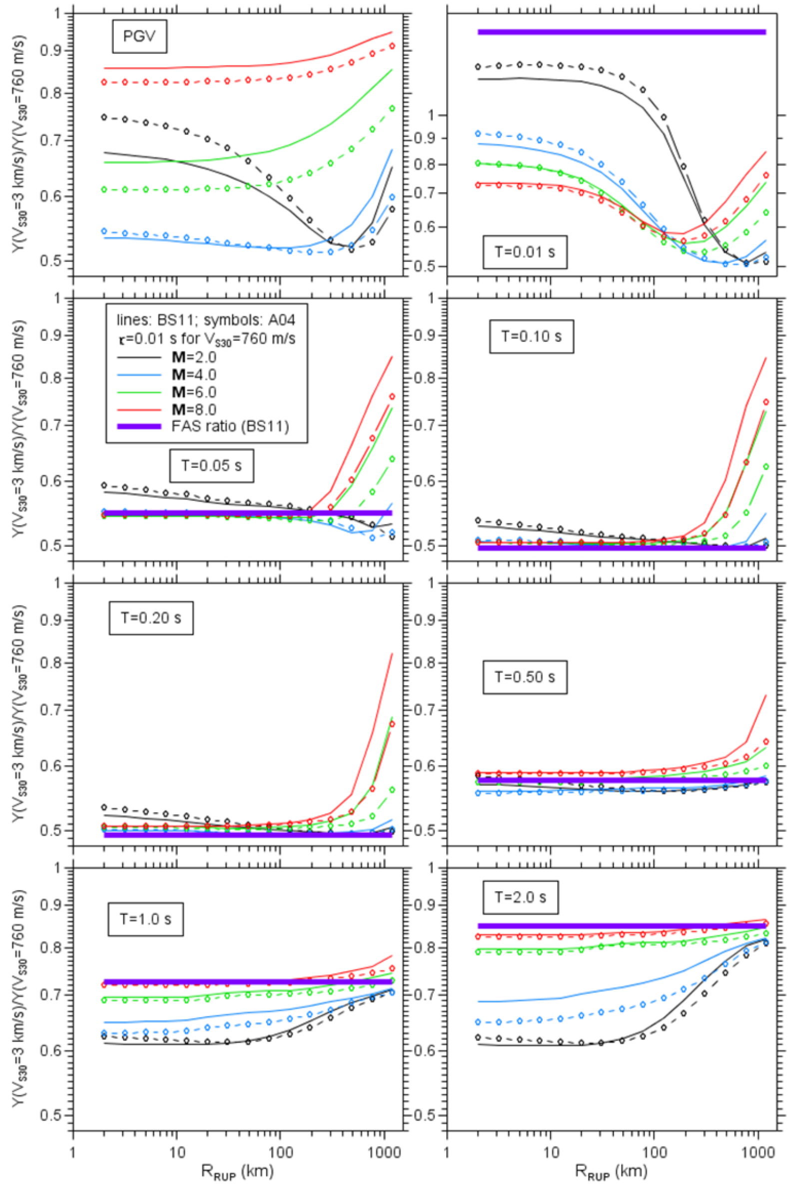

Figure 14 **Ratios of PSA as a function of distance for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec for the Atkinson [2004] (A04) and Boatwright and Seekins [2011] (BS11) attenuation models. Also shown are ratios of Fourier acceleration spectra (FAS) (no FAS ratio is shown for PGV). Each graph is for a single measure of ground motion (5%-damped PSA at the indicated periods and PGV) and a range of moment magnitudes (M). κ = 0.006 sec for V_{S30} = 3000 m/sec and κ = 0.010 sec for V_{S30} = 760 m/sec. The modified Frankel et al. [1996] model was used for the V_{S30} = 760 m/sec crustal amplifications.**

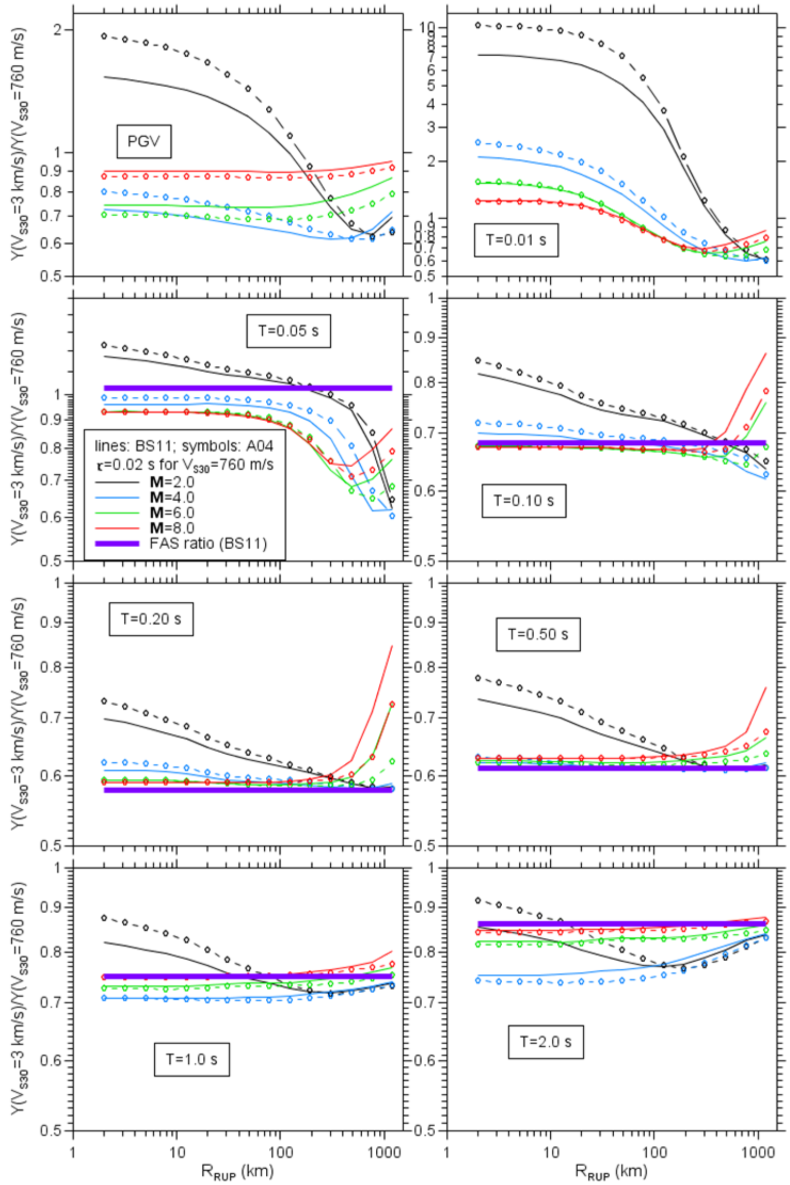

Figure 15 **Ratios of PSA as a function of distance for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec for the Atkinson [2004] (A04) and Boatwright and Seekins [2011] (BS11) attenuation models. Also shown are ratios of Fourier acceleration spectra (FAS) [no FAS ratio is shown for PGV, and it is off the top of the grph (33.9) for T = 0.01 sec]. Each graph is for a single measure of ground motion (5%-damped PSA at the indicated periods and PGV) and a range of moment magnitudes (M). κ = 0.006 sec for V_{S30} = 3000 m/sec and κ = 0.020 sec for V_{S30} = 760 m/sec. The modified Frankel et al. [1996] model was used for the V_{S30} = 760 m/sec crustal amplifications.**

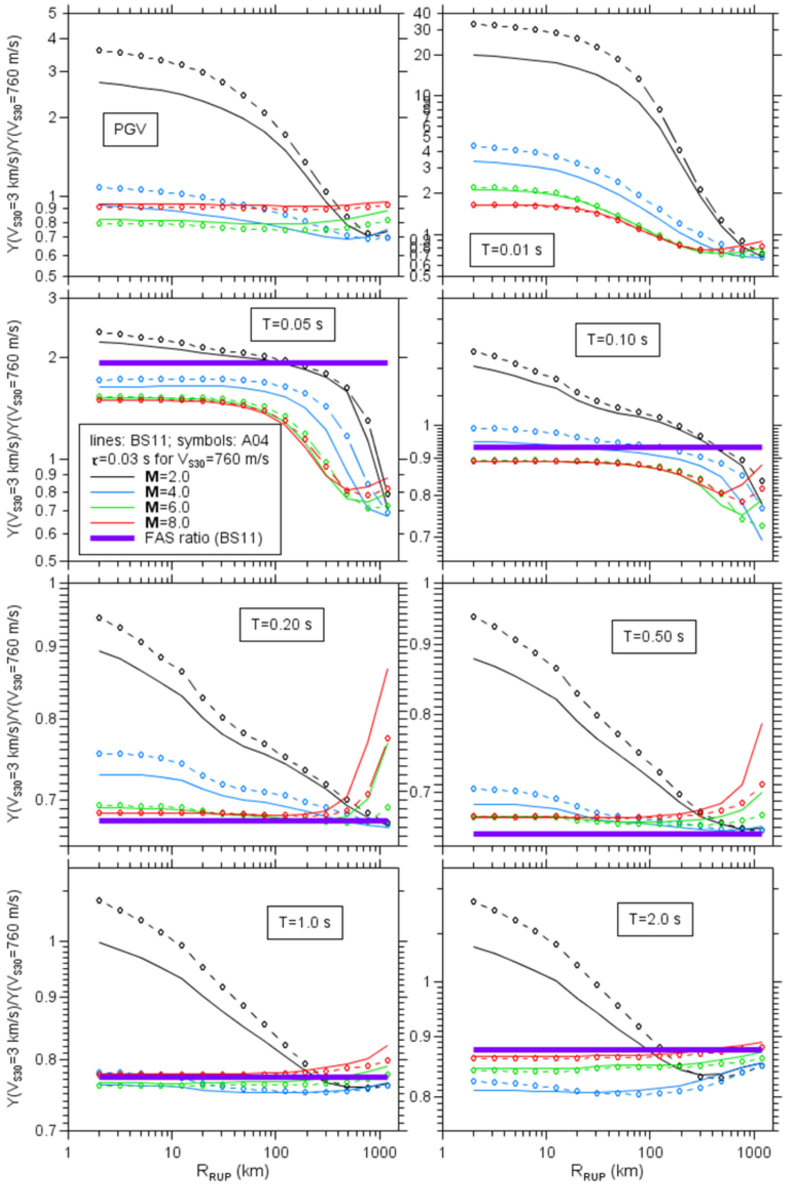

Figure 16 **Ratios of PSA as a function of distance for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec for the Atkinson [2004] (A04) and Boatwright and Seekins [2011] (BS11) attenuation models. Also shown are ratios of Fourier acceleration spectra (FAS) [no FAS ratio is shown for PGV, and it is off the top of the grph (784) for *T* = 0.01 sec]. Each graph is for a single measure of ground motion (5%-damped PSA at the indicated periods and PGV) and a range of moment magnitudes (M). κ = 0.006 sec for V_{S30} = 3000 m/sec and κ = 0.020 sec for V_{S30} = 760 m/sec. The modified Frankel et al. [1996] model was used for the V_{S30} = 760 m/sec crustal amplifications.**

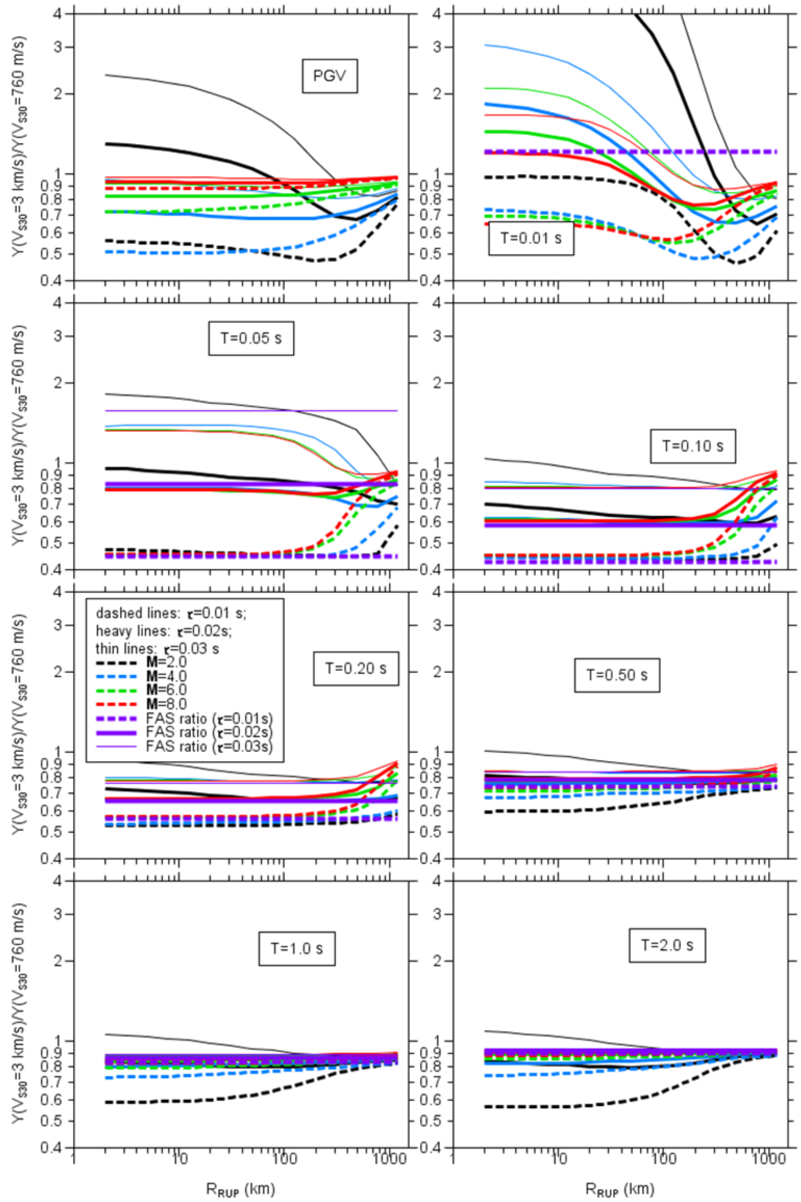

Figure 17 Ratios of PSA as a function of distance for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec for the Atkinson [2004] (A04) and Boatwright and Seekins [2011] (BS11) attenuation model and the three values of κ (0.01 sec, 0.02 sec, and 0.03 sec) used for the V_{S30} = 760 m/sec site condition. The modified Frankel et al. [1996] model was used for the V_{S30} = 760 m/sec crustal amplifications. Also shown are ratios of Fourier acceleration spectra (FAS) [no FAS ratio is shown for PGV, and the ratios for κ = 0.02 sec and 0.03 sec are off the top of the graph for T = 0.01 sec]. Each graph is for a single measure of ground motion (5%-damped PSA at the indicated periods and PGV) and a range of moment magnitudes (M). κ = 0.006 sec for V_{S30} = 3000 m/sec . To make the period-dependent sensitivity of the ratios clear, all graphs have the same scale for the ordinate (sacrificing the ratios for M =2 and T = 0.01 sec, which are off scale).

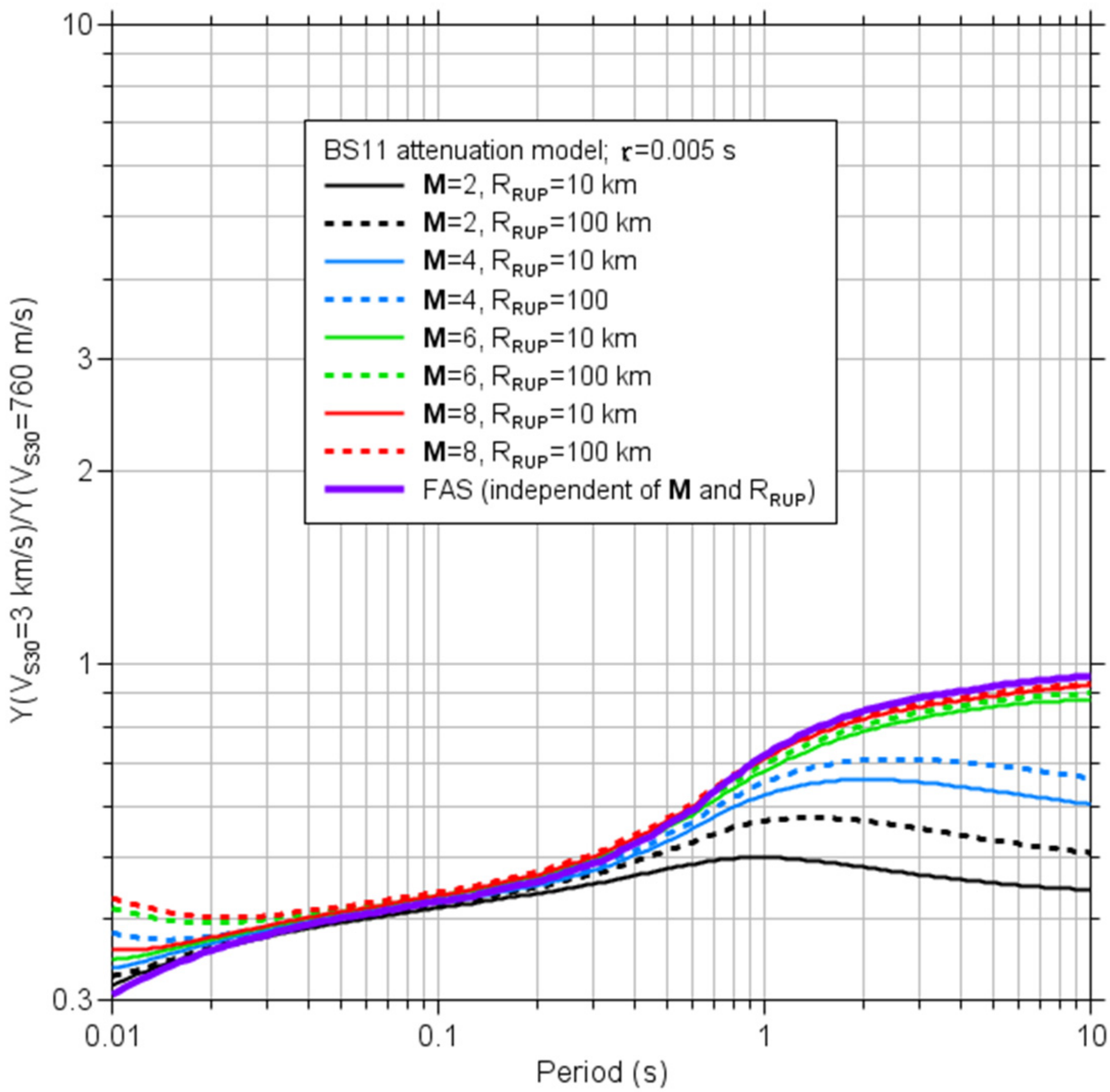

Figure 18 **Ratios of PSA for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec as a function of period for distances of 10 km and 100 km. The Boatwright and Seekins [2011] (BS11) attenuation model and a diminution operation with κ = 0.005 sec was used for the V_{S30} = 760 m/sec site condition. The modified Frankel et al. [1996] model was used for the V_{S30} = 760 m/sec crustal amplifications. Also shown are ratios of Fourier acceleration spectra (FAS).**

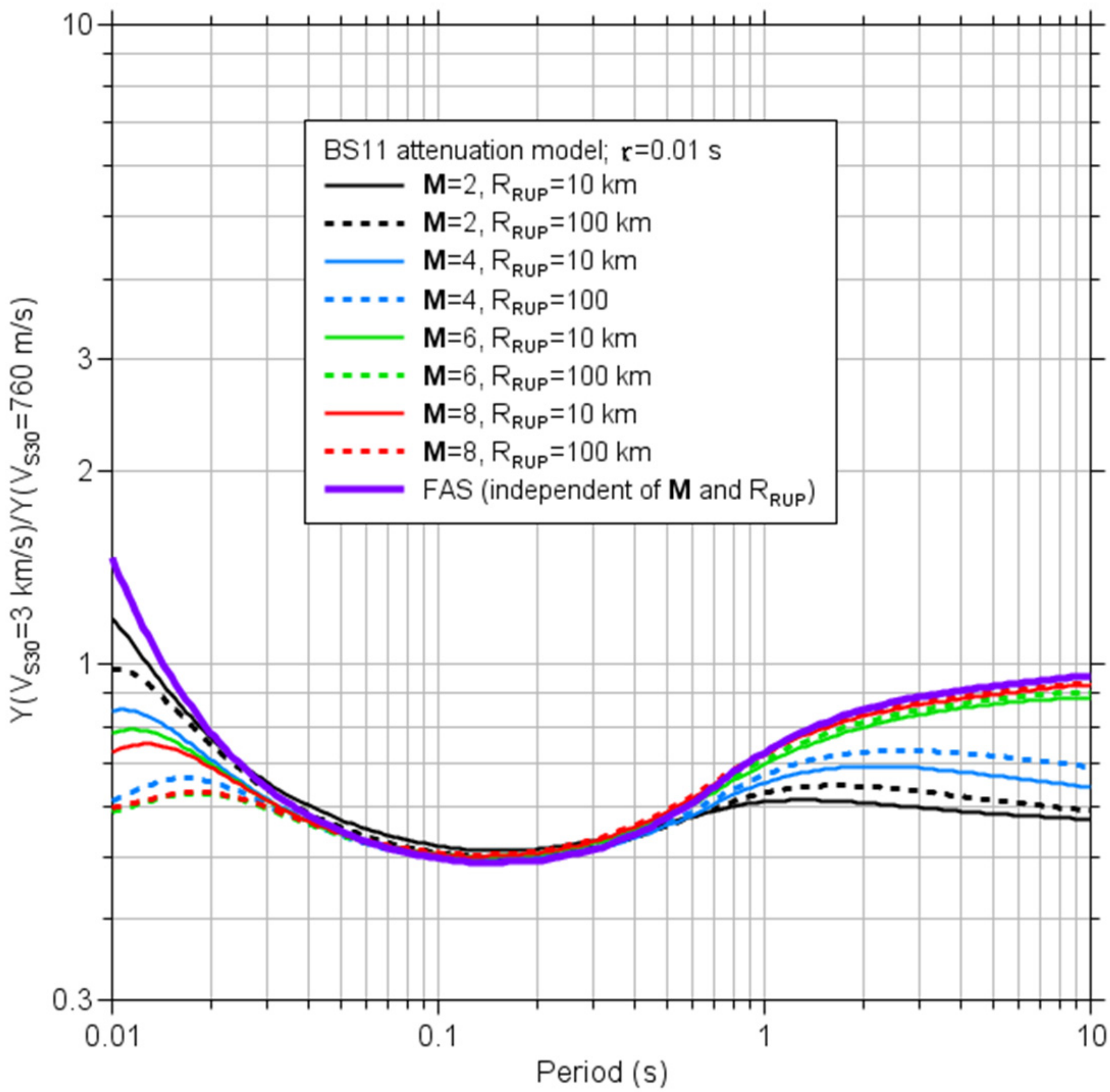

Figure 19 Ratios of PSA for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec as a function of period for distances of 10 km and 100 km. The Boatwright and Seekins [2011] (BS11) attenuation model and a diminution operation with κ = 0.01 sec was used for the V_{S30} = 760 m/sec site condition. The modified Frankel et al. [1996] model was used for the V_{S30} = 760 m/sec crustal amplifications. Also shown are ratios of Fourier acceleration spectra (FAS).

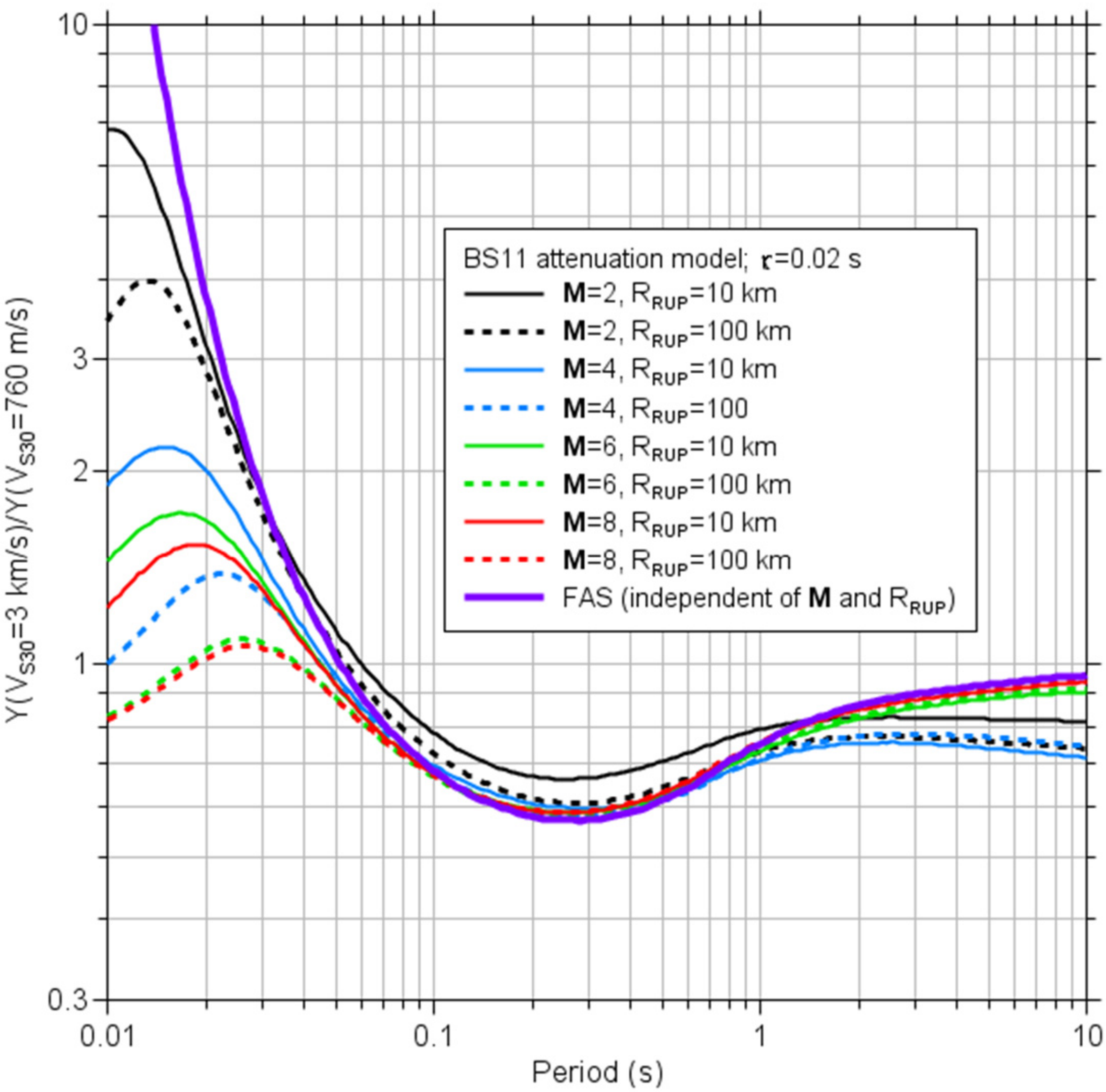

Figure 20 **Ratios of PSA for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec as a function of period for distances of 10 km and 100 km. The Boatwright and Seekins [2011] (BS11) attenuation model and a diminution operation with κ = 0.02 sec was used for the V_{S30} = 760 m/sec site condition. The modified Frankel et al. [1996] model was used for the V_{S30} = 760 m/sec crustal amplifications. Also shown are ratios of Fourier acceleration spectra (FAS).**

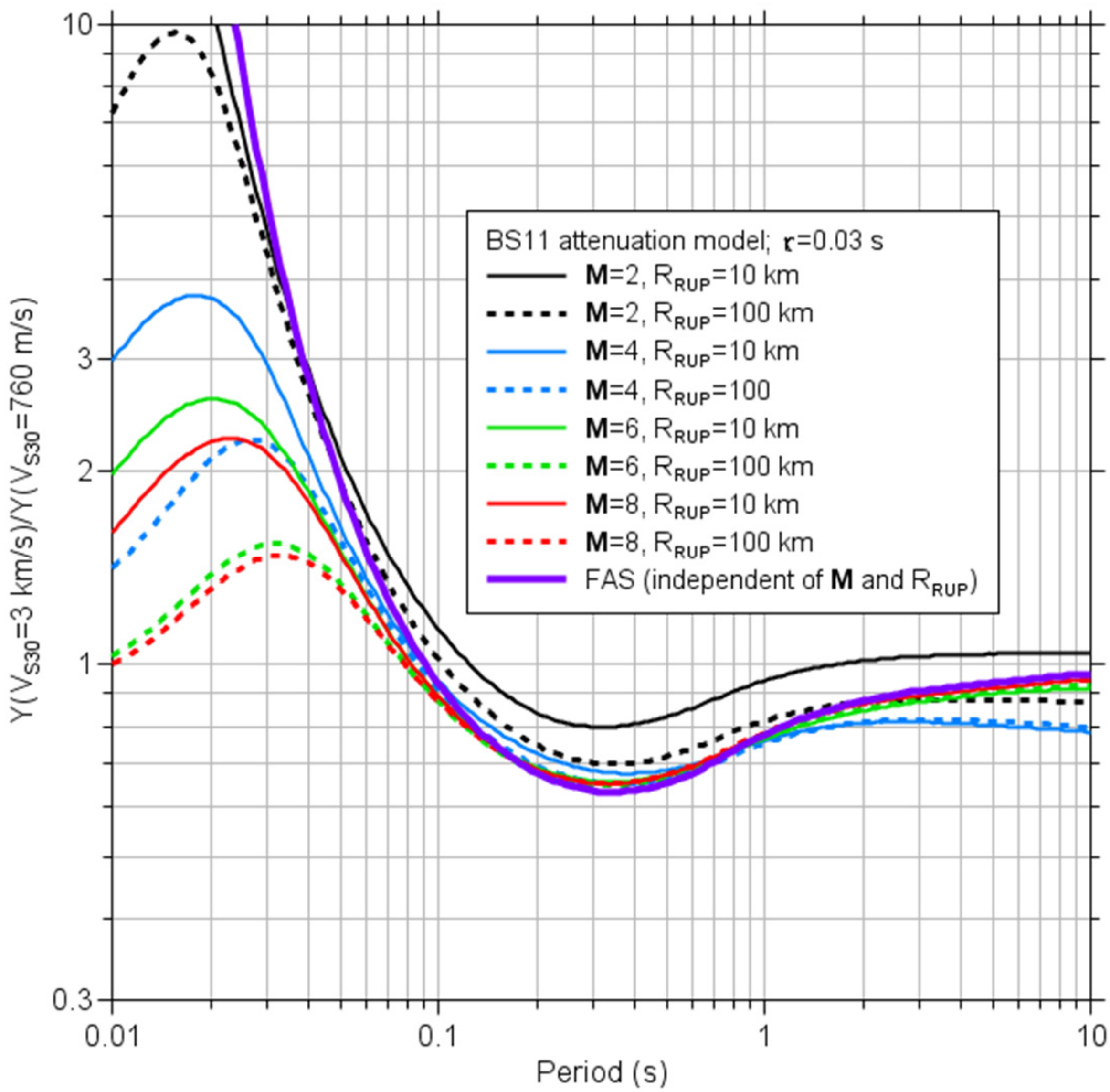

Figure 21 **Ratios of PSA for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec as a function of period for distances of 10 km and 100 km. The Boatwright and Seekins [2011] (BS11) attenuation model and a diminution operation with κ = 0.03 sec was used for the V_{S30} = 760 m/sec site condition. The modified Frankel et al. [1996] model was used for the V_{S30} = 760 m/sec crustal amplifications. Also shown are ratios of Fourier acceleration spectra (FAS).**

6 VARIABILITY OF THE *BC2RRAF*s

The *BC2RRAF*s for several different BC models are compared in Figures 22 through 25. Each figure shows the adjustment factors as a function of period for a fixed distance and a suite of magnitudes; no FAS ratios are given in the figures. Figures 22 and 23 compare BC models HH1000, HH3000, and OTT. The *BC2RRAF*s are similar for these three BC models, which is expected from the similarity of the crustal amplifications in Figure 7. The adjustment factors are not sensitive to the distances used in the figures (10 km and 100 km), although earlier figures (e.g., Figure 17) shows a distance dependence of the *BC2RRAF*s for greater distances and short periods. On the other hand, Figure 7 shows that the crustal amplifications for the Fea96, Average BC and OTT models are different, and this maps the differences in amplitude and shape of the *BC2RRAF*s shown in Figures 24 and 25. Although not shown in the figures, for completeness I provide the FAS ratios for the Average BC and the OTT BC models in Tables 4 and 5. A direct comparison of the *BC2RRAF*s for the Fea96, Average BC and OTT models are given in Figure 26, which shows the ratio of the *BC2RRAF*s for the Fea96 and OTT models relative to that of the Average BC model. Also included in Figure 26 are the ratios of the FAS ratios for the three models. This figure shows that the *BC2RRAF*s are generally within 20% of one another; it also shows that the FAS ratios are a good predictor of the variation in *BC2RRAF*s except for short periods.

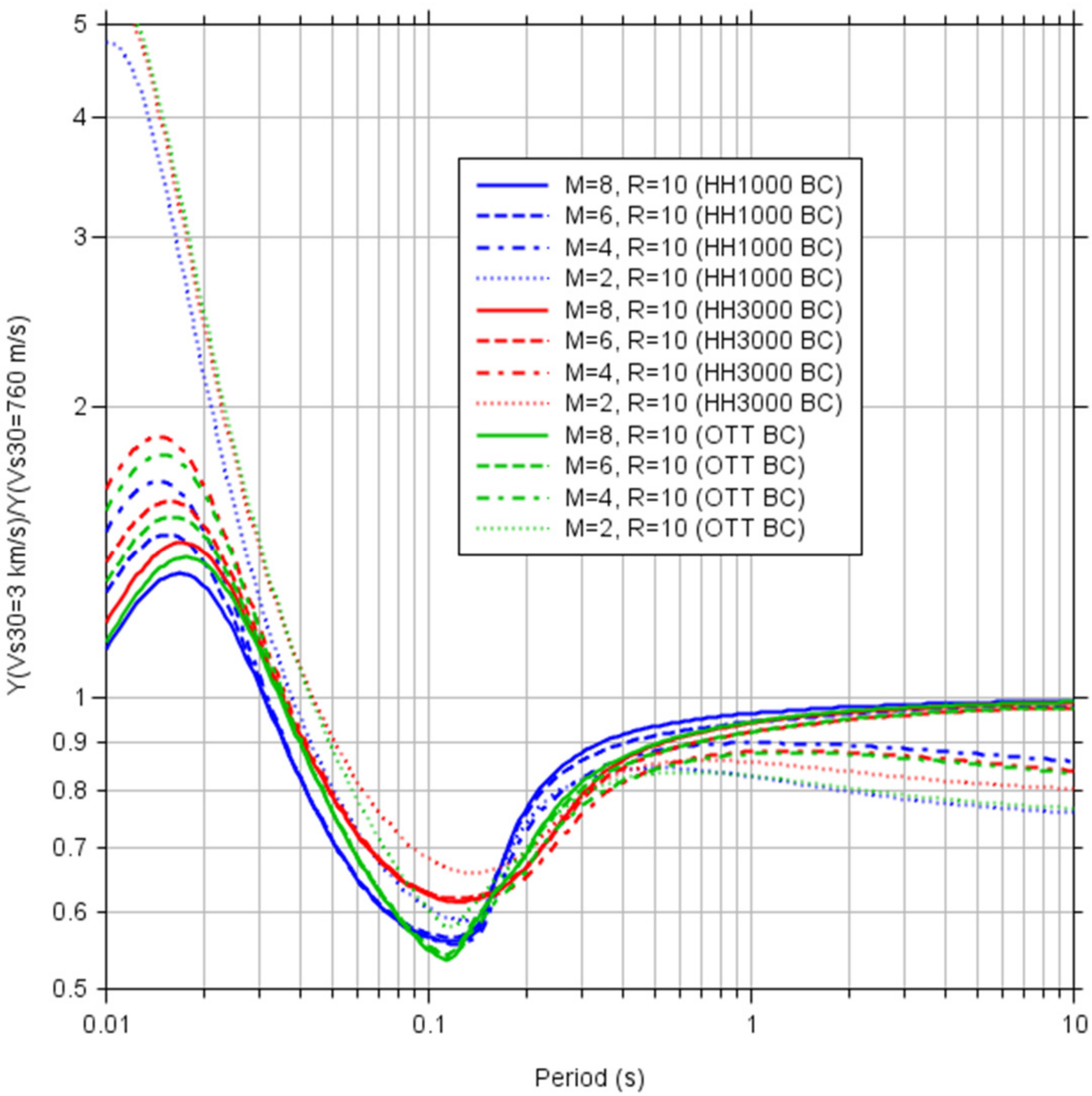

Figure 22 **Ratios of PSA for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec as a function of period for a distance of 10 km. The Boatwright and Seekins [2011] (BS11) attenuation model and a diminution operation with κ = 0.02 sec was used for the V_{S30} = 760 m/sec site condition. Three models were used for the V_{S30} = 760 m/sec crustal amplifications: Hashash and Harmon models HH1000 and HH3000, and the OTT model of Beresnev and Atkinson [1997].**

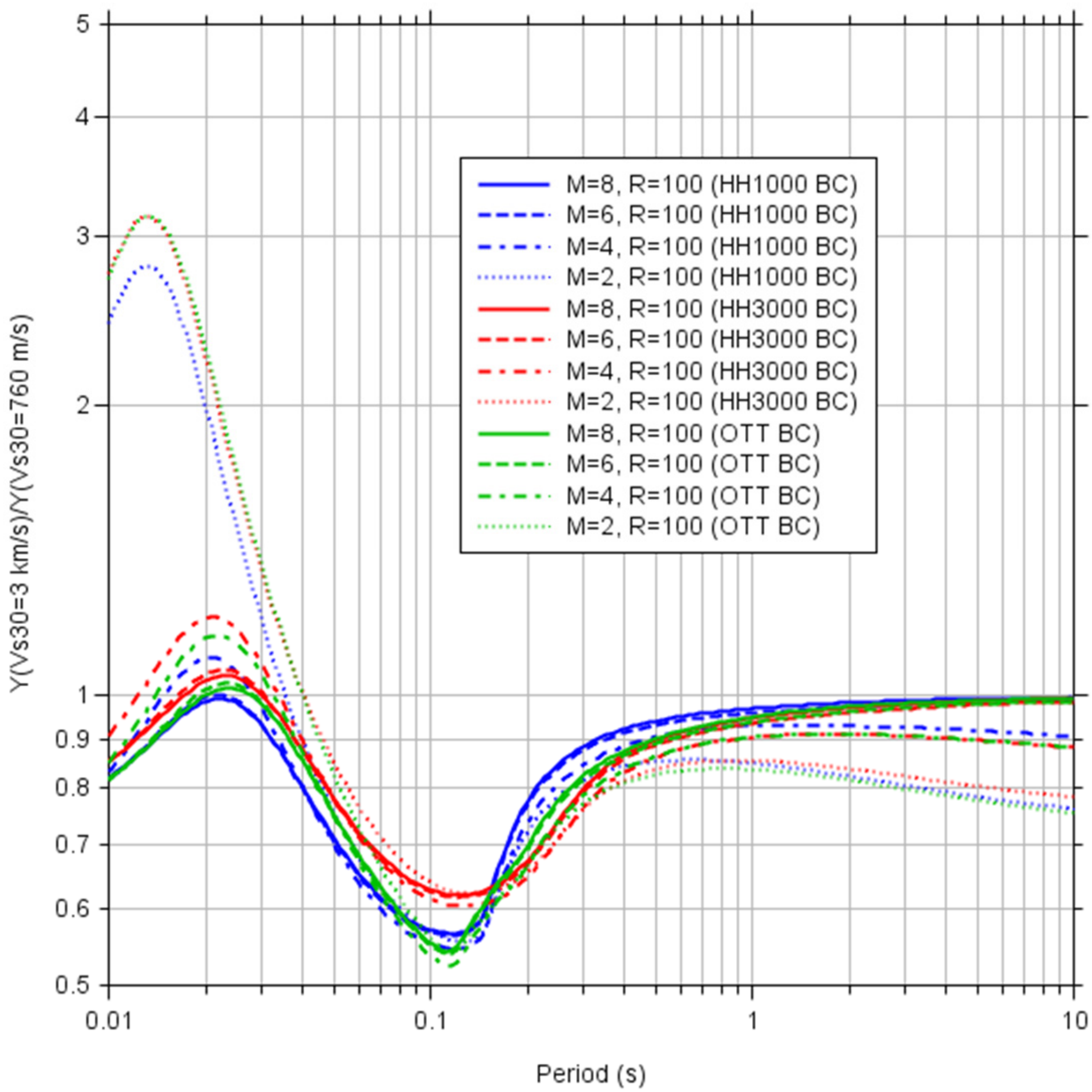

Figure 23 **Ratios of PSA for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec as a function of period for a distance of 100 km. The Boatwright and Seekins [2011] (BS11) attenuation model and a diminution operation with κ = 0.02 sec was used for the V_{S30} = 760 m/sec site condition. Three models were used for the V_{S30} = 760 m/sec crustal amplifications: Hashash and Harmon models HH1000 and HH3000, and the OTT model of Beresnev and Atkinson [1997].**

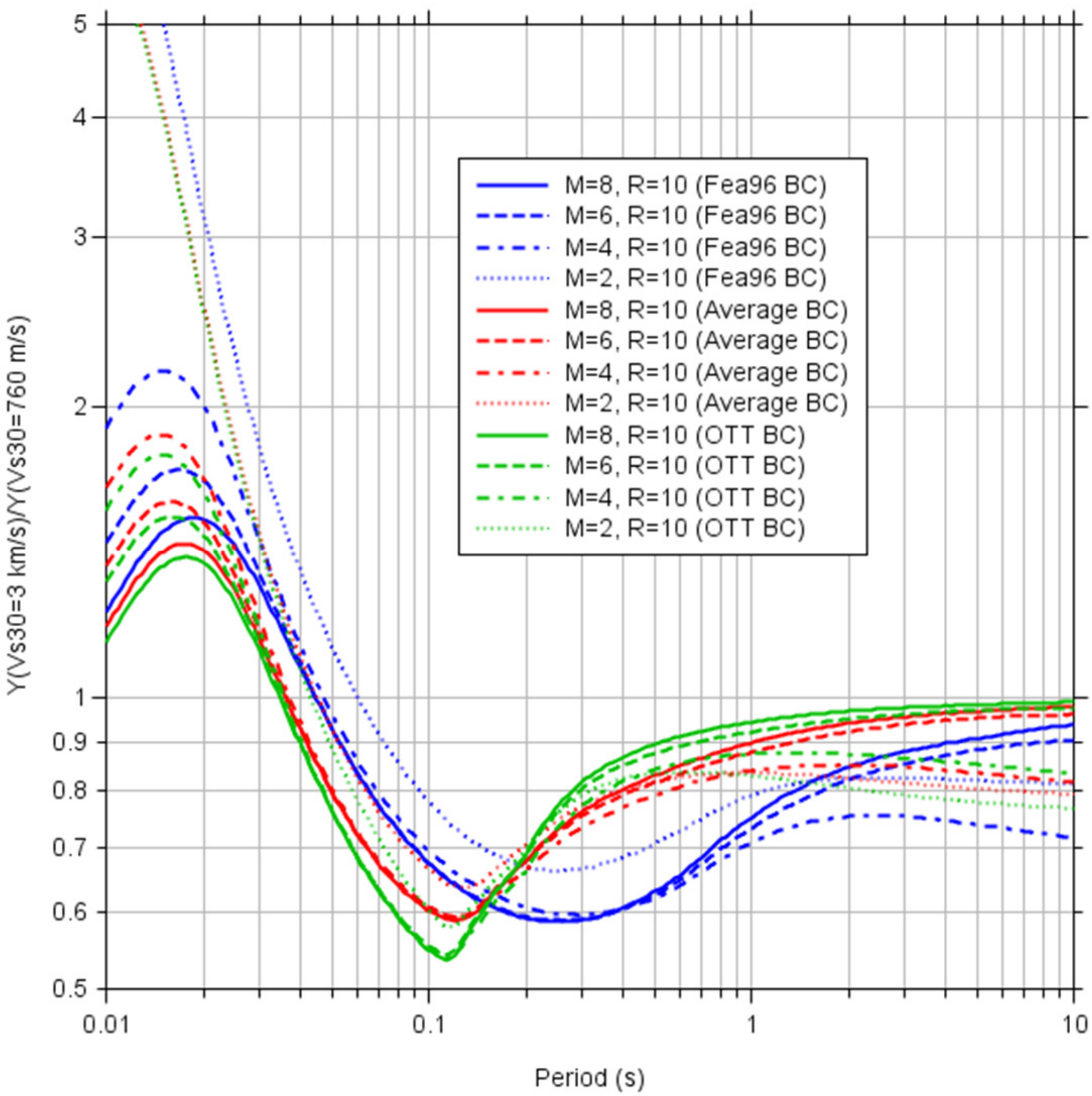

Figure 24 **Ratios of PSA for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec as a function of period for a distance of 10 km. The Boatwright and Seekins [2011] (BS11) attenuation model and a diminution operation with κ = 0.02 sec was used for the V_{S30} = 760 m/sec site condition. Three models were used for the V_{S30} = 760 m/sec crustal amplifications: Frankel et al. [1996] (Fea96), the average BC model derived in this report (Average BC), and the OTT model of Beresnev and Atkinson [1997].**

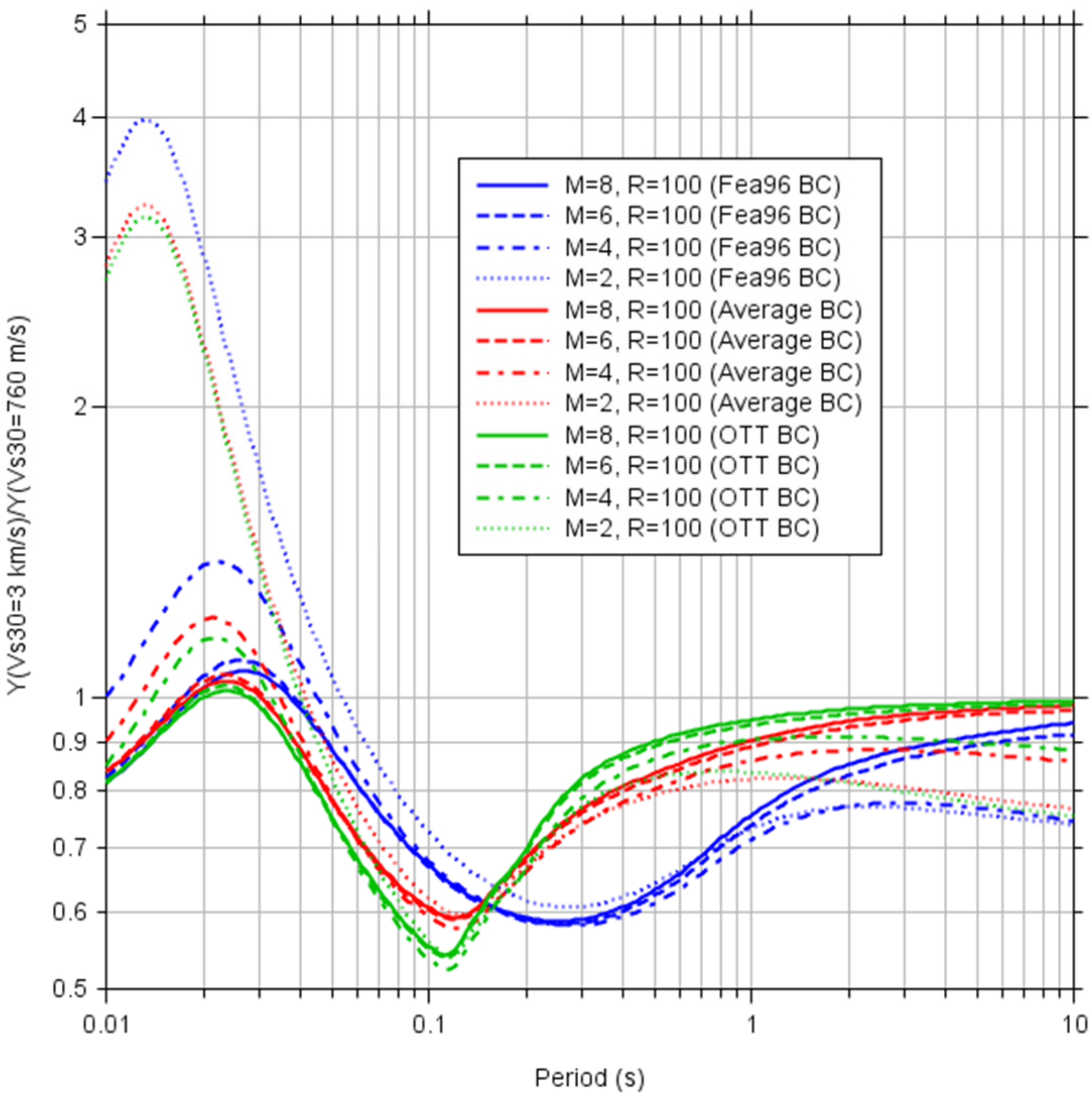

Figure 25 **Ratios of PSA for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec as a function of period for a distance of 100 km. The Boatwright and Seekins [2011] (BS11) attenuation model and a diminution operation with κ = 0.02 sec was used for the V_{S30} = 760 m/sec site condition. Three models were used for the V_{S30} = 760 m/sec crustal amplifications: Frankel et al. [1996] (Fea96), the average BC model derived in this report (Average BC), and the OTT model of Beresnev and Atkinson [1997].**

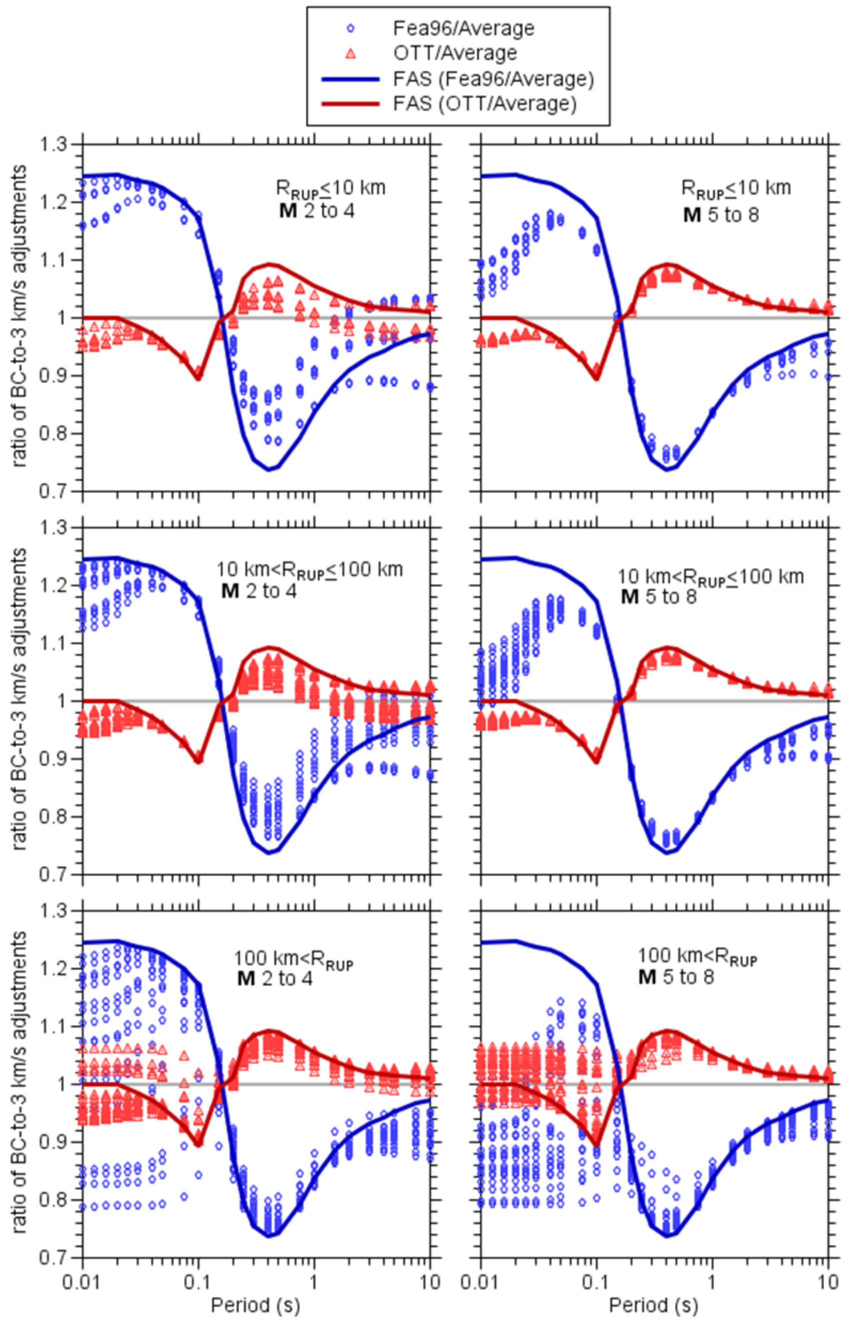

Figure 26 Ratios of PSA for V_{S30} = 3000 m/sec and V_{S30} = 760 m/sec as a function of period for distances of 10 km and 100 km. The Boatwright and Seekins [2011] (BS11) attenuation model and a diminution operation with κ = 0.03 sec was used for the V_{S30} = 760 m/sec site condition. The modified Frankel et al. [1996] model was used for the V_{S30} = 760 m/sec crustal amplifications. Also shown are ratios of Fourier acceleration spectra (FAS).

Table 4 **Ratio of Fourier amplitude spectra (FAS): FAS for a site with V_{S30} = 3000 m/sec and κ = 0.006 sec divided by the FAS of a site with V_{S30} = 760 m/sec for the Average BC model and four values of κ.**

T (sec)	ratio (3kps/Avg; κ = 0.005 sec)	ratio (3kps/Avg; κ = 0.01 sec)	ratio (3kps/Avg; κ = 0.02 sec)	ratio (3kps/Avg; κ = 0.03 sec)
0.010	0.245	1.178	27.268	630.990
0.020	0.287	0.629	3.024	14.547
0.025	0.298	0.559	1.962	6.895
0.030	0.306	0.517	1.473	4.199
0.040	0.319	0.472	1.035	2.270
0.050	0.328	0.449	0.841	1.577
0.075	0.347	0.428	0.651	0.989
0.100	0.364	0.426	0.583	0.799
0.150	0.430	0.477	0.588	0.726
0.200	0.523	0.566	0.662	0.775
0.250	0.595	0.634	0.719	0.815
0.300	0.647	0.682	0.757	0.841
0.400	0.712	0.741	0.801	0.867
0.500	0.755	0.779	0.830	0.883
0.750	0.823	0.841	0.877	0.914
1.000	0.861	0.875	0.903	0.932
1.500	0.904	0.914	0.933	0.953
2.000	0.930	0.937	0.952	0.967
3.000	0.953	0.958	0.968	0.978
4.000	0.963	0.967	0.975	0.982
5.000	0.968	0.972	0.978	0.984
7.500	0.978	0.980	0.985	0.989
10.000	0.985	0.987	0.990	0.993

Table 5 **Ratio of Fourier amplitude spectra (FAS): FAS for a site with V_{S30} = 3000 m/sec and κ = 0.006 sec divided by the FAS of a site with V_{S30} = 760 m/sec for the OTT model and four values of κ.**

T (sec)	ratio (3kps/OTT; κ = 0.005 sec)	ratio (3kps/OTT; κ = 0.01 sec)	ratio (3kps/OTT; κ = 0.02 sec)	ratio (3kps/OTT; κ = 0.03 sec)
0.010	0.245	1.177	27.235	630.235
0.020	0.286	0.628	3.020	14.530
0.025	0.295	0.554	1.946	6.836
0.030	0.302	0.509	1.451	4.135
0.040	0.310	0.459	1.006	2.206
0.050	0.315	0.431	0.807	1.513
0.075	0.321	0.396	0.602	0.915
0.100	0.325	0.380	0.520	0.712
0.150	0.426	0.473	0.584	0.720
0.200	0.529	0.572	0.670	0.784
0.250	0.635	0.676	0.766	0.869
0.300	0.701	0.739	0.821	0.911
0.400	0.777	0.808	0.874	0.945
0.500	0.821	0.848	0.903	0.961
0.750	0.881	0.900	0.938	0.978
1.000	0.908	0.923	0.952	0.982
1.500	0.938	0.948	0.968	0.989
2.000	0.957	0.965	0.980	0.996
3.000	0.972	0.977	0.987	0.998
4.000	0.979	0.983	0.990	0.998
5.000	0.982	0.985	0.991	0.997
7.500	0.989	0.991	0.995	0.999
10.000	0.993	0.994	0.998	1.001

7 Conclusions

None of the ground motions in the NGA-East database were recorded on sites with a V_{S30} as high as that for the reference-rock site condition (3000 m/sec). Most of the motions come from sites with estimated values of V_{S30} near 500 m/sec. A procedure to adjust these motions to the reference-rock condition is given here. The first step is to adjust the observed motions to a $V_{S30} = 760$ m/sec site condition, and then use adjustment factors to convert that motion to a site with $V_{S30} = 3000$ m/sec. The conversion to $V_{S30} = 760$ m/sec is not given here, as it can be based on existing ground-motion models. This study focuses on the adjustments from $V_{S30} = 760$ m/sec to $V_{S30} = 3000$ m/sec, but I also provide adjustments for sites with $V_{S30} = 2000$ m/sec to those with $V_{S30} = 3000$ m/sec, as a number of the recordings in northeastern U.S. and southeastern Canada are on sites for which the estimated V_{S30} is 2000 m/sec. The adjustment factors are based on stochastic-method simulations, using crustal amplifications derived in this report. Adjustment factors are provided as tables of ratios of simulated ground-motion intensity measures for sites with $V_{S30} = 3000$ m/sec and either 760 m/sec or 2000 m/sec. The adjustment factors are for magnitudes ranging from 2 to 8, rupture distances from 2 km to 1200 km, and periods from 0.01 sec to 10 sec, in addition to PGA and PGV. One model was considered for $V_{S30} = 3000$ m/sec, as the amplifications are not sensitive to the details of hard-rock velocity profiles. In contrast, 10 models that have been used in CENA, all with V_{S30} very close to 760 m/sec, were considered. I provide adjustment factors for two of those models that approximately span the range of models, as well as an average model (for the convenience of the user). For each of the models with $V_{S30} = 760$ m/sec, adjustment factors are provided for four values of κ : 0.005 sec, 0.01 sec, 0.02 sec, and 0.03 sec.

The adjustment factors for the three models of the crustal amplifications for sites with $V_{S30} = 760$ m/sec are generally within 20% of one another for a given value of the diminution parameter κ. On the other hand, the adjustment factors for each model are sensitive to κ at short periods. For a given period, the adjustment factors can be a function of magnitude and distance, but except for short-period motions, small magnitudes, and distances greater than about 200 km, the factors are relatively insensitive to magnitude and distance. In these cases, the ratios of the Fourier spectra of the ground motions (which are essentially ratios of the site amplifications) are a convenient substitute for the adjustment factors based on the ratios of simulated ground-motion intensity measures. These Fourier spectral ratios are given in tables.

8 Data and Resources

The square-root-impedance and full resonant amplifications were computed using the programs *site_amp* and *nrattle*, respectively; they and various utility programs used in the computations are part of the SMSIM suite of programs, available from the online software link at *www.daveboore.com* [last accessed 10 April 2015]. *nrattle* is a modification by R. Herrmann of C. Mueller's program *rattle*; *nrattle* is included in the SMSIM suite of software with their permission. The densities used in some of the models were obtained from velocity-density relations given in *daves_notes_on_relating_density_to_velocity_v1.2.pdf*, available from *www.daveboore.com/daves_notes.html* [last accessed 10 April 2015]. The ground-motion intensity measures and the Fourier spectra were computed using the SMSIM programs *tmrs_loop_rv_drvr* and *fmrs_loop_fas_drvr*, respectively. The figures were prepared using CoPlot (*http://www.cohort.com*).

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Appendix A SMSIM Parameters Files Used in the Simulations

Appendix A contains the Electronic Appendix SMSIM parameters files used in the simulations.

Appendix B Tables of PGV, PGA, and PSA V_{S30} = 760 m/sec to V_{S30} = 3000 m/sec Adjustment Factors

Appendix B contains the Electronic Appendix tables of PGV, PGA, and PSA V_{S30} = 760 m/sec-to-V_{S30} = 3000 m/sec adjustment factors. Separate files are given for the Atkinson [2004] (A04) and Boatwright and Seekins [2011] (BS11) attenuation models, and for each model, separate files are given for each BC kappa (0.005, 0.010, 0.020, and 0.030 sec). In addition, adjustment factors are given for V_{S30} = 2000 m/sec to V_{S30} = 3000 m/sec.

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