PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Semi-Empirical Nonlinear Site Amplification and its Application in NEHRP Site Factors

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ABSTRACT

Site factors are used to modify ground motions from a reference rock site condition to reflect the influence of geologic conditions at the site of interest. Site factors typically have a small-strain (linear) site amplification that captures impedance and resonance effects coupled with nonlinear components. Site factors in current NEHRP *Provisions* are empirically-derived at relatively small ground motion levels and feature simulation-based nonlinearity. We show that NEHRP site factors have discrepancies with respect to the site terms in the 2008 Next Generation Attenuation (NGA) ground motion prediction equations, both in the linear site amplification (especially for Classes B, C, D, and E) and the degree of nonlinearity (Classes C and D). The misfits are towards larger linear site factors and stronger nonlinearity in the NEHRP factors. The differences in linear site factors result largely from their normalization to a reference average shear wave velocity in the upper 30 m (V_{S30}) of about 1050 m/sec, whereas the reference velocity for current application is 760 m/sec. We show that the levels of nonlinearity in the NEHRP factors are generally stronger than simulation- and empirically-based models used in the original (2008) Next Generation Attenuation (NGA) project.

We analyze the NGA-West 2 data set to evaluate site amplification both with respect to V_{S30}-scaling and nonlinearity. The motivation of this analysis was to support the development of a proposal for revising the NEHRP site factors and a site amplification model that is used in an NGA-West 2 GMPE (Boore et al., 2014; BEA14). The development of that site amplification model is described by Seyhan and Stewart (2014; SS14); this report presents supporting work that guided model development relative to regional variations in site amplification and levels of nonlinearity implied by simulations.

We investigated regional trends in V_{S30}-scaling and found the presence of such trends to be sensitive to data selection criteria. When only data at fault distances under 80 km were selected (motivated by avoiding complications from regional variations in anelastic attenuation), we found strong regional site amplification trends, with the Japanese data showing markedly weaker V_{S30}-scaling than other regions at short periods. Regional variations are less significant at mid- and long-periods. When data from greater distances were considered (up to approximately 400 km) with appropriate corrections for regional variations in anelastic attenuation, regional variations in V_{S30}-scaling are diminished to the point that the proposed site amplification model (in SS14) does not include a regional term.

We investigated the regionalization of nonlinearity in site amplification using NGA-West 2 data. While modest between-region variations are present in the data, the trends were not considered sufficiently robust to be included in the site amplification model. Levels of nonlinearity evaluated empirically were found to generally be similar to those implied by a simulation-based model (Kamai et al., 2014; KEA14), except for pseudo spectral accelerations at periods between 0.5 and 3.0 sec where the data exhibits more nonlinearity than is evident from the simulations. Both the empirical- and simulation-based nonlinearities were considered in the development of the nonlinear component of the SS14 site amplification model.

The complete site amplification model (for V_{S30}-scaling and nonlinearity) is used to derive new NEHRP site factors using a reference velocity of 760 m/sec. For relatively weak levels of shaking, the new NEHRP site factors are generally smaller than current values due to the change in reference velocity from 1050 to 760 m/sec. For stronger shaking levels and Class C and D soils, the new site factors are close to, or exceed, those used currently because of reduced levels of nonlinearity, especially at long period (i.e., in the F_v parameter). Factors for soft soil (Class E) were set conservatively, as were the original NEHRP site factors, to account for larger epistemic uncertainty in the nonlinearity for this site class as compared to others. Other than Class E, the new NEHRP site factors match the BEA14 site terms nearly exactly and are generally consistent with site amplification models in other NGA-West 2 GMPEs as well. The new site factors have been approved by the Provisions Update Committee of the Building Seismic Safety Council and are expected to appear in the 2015 version of the NEHRP *Provisions*.

ACKNOWLEDGMENTS

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 Introduction

1.1 PROJECT OBJECTIVES AND SCOPE

The site factor terms in Next Generation Attenuation (NGA) ground motion prediction equations (GMPEs) express the effect of shallow site conditions on various ground motion intensity measures (IMs) as a function of V_{s30}. The parameter V_{s30} represents the average shear wave velocity of a site in the upper 30 m, and is computed as the ratio of 30 m to shear wave travel time through the upper 30 m of the site. Site factors in the NEHRP *Provisions*, which are used in building codes world-wide and also in financial loss modeling for insurance applications, are based on site categories derived from V_{s30}.

In both the NGA-West 1 and NGA-West 2 projects, the site factors are based on a combination of numerical simulations and empirical data analysis, with the empirical data derived from relatively large databases (Chiou et al. 2008; Ancheta et al. 2014). In contrast, the NEHRP site factors are based on a very small database of recordings in the San Francisco Bay Area from the 1989 Loma Prieta earthquake, which establishes relatively weak motion amplification empirically, in combination with nonlinear effects established from numerical simulations (Dobry et al. 2000). Not surprisingly, experience in practice and from some preliminary research (e.g., Mark Petersen, *personal communication*, 2008; Huang et al. 2010) indicates that the NGA and NEHRP site factors have some discrepancies, and those discrepancies have been shown to be consequential for loss estimation and other applications [e.g., Cao et al. (2003) and Rowshandel et al. (2005)]. An important objective of this project was to identify those discrepancies for the IMs of interest in the NGA-West 2 project and propose new site factors for application in NEHRP that will resolve the differences. The project team has worked in coordination with the NEHRP Provisions Update Committee (PUC) in this regard, and a proposal for revision of the NEHRP *Provisions* and *Commentary* was submitted and ultimately approved by the PUC.

Additional, related objectives of this project were to support the development of NGA-West 2 ground motion prediction equations (GMPEs) through both database work and data analysis related to nonlinear site response. The database work was concentrated on the development of an improved site database (relative to the version used in NGA-West 1), specifically in reference to incorporating the results of additional site characterization efforts, providing more complete reporting of site proxies used for V_{s30} estimation, and testing of proxy performance, providing recommended V_{s30} values with appropriate justification, and other issues (e.g., station housing, modified treatment of basin depth). The work on proxies has led to evidence-based protocols for estimating V_{s30} for sites without geophysical measurements and associated uncertainties. The results of the database work are provided in Seyhan et al. (2014).

The data analysis work utilized of the NGA-West 2 data to evaluate the dependence of site amplification on V_{S30} and nonlinear effects, and the regional variations of such effects. We worked closely with other NGA GMPE developers in this process in support of GMPE model development. The work has led to a site amplification model with two terms representing V_{S30}-scaling and nonlinear effects; details on the development of that model are presented by Boore et al. (2013; 2014) (BEA13, BEA14) and Seyhan and Stewart (2014) (SS14). The site amplification terms proposed for use in revising the NEHRP *Provisions* are computed on the basis of the SS14 model by averaging across applicable period ranges.

The NGA-West 2 Task 8 working group members are listed in Table 1.1. The members of the working group provided detailed technical input throughout the project and hence helped to shape the materials presented in the report.

Table 1.1 NGA-West2 Task 8 working group.

Graduate student	Emel Seyhan, UCLA
Project team	C. B. Crouse, URS Corporation, Seattle, WA
	Donald Anderson, CH2MHill, Bellevue, WA
	I. M. Idriss, Santa Fe, NM
	Kenneth W. Campbell, EQECAT, Beaverton, OR
	Maury S. Power, AMEC, Oakland, CA
	Robert W. Graves, USGS, Pasadena, CA
	Roger D. Borcherdt, USGS, Menlo Park, CA
	Walter J. Silva, PEA, El Cerrito, CA
	Thomas Shantz, Caltrans, Sacramento, CA
Principal Investigator	Jonathan P. Stewart, UCLA
Project Director	Yousef Bozorgnia, PEER, Berkeley, CA

1.2 REPORT ORGANIZATION

This report has six chapters. Chapter 2 presents technical background information on the site amplification factors in the NEHRP *Provisions* and in NGA-West 1 models. Chapter 3 explains the differences between NEHRP and NGA site factors and the causes for those differences. Chapter 4 summarizes the BEA14 site amplification model and presents supporting work that guided model development relative to regional variations in site amplification and levels of nonlinearity implied by simulations. Chapter 5 is concerned with the development of a proposal for revision of the NEHRP site factors, including the relationship between the Task 8 working group and the PUC, key issues faced in working group deliberations, and the manner by which the new NEHRP site factors were developed. Finally, Chapter 6 concludes the report and describes ongoing and future work.

2 Basis of Site Factors in Current NEHRP Provisions and NGA Models

2.1 SITE FACTORS IN NEHRP PROVISIONS

The NEHRP *Provisions* and *Commentary* (BSSC 2003) provide the documentation from which seismic provisions in building codes are periodically updated. One important aspect of the NEHRP *Provisions* and *Commentary* is the specification of design-basis ground motions, which are derived for rock site conditions at 0.2 sec and 1.0 sec period from probabilistic seismic hazard analysis (PSHA) and then modified by site factors. The PSHA-based rock site ground motions used in building codes are mapped by the U.S. Geological Survey (USGS) (http://earthquake.usgs.gov/hazards/). In the 2008 version of the maps, the reference site condition is specified as V_{s30} = 760 m/sec, where V_{s30} is the average shear wave velocity computed as the ratio of 30 m to shear wave travel time through the upper 30 m of the site.

As shown in Table 2.1, NEHRP site factors are based on site classes derived from V_{s30}. An exception to the V_{s30} criteria is made for soft clays (defined as having undrained shear strength < 24 kPa, plasticity index > 0.20, and water content > 0.40), for which Class E is assigned if the thickness of soft clay exceeds 3 m regardless of V_{s30}. The site factors are intended to modify ground motion relative to the reference condition used in development of the PSHA maps, which is at the boundary between Classes B and C (V_{s30} = 760 m/sec).

Table 2.1 Site Classes in NEHRP Provisions (Martin 1994).

NEHRP Category	Description	Mean Shear Wave Velocity to 30 m
A	Hard rock	>1500 m/s
B	Firm to hard rock	760–1500 m/s
C	Dense soil, soft rock	360–760 m/s
D	Stiff soil	180–360 m/s
E	Soft clays	<180 m/s
F	Special study soils, e.g., liquefiable soils, sensitive clays, organic soils, soft clays >36 m thick	

Figure 2.1 presents the short- and long-period NEHRP site factors (BSSC 2003) F_a and F_v, which depend on both site class and intensity of motion on reference rock. The ground motion parameters for the reference site condition used with site factors are: (1) S_s - the pseudo spectral acceleration (PSA) at 0.2 sec (used with F_a); and (2) S_1 – pseudo spectral acceleration (PSA) at 1 sec (used with F_v).

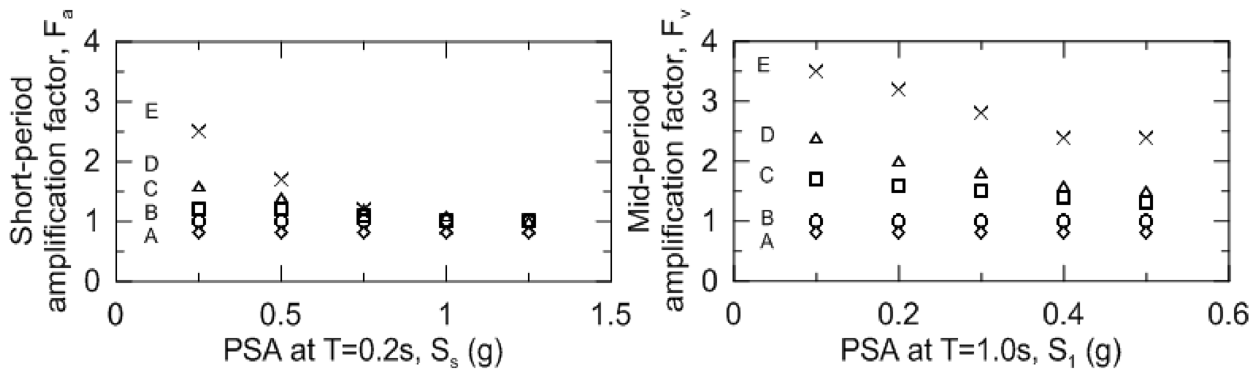


Figure 2.1 Site factors F_a and F_v in NEHRP Provisions (BSSC 2003).

Some physical processes underlying the trends in the NEHRP site factors shown in Figure 2.1 are as follows:

1. Site factors decrease with increasing V_{s30}. This effect is related to the impedance contrast between the shallow soil sediments and the underlying stiffer sediments and rock. Slow velocities in shallow sediments will amplify weak- to moderate-amplitude input motions, especially near the fundamental frequency of the soil column.

2. Site factors decrease with increasing S_s or S_1 and the rate of decrease is fastest for soft soils. As ground motion amplitude increases, the shear strains in the soil increase, causing increased hysteretic damping in the soil. The increased damping dissipates energy and reduces ground motion levels. Because softer sediments develop larger strains than stiffer sediments, this effect is most pronounced for Class E and is less significant for stiffer sites.

3. Site factor F_a (short periods) decreases more rapidly with increasing S_s than does F_v with S_1. The damping effect described in (2) acts on each cycle of ground motion. High-frequency ground motions will have larger fractions of wavelengths within the soil column than low-frequency motions. Because the soil has more opportunity to influence high-frequency motions, it produces greater nonlinearity.

Site factors can be developed using theoretical and empirical approaches. Existing NEHRP site factors were developed empirically for relatively low input rock ground motions (peak accelerations or S_l near 0.1g) and have levels of nonlinearity derived from simulations. Additional details on the development of NEHRP factors utilizing empirical and theoretical methods are given in the following sections. Justification for the use of V_{s30} as a site parameter is beyond the scope of this report, but is discussed elsewhere, including Stewart et al. (2001).

2.1.1 Empirical Basis for Weak Motion NEHRP Site Factors

The empirical basis for the relatively weak motion NEHRP site factors was developed by Borcherdt (1994b), Borcherdt and Glassmoyer (1994), and Joyner et al. (1994), who examined ground motions from the 1989 Loma Prieta earthquake recorded on a variety of site conditions varying from soft clay to rock in the San Francisco Bay Area. Site conditions at recording sites were generally characterized using bore-hole seismic-velocity measurements. A reference site approach was used in which Fourier spectral ratios were calculated for pairs of stations in which one is on soil and one is on reference rock. Figure 2.2 shows a map of the rock and soil sites considered by Borcherdt and Glassmoyer (1994) (BG94). For a particular period T and rock-soil site pair, the site factor determined by this method is:

$$F(T) = \frac{FA_{Vs30}(T)}{FA_{ref}(T)} \tag{2.1}$$

where $FA_{Vs30}(T)$ is the Fourier amplitude at period T from a recording on a site condition with velocity V_{s30}, and $FA_{ref}(T)$ is a recording from a neighboring rock site that is taken as the reference (V_{s30} > 760 m/sec). Fourier amplitude spectral ratios were computed at frequency intervals of 1/40.96 sec in the frequency domain. Period-specific spectral ratios calculated from Equation (2.1) were averaged across a short period band (0.1–0.5 sec) and mid-period band (0.4–2.0 sec) to estimate F_a and F_v for each rock-soil pair. Resultant empirical estimates of F_a and F_v and the corresponding regression lines are presented in BG94 and have been reproduced in Figure 2.3. The reference rock motions used by BG94 have bedrock peak ground accelerations that range from 0.075 to 0.11g, with an average of about 0.1g.

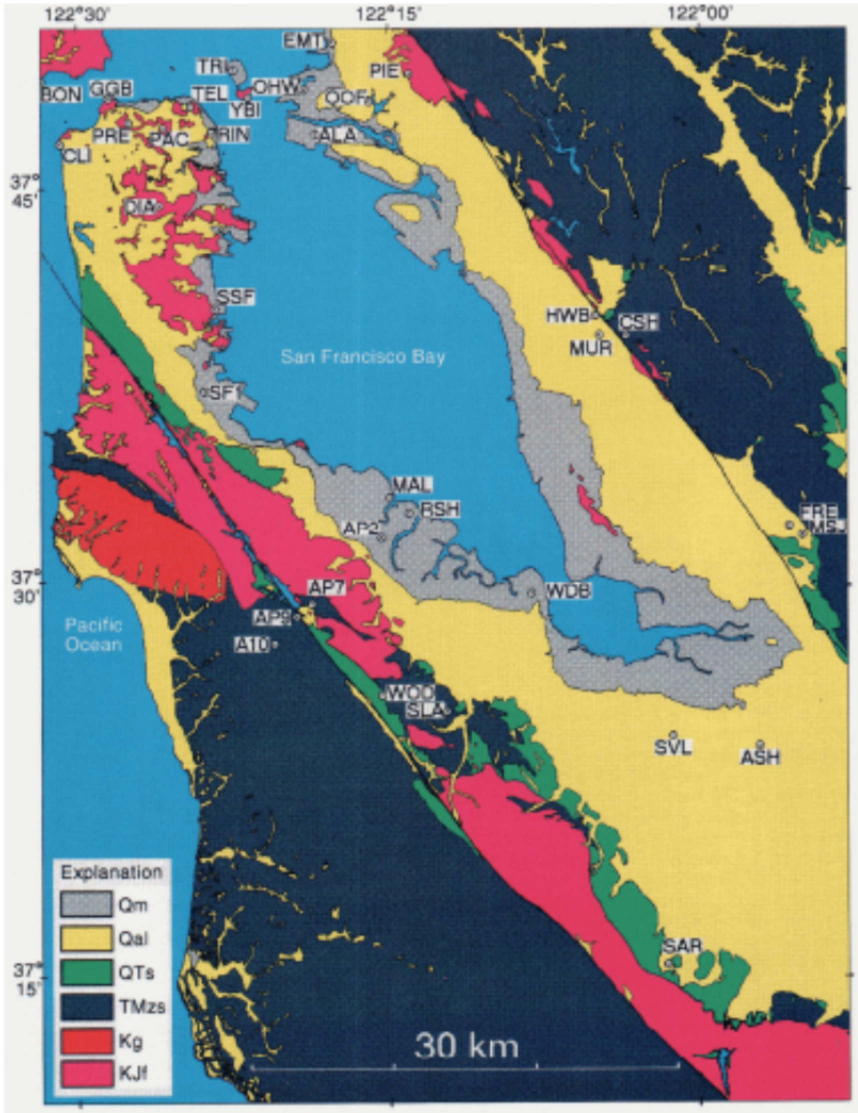


Figure 2.2 **Map of San Francisco Bay region, showing locations of 34 of 37 free-field stations that recorded 1989 Loma Prieta earthquake and generalized geologic units. KJf corresponds to Franciscan formation bedrock of Cretaceous and Jurassic age that was taken as reference rock (Borcherdt and Glassmoyer 1994).**

Figure 2.3 shows the F_a and F_v factors produced by BG for each station pair plotted as a function of V_{s30} along with regression lines, 95% confidence intervals for the ordinate to the true population regression line, and the limits for two standard deviations of the estimate. The relatively narrow confidence intervals indicate that the scaling of the site terms with V_{s30} is statistically significant, but it is apparent from the trends in Figure 2.3 that the scaling is more pronounced at mid periods than at short periods. This is thought to occur because most soil sites have fundamental vibration periods within the mid-period band, producing stronger site effects in that period range than at shorter periods.

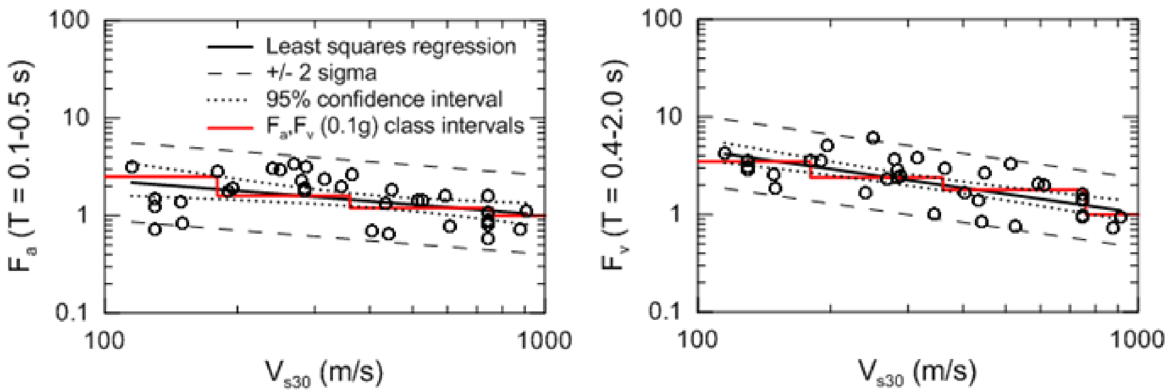


Figure 2.3 **Site factors F_a and F_v evaluated from reference site approach from recordings of 1989 Loma Prieta earthquake as function of V_{s30} [data from Borcherdt, (1994b)]. The reference motion amplitude for the data is PGA_r = 0.1g. Red stepped lines correspond to site factors in site class intervals.**

The reference sites used by BG94 correspond to a competent rock site condition, which in the San Francisco Bay Area corresponds specifically to Franciscan formation bedrock of Cretaceous and Jurassic age. The average values of V_{s30} among the reference sites is approximately 795 m/sec, but the linear trend line through the data in Figure 2.3 reaches unity at V_{s30} = 1050 m/sec. Hence, the linear trend line produces non-unity amplification levels at the contemporary reference condition of V_{s30} = 760 m/sec (B-C boundary).

In Figure 2.3 the red stepped lines correspond to F_a and F_v values in use since publication of the 1994 NEHRP *Provisions* (BSSC 1995). As shown in Figure 2.3, the NEHRP F_a and F_v factors are generally consistent with the trend of the regression lines. The stepped site factors in Figure 2.3 are slightly different from those presented by Borcherdt (1994b), which match the lines at V_{s30} = 150, 270, 560, and 1050 m/sec. The modifications in NEHRP factors relative to Borcherdt (1994b) are in (1) the velocity boundaries, the final values of which were selected in committee; and (2) the amplification levels for particular categories (e.g., F_a for E) that were increased by committee consensus [details in Dobry et al. (2000)]. As seen from Figure 2.3, the NEHRP factors match the regression lines at V_{s30} = 120, 290, 600; and 1050 m/sec (for F_a) and at 160, 290, 450, and 1050 m/sec (for F_v).

With regard to the V_{s30} = 1050 m/sec reference condition provided by Borcherdt (1994b) and adopted for the 1994 NEHRP *Provisions*, it is useful to recall the national ground motion maps with which the NEHRP site factors were originally applied. As described by Algermissen and Perkins (1976), the GMPE used at that time was a model for rock conditions by Schnabel and Seed (1973), which was used directly for peak acceleration in the western U.S. (non-subduction regions) and with some modification for other conditions (i.e., other regions and longer periods, as described by Algermissen and Perkins (1976). The rock site conditions represented by the GMPE are poorly defined, although many of the motions used in GMPE development are from soil sites and were deconvolved to rock using wave propagation analysis (Schnabel et al. 1971). The rock conditions used in the deconvolution appear to have been hard (V_s = 2400 m/sec), whereas the motions from rock sites were associated with much softer geologic conditions. Considering that the rock GMPE represents the average of these conditions, the 1994 national maps likely applied for firm rock conditions. Therefore, we postulate that general compatibility existed between those maps and the NEHRP site factors, which in equation form are referenced to firm rock (V_{s30} = 1050 m/sec). By the time of the 1996 national maps (Frankel et al. 1996) as adopted by BSSC (1998), the reference condition used for the PSHA calculations was clearly defined as V_{s30} = 760 m/sec [e.g., Frankel et al. (1996, pgs. 5 and 17)], but the incompatibility with the reference condition for site factors was either not recognized or not considered to be significant. This condition has remained to the present time.

2.1.2 Theoretical Basis for Nonlinearity in NEHRP Site Factors

Theoretical ground response analyses generally model the stratigraphy as one-dimensional (1D) and simulate the nonlinear soil behavior using equivalent-linear or nonlinear methods. Site factors can be evaluated from ground response analysis using the ratio of response spectra at the top of the soil column to that of the outcropping base motion. Some key issues in the utilization of ground response analysis to develop site factors are: (1) the shear wave velocity profiles utilized in the analysis should be representative of the region where the site factors will be applied; (2) the selected modulus reduction and damping (MRD) curves should be appropriate for the predominant soil types; and (3) input motions should have appropriate amplitude and frequency content for the seismicity of the region. Similar considerations apply for nonlinear ground response analysis.

Borcherdt (1994b) and Dobry et al. (2000) described the process by which the ground response analysis results from equivalent linear and nonlinear methods were used to supplement the weak motion amplification levels depicted in Figure 2.3. Suites of profiles were analyzed by Seed et al. (1994) and Dobry et al. (1994) for Classes C-E using measured velocity profiles from sites in California and Mexico City. The empirical amplification values shown in Figure 2.4 were found to be in good agreement with those derived independently by Seed et al. (1994), those computed parametrically by Dobry et al. (1994) at input ground motion levels near 0.1*g*, and response spectral ratios computed by Joyner et al. (1994). Hence, the modeling results were used to extrapolate the inferred amplification factors to higher input peak acceleration levels of 0.2, 0.3, and 0.4*g*. Borcherdt (1994b) and Dobry et al. (2000) describe how the computed site factors were expressed in a linear form in log-log space as shown in Figure 2.4 and given by the following expressions:

$$F_a = \left(\frac{V_{ref}}{V_{s30}}\right)^{m_a} \tag{2.2}$$

$$F_v = \left(\frac{V_{ref}}{V_{s30}}\right)^{m_v} \tag{2.3}$$

where V_{ref} = 1050 m/sec and m_a and m_v are fit coefficients that vary with input motion amplitude to capture trends in the simulations with the results shown in the legend of Figure 2.4 (Borcherdt 1994b; Dobry et al. 2000). The black line in Figure 2.4 applies to $PGA_r = 0.1g$. For $PGA_r > 0.1g$ the amplification levels decrease in accordance with the simulation results, with the amount of decrease being greatest at low V_{s30}. Note from Figure 2.4 that these expressions for site factors are referenced to a common V_{s30} = 1050 m/sec. For the NEHRP site factors (Figure 2.1), the input motion ground motion amplitude was re-expressed as S_s and S_1 in lieu of PGA according to $S_s = 2.5$ PGA and $S_1 =$ PGA.

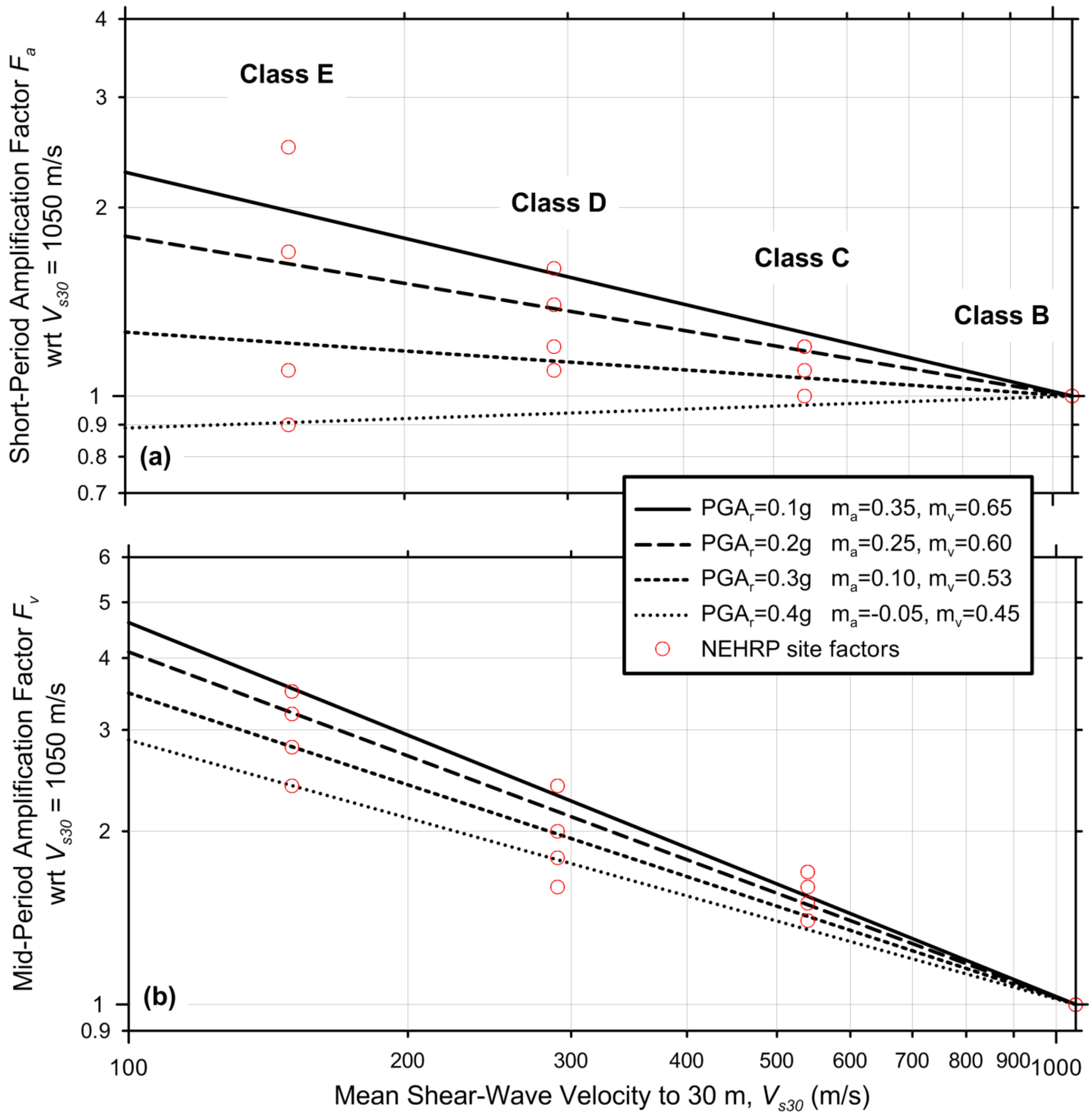


Figure 2.4 (a) Short-period F_a; and (b) mid-period F_v amplification factors. Parameters m_a and m_v are slopes of the amplification factors with V_{s30} in log-log space; PGA_r corresponds to the input ground motion level on rock in units of g (Dobry et al. 2000). Reported slopes from Borcherdt (1994a, b).

Figure 2.4 also shows the NEHRP site factors plotted at the V_{s30} values for which category-based site factors were originally developed by Borcherdt (1994b), as explained previously. The NEHPR factors have some discrepancies from the regression lines, especially for F_a in Category E and F_v in Categories C-D. As mentioned previously, those discrepancies arose from committee decisions.

2.2 SITE FACTORS IN NGA MODELS

The 2008 version of the Next Generation Attenuation (NGA) project produced GMPEs for shallow crustal earthquakes in active tectonic regions (Power et al. 2008). GMPEs were developed by five teams consisting of Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), and Idriss (2008). For ease of use, the abbreviations of AS08, BA08, CB08, CY08, and I08 are applied. The models are based on analyses of the PEER-NGA empirical strong ground motion database, which contains 3551 recordings from 173 earthquakes (Chiou et al. 2008).

The NGA models are semi-empirical equations for peak ground acceleration (PGA), peak ground velocity (PGV) and 5% damped elastic pseudo-acceleration spectra (PSA) for periods up to 10 sec. These ground motion prediction equations (GMPEs) have a typical form of:

$$\ln Y = f_1(M) + f_2(R) + f_3(F) + f_4(HW) + f_5(S) + \varepsilon_T \tag{2.4}$$

where Y is the median geometric mean ground motion intensity measure (IM); f_i are functions of magnitude (M), source-to-site distance (R), style of faulting (F), hanging-wall effects (HW), and site conditions (S). Parameter ε_T is a random error term with a mean of zero and a total aleatory standard deviation given by

$$\sigma_T = \sqrt{\sigma^2 + \tau^2} \tag{2.5}$$

where σ is the standard deviation of the intra-event residuals, and τ is the standard deviation of the inter-event residuals.

The site factors in the NGA GMPEs express the effect of shallow site conditions on various ground motion IMs as a function of V_{s30}, and in the case of the AS08, CB08, and CY08 relations, a basin depth term as well. Different NGA developers used different methods to obtain site factors. AS08 and CB08 set coefficients describing the linear site response empirically and constrain the nonlinearity in site response based on simulations by Walling et al. (2008) (WEA08). BA08 and CY08 fit the coefficients for both the linear and nonlinear components of their site amplification model empirically.

When site amplification factors are developed empirically, the process can be described as a non-reference site approach. In contrast with the reference site approach utilized by BG94, the non-reference site approach compares IMs from recordings (IM_{rec}) to median predictions from a GMPE for a reference site condition [$S_a^r(T)_{GMPE}$] as follows:

$$F(T) = \frac{\left(S_a^{rec}(T)\right)}{\left(S_a^{r}(T)_{GMPE}\right)} \tag{2.6}$$

Note that this approach does not require a reference site recording, hence a much larger set of ground motions can be used to develop site amplification levels, the median of which is taken as the site factor. In natural log units, $\ln F(T)$ can be viewed as the data residual relative to the rock GMPE:

$$\ln F(T) = \ln\left(S_a^{rec}(T)\right) - \ln\left(S_a^{r}(T)_{GMPE}\right) \tag{2.7}$$

The site factors are generally evaluated during the development of the GMPE in such a way as to minimize residuals.

As noted previously, the AS08 and CB08 GMPEs utilize site amplification models whose nonlinear component is set from the results of 1D ground response analyses. The ground response analyses and model building process are described in WEA08. The ground response analyses used an equivalent-linear analysis method with random vibration theory as implemented in the program RASCALS (Silva and Lee 1987). The velocity profiles were taken from a proprietary database maintained by Pacific Engineering and Analysis (PEA) for active tectonic regions. The modulus reduction and damping (MRD) curves were taken from judgment-driven relations known as the Peninsular Range curves. For each soil profile, amplification factors were computed for input rock PGA values ranging from 0.001 to 1.5*g*. For each case, the amplification with respect to V_{s30} = 1100 m/sec was computed. Example site factors for V_{s30} = 270 m/sec and 560 m/sec, obtained at T = 0.2 sec from this process, are plotted against PGA for V_{s30} = 1100 m/sec m/sec (i.e., PGA1100) in Figure 2.5. Additional calculations were performed using MRD curves from EPRI (1993), with otherwise identical conditions. Models developed from those results are unpublished but were provided by Walling (*personal communication*, 2011).

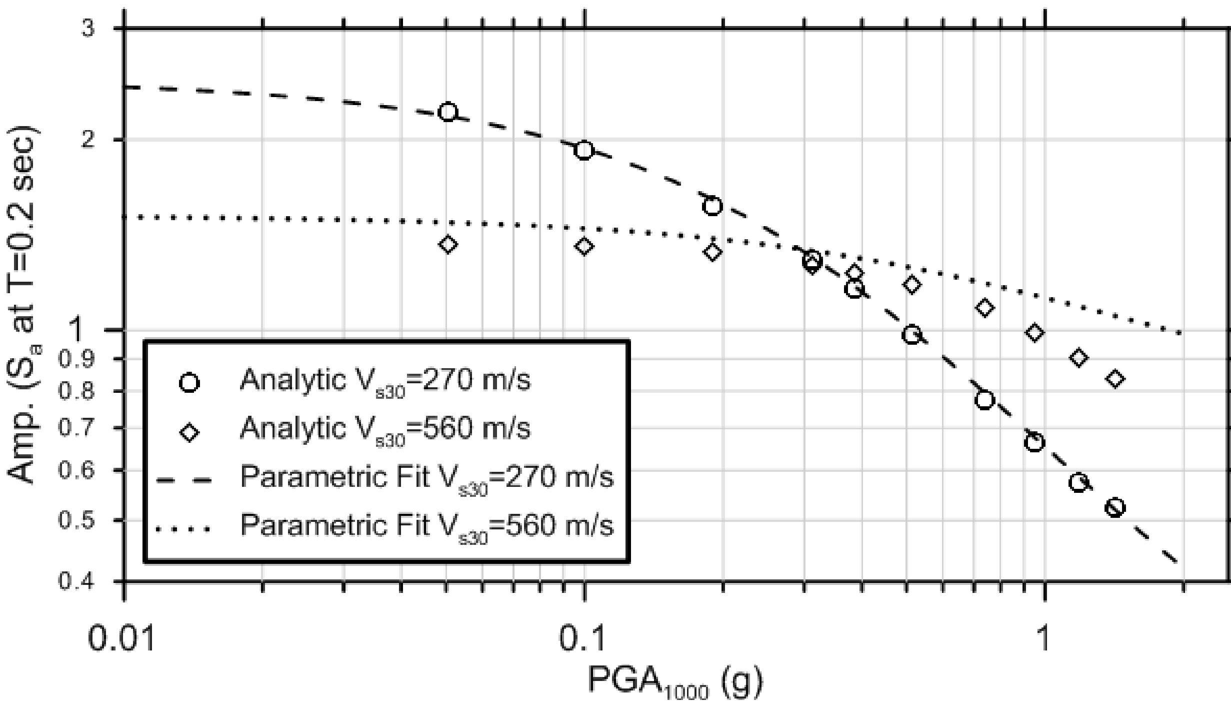


Figure 2.5 **Examples of the site factors computed by WEA08 and parametric fits to the analysis results. Adapted from WEA08.**

3 Differences between NEHRP and NGA Factors

3.1 SITE FACTORS COMPARISON

In this chapter we compare the NEHRP site factors with NGA-West 1 site factors derived from the four 2008 NGA GMPEs having site terms. Our objective is to identify discrepancies, with specific attention paid to evaluating differences in median amplification at low levels of rock ground motion, as well as possible differences in the nonlinearity of site amplification. In this chapter, when we refer to NGA GMPEs, we mean the 2008 version (NGA-West 1), not those associated with the NGA-West 2 project.

The NGA relations use different functional forms for the site terms. The reference rock ground motion amplitude parameter used to drive nonlinearity in the models is taken as PGA for AS08, BA08, and CB08 and as spectral acceleration at the period of interest for CY08. Site terms F_x (V_{s30}, A_x) are assumed to be log normally distributed and depend on A_x, the ground motion amplitude for a reference site condition having a particular $V_{s30} = x$. Reference motion amplitude A_x is a median PGA for AS08, BA08, and CB08, and an event-term adjusted median S_a at the period of interest for CY08. The event term (η_i) is approximately the median residual for well recorded events and is formally evaluated from random effects regression procedures (Abrahamson and Youngs 1992). To summarize, input parameters for the site amplification models are:

NEHRP: V_{s30}, S_s, S_1

AS08: V_{s30}, Median PGA_{1100} (PGA for V_{s30}=1100 m/sec)

BA08: V_{s30}, Median PGA_{760} (PGA for V_{s30}=760 m/sec)

CB08: V_{s30}, Median PGA_{1100} (PGA for V_{s30}=1100 m/sec)

CY08: V_{s30}, Median + η_i $(S_a)_{1130}$ (S_a for V_{s30}=1130 m/sec)

Note that the reference motions are defined for different reference rock site conditions in the GMPEs.

To facilitate comparisons between the NGA and NEHRP site factors, we compute site terms relative to the V_{s30} = 760 m/sec reference condition used in the national PSHA maps published by USGS. This condition is selected because the NEHRP factors are used to modify ground motions for site conditions that differ from the V_{s30} = 760 m/sec reference. The NGA site factors are calculated relative to this reference condition as:

$$\ln\left(F_{760}(V_{s30},\, A_x)\right) \;=\; \ln\left(F_x(V_{s30},\, A_x)\right) - \ln\left(F_x(760,\, A_x)\right)$$

or

$$F_{760}(V_{s30},\, A_x) \;=\; \frac{F_x(V_{s30},\, A_x)}{F_x(760,\, A_x)} \tag{3.1}$$

We define the reference site motion amplitude as A_x = median PGA for V_{s30} = 760 m/sec, which is denoted PGA_r in the following text. Site factors are evaluated for PGA_r = 0.01–0.9*g*. The CY08 site term uses S_a at the period of interest instead of using the median *PGA*. For this model, reference motion amplitude is estimated from PGA_r as:

$$S_a\left(T = 0.2\,\text{sec}\right) \approx 2.3PGA_r \qquad\qquad S_a\left(T = 1.0\,\text{sec}\right) \approx 0.7PGA_r \tag{3.2}$$

The factors of 2.3 and 0.7 in Equation (3.2) are based on differences in the median spectral ordinates (e.g., 0.2 sec S_a versus PGA) from the NGA-West 1 GMPEs for rock site conditions and typical ranges of M_w (6–8) and distance (< 30 km) that control seismic hazard. These values are updated from 2.5 and 1.0 in the original NEHRP factors. The factor S_a (1.0 sec)/PGA is significantly dependent on magnitude, and the value of 0.7 corresponds approximately to **M**7.0. Huang et al. (2010) use a procedure similar to that described above—instead of calculating the site term directly, they apply the NGA GMPEs for a range of magnitudes, distances, and other parameters to compute median S_a for selected V_{s30} values. They take the ratio of median S_a at V_{s30} to median S_a at 760 m/sec as a period-dependent site factor. Huang et al. (2010) average these values across three GMPEs (i.e., BA08, CB08 and CY08) and across period ranges to develop recommendations for F_a and F_v site factors.

We use the NGA-West 1 site models at representative V_{s30} values for each NEHRP category. The representative velocities are evaluated from medians within the various classes B-E using the site database compiled for the NGA-West 2 project (Ancheta et al. 2013). That database contains 1144 California and international sites with measured V_{s30} values derived from profiles 30 m or greater in depth, which are distributed as shown in Figure 3.1. The median V_{s30} values for each site class are indicated in Figure 3.1. More detailed histograms within the relatively well populated C and D classes are given in Figure 3.2. The representative category velocities given in Figure 3.1 are generally similar to those used by Borcherdt (1994b) to set the empirical site factors (i.e., 155 versus 150 m/sec for E; 266 versus 290 m/sec for D; 489 versus 540 m/sec for C; 913 versus 1050 m/sec for B) and the geometric means of the boundary end points (254 m/sec for D; 523 m/sec for C; 1070 m/sec for B).

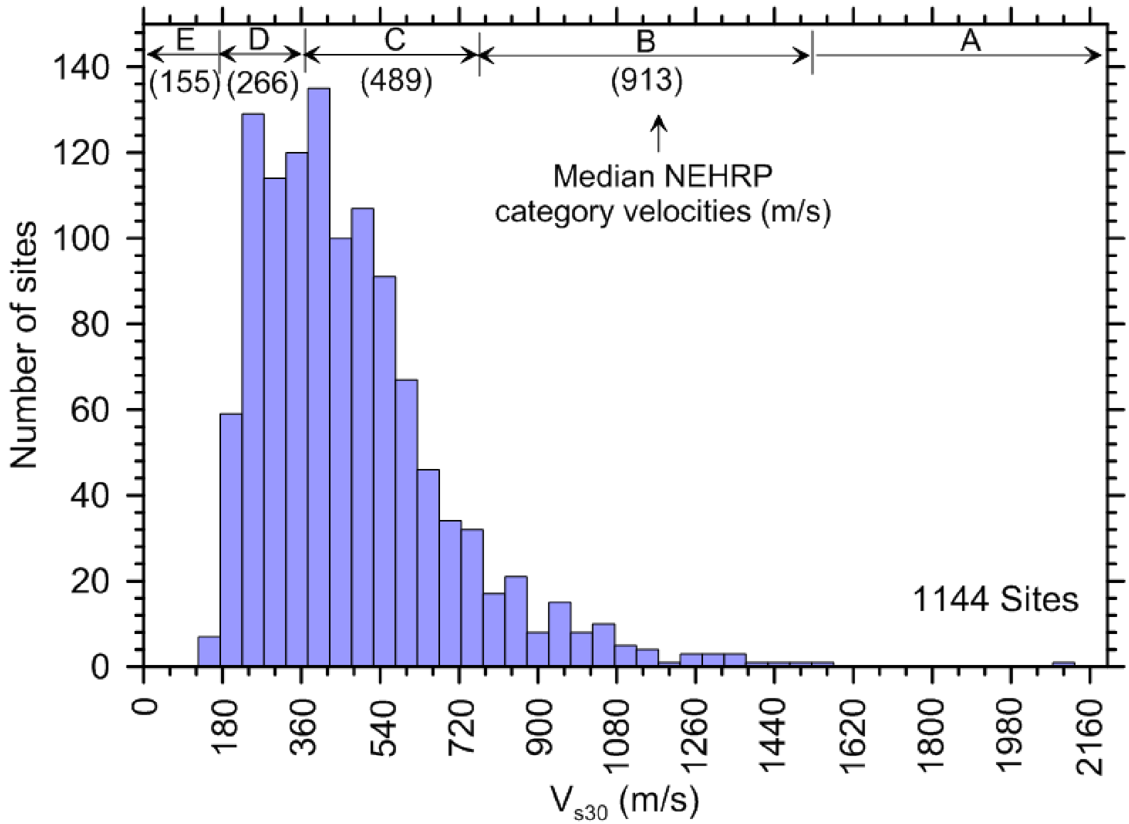


Figure 3.1 **Histogram of measured V_{s30} values for strong motion sites used in this study.**

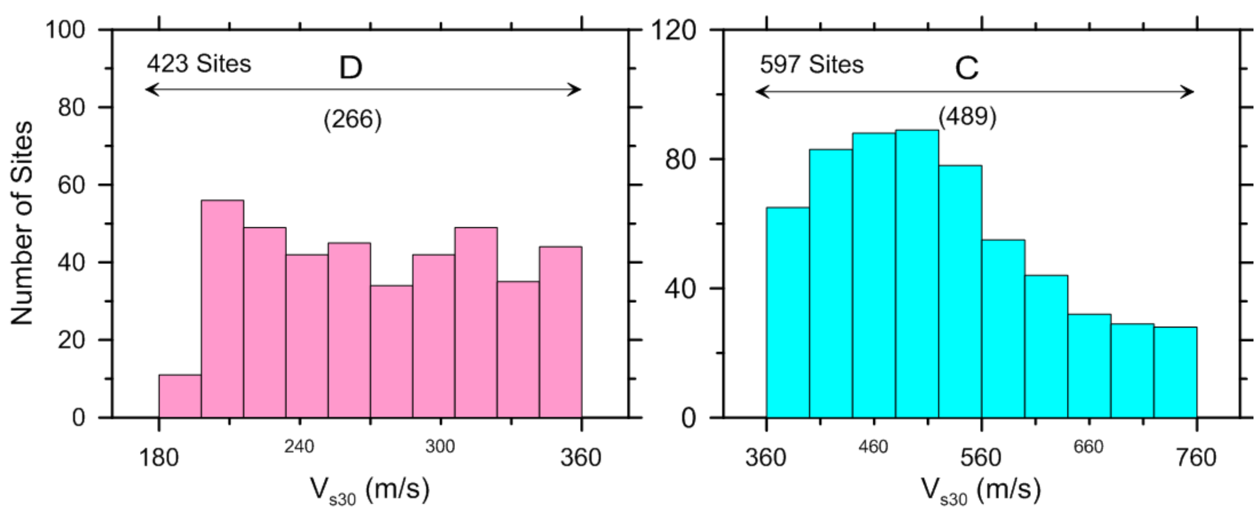


Figure 3.2 **Histogram of V_{s30} values within Site Classes C-D.**

Figure 3.3 compares the discrete published NEHRP site factors (black solid symbols) with NGA-West 1 site amplification terms computed for median spectral accelerations across the period range for F_a ($T = 0.1–0.5$ sec) and F_v ($T = 0.4–2.0$ sec) relative to V_{s30} = 760 m/sec. Adjustments to the NEHRP factors are also shown in Figure 3.3 (black open symbols), which are discussed further below. Also shown for comparison are site amplification factors from Huang et al. (2010) for Classes D and E (results for comparable V_{s30} values are not available for other site classes). Note the Huang et al. (2010) factors plotted in Figure 3.3 are averaged from their values for specific spectral periods within the respective period ranges for F_a (0.1–0.5 sec) and F_v (0.4–2.0 sec). Because the reference rock amplitudes used by Huang et al. (2010) are 0.2 sec and 1.0 sec S_a, we convert to PGA_r using S_a/PGA_r ratios in Equation (3.2), which are compatible with the magnitude and distance range selected by Huang et al. (2010).

The spread of NGA-West 1 site factors in Figure 3.3 reflects epistemic uncertainty, which is relatively large for Class E and modest elsewhere. We judged differences in NGA and NEHRP site factors to be significant when they clearly exceed the epistemic uncertainty for a given site class. In Classes C-D, NEHRP and NGA factors have different slopes for F_v, indicating different levels of nonlinearity. This issue is discussed further in the following section. In Classes C and D, NEHRP and NGA site factors are in reasonable agreement for F_a. In Classes B and E, NEHRP site factors are larger than NGA factors for F_a and F_v. The NEHRP C and D factors for F_v are also larger than NGA factors for weak motions (i.e., $PGA_r = 0.1g$). The trends shown in Figure 3.3 are not changed appreciably if the V_{s30} values used to compute the NGA site factors are changed to the values selected by Borcherdt (1994b) of 150, 290, 540, and 1050 m/sec. The Huang et al. (2010) site factors are generally similar to the NGA factors shown in Figure 3.3 for Classes D and E (and hence they also have similar discrepancies relative to NEHRP). The modest differences between our site factors and those of Huang et al. (2010) likely result from variability in the S_a/PGA_r ratios used to correct the abscissa, the use of different averaging procedures (i.e., different numbers of averaged spectral periods within F_a and F_v period bands) and other details. Huang et al. (2010) also report similar discrepancies between their site factors and NEHRP factors (e.g., their Figure 2).

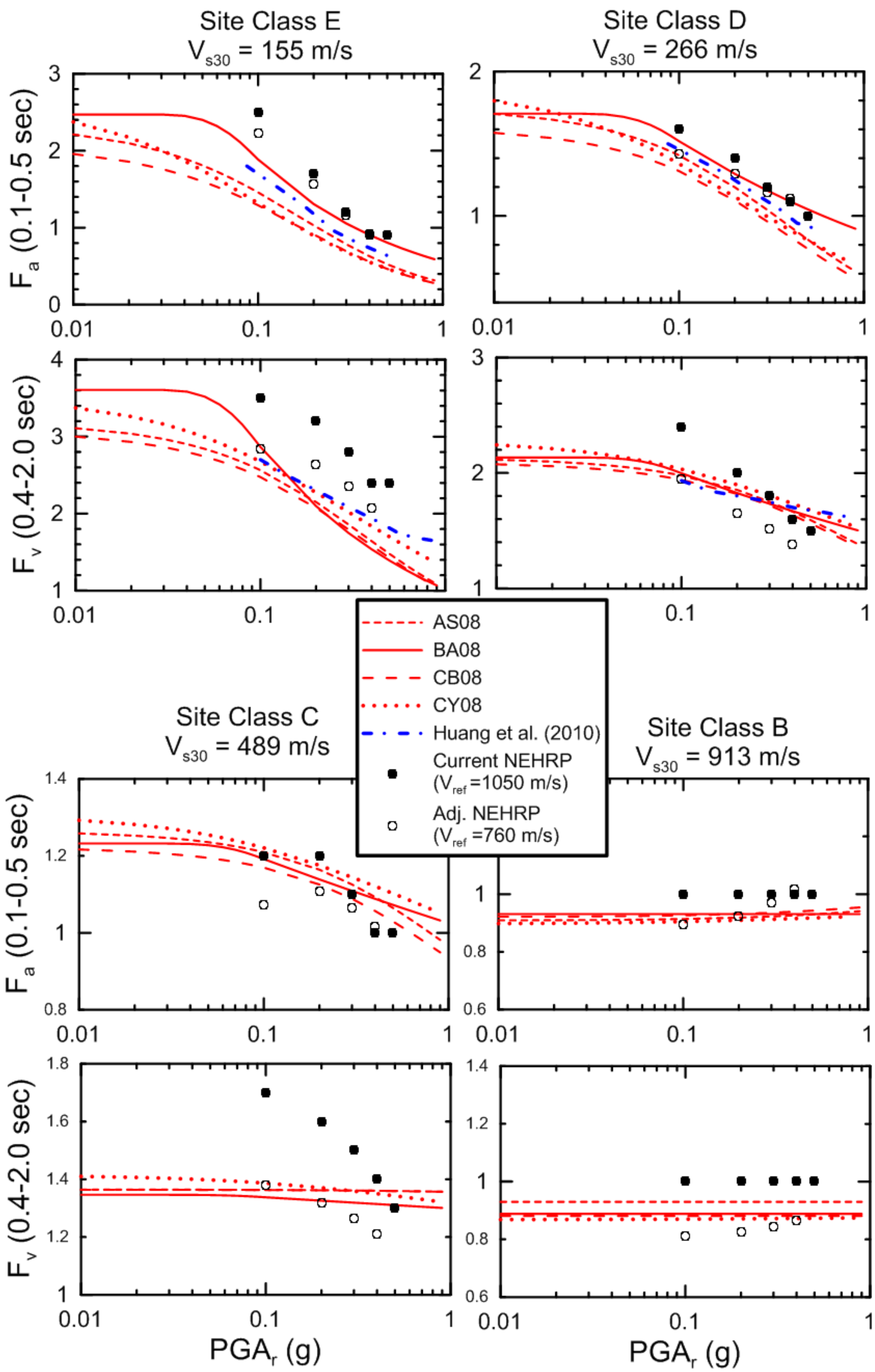


Figure 3.3 **Comparison of original and adjusted NEHRP site factors to site factors from NGA relationships averaged across corresponding period ranges (0.1–0.5 sec for F_a; 0.4–2.0 sec for F_v).**

As mentioned previously, adjusted NEHRP factors are also shown in Figure 3.4. The adjustment is computed to re-normalize the NEHRP factors from a reference velocity of 1050 m/sec to 760 m/sec as follows:

$$F_a^N = F_a \left(\frac{V_{ref}}{760} \right)^{-m_a}, \; F_v^N = F_v \left(\frac{V_{ref}}{760} \right)^{-m_v} \tag{3.3}$$

where superscript '*N*' indicates re-normalization, F_a and F_v are the original, published NEHRP factors, V_{ref} = 1050 m/sec per Borcherdt (1994b) and Dobry et al. (2000), and m_a and m_v are taken from Dobry et al. (2000) (shown in Figure 2.4). No adjustments are made at $PGA_r = 0.5g$ due to a lack of published m_a and m_v values in Figure 2.4.

Shown with the open black symbols in Figure 3.4, the re-normalized NEHRP site factors are generally in better agreement with NGA site factors. The re-normalization essentially removes all misfit for Class D; misfits for other classes remain but are generally reduced. We wish to emphasize that the 'adjusted' NEHRP factors in Figure 3.3 are not proposed for adoption in NEHRP, but are presented to demonstrate the reduction in site factors discrepancies that is possible through the use of a consistent reference rock condition (in this case, V_{s30} = 760 m/sec).

The variation of amplification factors with V_{s30} is also investigated to isolate the V_{s30} dependence of the amplification factors from the dependence on PGA_r. Figure 3.4 plots F_a and F_v from NEHRP and NGA (based on median spectral accelerations across the period range for T = 0.1–0.5 sec for F_a; T = 0.4–2.0 sec for F_v) versus V_{s30} for PGA_r = 0.01g, 0.1g, 0.3g, and 0.5g. The original and adjusted NEHRP factors are plotted at the category-averaged V_{s30} values of 155 m/sec, 266 m/sec, 489 m/sec, and 913 m/sec, corresponding to categories E, D, C, and B, respectively. The PGA_r values used in Figure 3.4, when modified to S_s and S_1 per Equation (3.2), do not perfectly coincide with the tabulated NEHRP factors. Accordingly, we have interpolated as needed to produce the points in Figure 3.4. The results indicate consistent slopes of the F_a and F_v versus V_{s30} relations for PGA_r = 0.01g and 0.1g. This indicates that the scaling of site factors with V_{s30} in the original BG94 and Borcherdt (1994b) relations is robust (i.e., similar V_{s30}-scaling is present in the NGA site terms). The offset between the NEHRP and NGA factors is partly due to the 1050 m/sec reference condition in the NEHRP factors. For larger PGA_r values, significant differences in site factors occur for V_{s30} < ~500 m/sec, which encompasses conditions at most soil sites. Those differences arise principally from different levels of nonlinearity, which is addressed further in the following section.

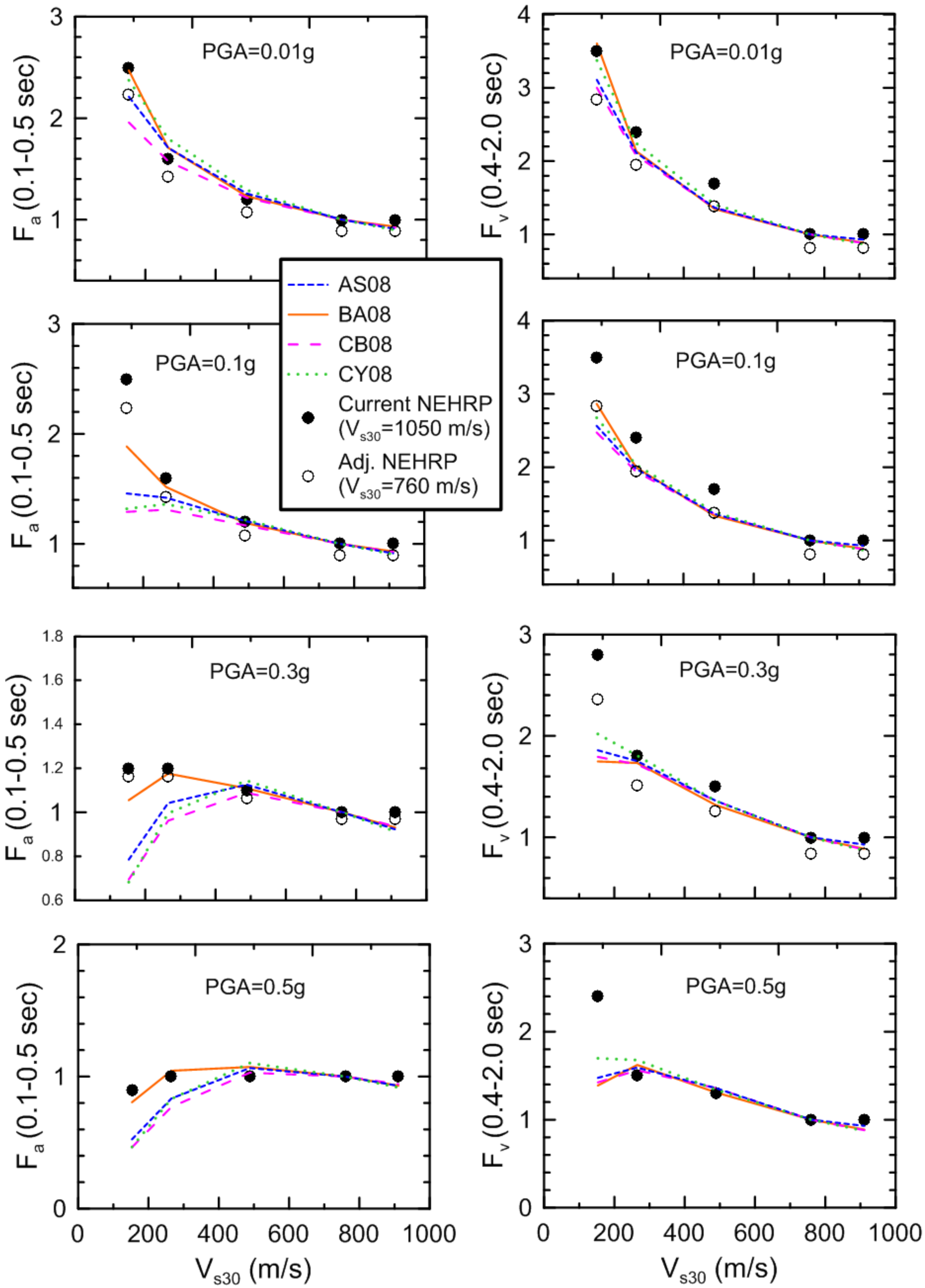


Figure 3.4 Variation of site amplification with V_{s30}.

3.2 EVALUATION OF NONLINEARITY IN SIMULATION-BASED SITE FACTORS

Figure 3.5 compares the results of analytical studies presented by Dobry et al. (2000) (Figure 2.4) with the site factors derived from more comprehensive equivalent-linear analyses by WEA08, in which the "Peninsular Range" modulus reduction and damping (MRD) curves (i.e., PEN model) were used. Results are shown for the short-period band amplification factor, F_a (0.2 sec) and mid-period band amplification factor, F_v (1.0 sec). The important conclusions to draw from this comparison relate to the relative slopes of the WEA08 and Dobry et al. (2000) relations (not necessarily the vertical position of the curves). For instance, whereas the slopes for V_{s30} = 270 m/sec are similar, the slopes for faster velocities are flatter in the more recent work.

Figure 3.6 illustrates the same type of comparison, but the results derived from the PEN model by WEA08 are replaced with similar results provided by Walling (*personal communication*, 2011) that are derived from more nonlinear MRD curves from EPRI (1993). Using this soil model, the F_a slopes are steeper than those from Dobry et al. (2000). For F_v, the slopes are comparable at V_{s30} = 270 m/sec; the Walling slopes are flatter for faster velocities.

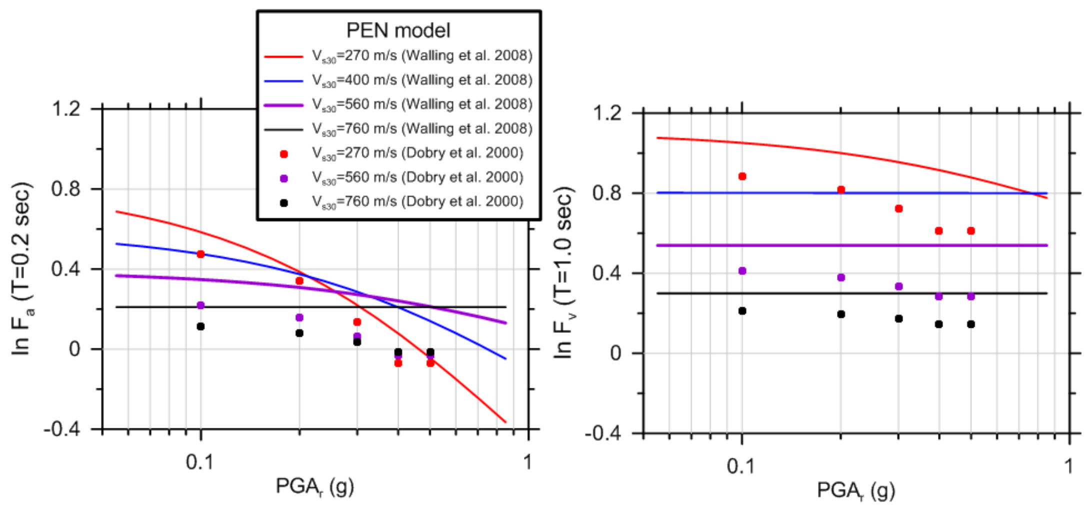


Figure 3.5 Comparison of short-period F_a (0.2 sec) and mid-period F_v (1.0 sec) amplification factors between Dobry et al. (2000) and WEA08 (PEN model). Results show flatter nonlinear relationship in the WEA08 model for V_{s30} > 270 m/sec.

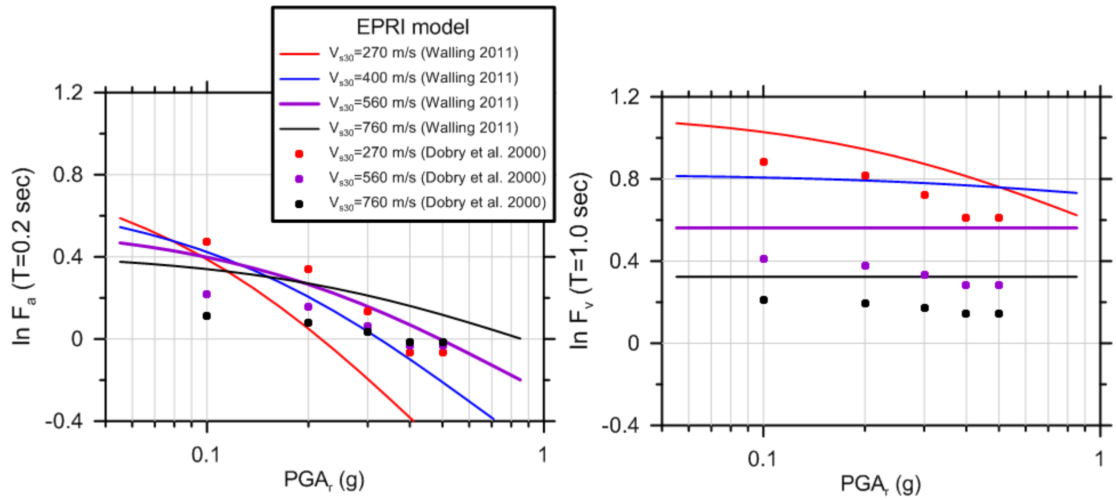


Figure 3.6 Comparison of short-period F_a (0.2 sec) and mid-period F_v (1.0 sec) amplification factors between Dobry et al. (2000) and Walling (personal communication, 2011) (EPRI model).

The principal factor responsible for the varying levels of nonlinearity is different MRD models used in the ground response simulations. The Dobry et al. (2000) site factors are based on simulations by Seed et al. (1994) and Dobry et al. (1994), both of which used MRD curves from Vucetic and Dobry (1991) (i.e., VD91) for cohesive soils. For sands, Seed et al. (1994) used MRD curves from Seed et al. (1984) (i.e., S84) while Dobry et al. (1994) used the VD91 MRD curve for $PI = 0$. Figure 3.7 compares the PEN curves from WEA08 with the aforementioned curves that provide the basis for the Dobry et al. (2000) site factors. The PEN curves are more linear than VD91 MRD at $PI = 0$and the Seed et al. (1984) MR curves, although the VD91 $PI = 50$ MRD curves are similar to PEN. Accordingly, the generally high nonlinearity in the MRD curves used in the studies behind the Dobry et al. (2000) amplification factors explains the relatively nonlinear site amplification terms.

The varying levels of nonlinearity in amplification factors derived from the PEN and EPRI MRD curves reflects epistemic uncertainty, in the sense that we lack knowledge regarding which set of MRD curves are most "correct" for ground response calculations. Given that the simulation results from WEA08 and Walling (*personal communication*, 2011) to some extent bracket the Dobry et al. (2000) curves (at least for F_a), we cannot conclude that the nonlinearity present in the NEHRP provisions is invalid on this basis.

However, nonlinearity from theoretical simulations can be checked against empirical data. Kwok and Stewart (2006) compared recorded ground motion recordings from various site conditions in California to predictions from rock GMPEs modified by theoretically-based site factors very similar to those of WEA08. Residuals were calculated in a manner similar to Equation 2.7, but with the rock GMPE median modified with the theoretical site factor and event term η. An example result is shown in Figure 3.8, which shows no trend in residuals versus PGA_r, indicating that the nonlinearity in the theoretical site factors captures the data trends. This comparison provides support for the more linear recent amplification factors presented by WEA08 and used in several of the NGA site terms.

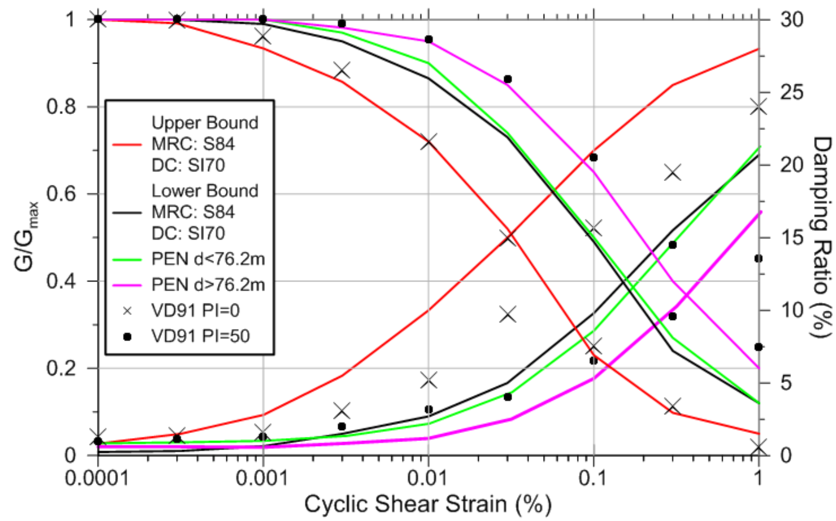


Figure 3.7 **Comparison of modulus reduction and damping curves from Dobry et al. (1994), Seed et al. (1984), and WEA08 (PEN model). S84 means Seed et al. (1984), SI70 represents Seed and Idriss (1970), and VS91 comes from Vucetic and Dobry (1991).**

3.3 CONCLUSIONS

The NGA and NEHRP site factors are consistent in certain respects (e.g., the scaling of linear site amplification with V_{s30}), but have discrepancies in linear site amplification (applicable for rock PGA $\leq 0.1g$) for site Classes B to E and in the levels of nonlinearity for Classes C and D. The amount of these discrepancies ranges from up to 50% for Class E to amounts ranging from about 0 to 20% for Classes B-D. Previous work has identified similar discrepancies in NEHRP and NGA site factors (Huang et al. 2010), but the discrepancies were not clearly associated with differences in linear site amplification levels and nonlinearities. Such associations are useful to understand causes of misfits and to formulate possible future updates to NEHRP factors.

A major cause of the weak motion amplification misfit is that the NEHRP factors are normalized relative to a reference site condition of V_{ref} = 1050 m/sec (i.e., the equations behind the tabulated factors reach unity at this velocity), whereas their current application is relative to V_{s30} = 760 m/sec. When re-normalized to V_{s30} = 760 m/sec, the NEHRP factors are much closer to NGA factors (especially for Class D), although misfits remain for Classes B, C, and E.

We find that the nonlinearity in F_a and F_v from recent simulation-based work (WEA08) is smaller than the nonlinearity in the NEHRP factors (Dobry et al. 2000). Those reduced levels of nonlinearity are consistent with trends from empirical ground motion data.

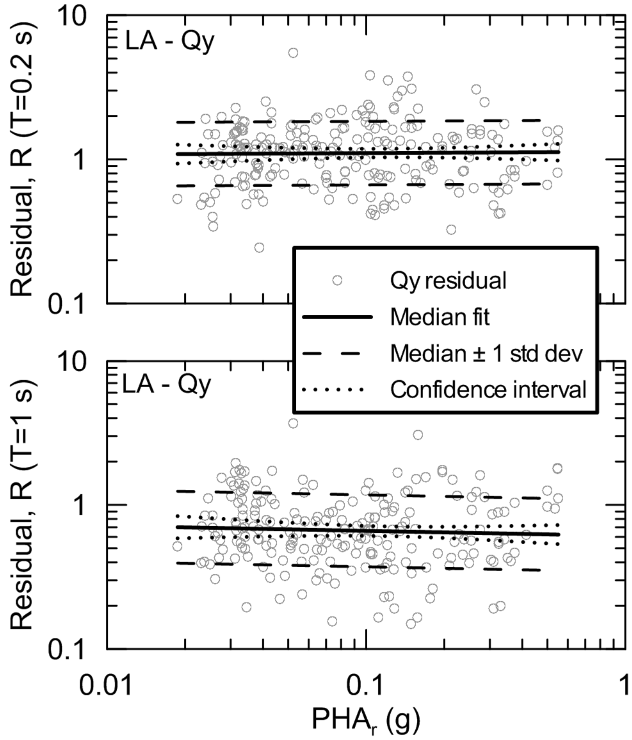


Figure 3.8 Trend of residuals with *PHA$_r$* [from Kwok and Stewart (2006)].

4 Nonlinear Site Amplification from Data and Simulations

In this chapter we first review the nonlinear site amplification model developed in this research. The data analysis behind the model is presented in BEA13 and SS14. We present supporting work that guided model development with respect to levels of nonlinearity implied by simulations and regional variations in site amplification. We conclude by comparing the site amplification model developed in this work with those of other NGA-West 2 GMPEs.

4.1 NONLINEAR SITE AMPLIFICATION MODEL

4.1.1 Model Equations

The nonlinear site amplification model in the base-case GMPE of BEA13 and BEA14 is comprised of two additive terms representing V_{S30}-scaling and nonlinearity as follows:

$$F_{S,B} = \ln\left(F_{lin}\right) + \ln\left(F_{nl}\right) \tag{4.1}$$

where $F_{S,B}$ represents 'base case' (i.e., ignoring basin effects) site amplification in natural logarithmic units; F_{lin} represents the linear component of site amplification, which is dependent on V_{S30}; and F_{nl} represents the nonlinear component of site amplification, which depends on V_{S30} and the amplitude of shaking on reference rock (taken as V_{S30} = 760 m/sec).

The linear component of the model (F_{lin}) describes the scaling of ground motion with V_{S30} for linear soil response conditions (i.e., small strains) as follows:

$$\ln\left(F_{lin}\right) = \begin{cases} c\ln\left(\dfrac{V_{S30}}{V_{ref}}\right) & V_{S30} \le V_c \\ c\ln\left(\dfrac{V_c}{V_{ref}}\right) & V_{S30} > V_c \end{cases} \tag{4.2}$$

where c describes the V_{S30}-scaling in the model, V_c is the limiting velocity beyond which ground motions no longer scale with V_{S30}, and V_{ref} is the site condition for which the amplification is unity (taken as 760 m/sec).

The nonlinear term in the site amplification model (F_{nl}) modifies the linear site amplification so as to decrease amplification for strong shaking levels. The F_{nl} term is constructed so as to produce no change relative to the linear term for low PGA_r levels. The functional form for the F_{nl} term is as follows:

$$\ln\left(F_{nl}\right) = f_1 + f_2 \ln\left(\frac{PGA_r + f_3}{f_3}\right) \tag{4.3}$$

where f_1, f_2, and f_3 are coefficients in the model and PGA_r is the median peak horizontal acceleration for reference rock (taken as V_{S30}=760 m/sec). We take $f_1 = 0.0$ to force $\ln(F_{nl})$ to zero for $PGA_r \ll f_3$. Parameter f_3 is set as 0.1g based on analyses presented in Section 4.3 of this report, whereas f_2 is a function of period and V_{S30} as follows:

$$f_2 = f_4\left[\exp\left\{f_5\left(\min\left(V_{S30}, 760\right) - 360\right)\right\} - \exp\left\{f_5\left(760 - 360\right)\right\}\right] \tag{4.4}$$

where f_4 and f_5 are period-dependent coefficients and . This functional form for f_2 is the same as that used by Chiou and Youngs (2008).

4.1.2 Model Development

As described in SS14, Stage 1 of the model development established the nonlinear component (terms f_2, f_3, f_4, and f_5). The evaluation of these terms considered both simulation results and empirical data analysis. The extraction of f_2 and f_3 terms from the KEA14 simulation-based nonlinear site amplification model is described in Section 4.2 of this report. The empirical data analysis began with the computation of rock residuals for each recording in the selected data set:

$$R_{ij} = \ln Y_{ij} - \left[\left(\mu_r\right)_{ij} + \eta_i\right] + \varepsilon_{i,j} \tag{4.5}$$

where R_{ij} is the rock residual, Y_{ij} is the j^{th} observed (recorded) value of the ground-motion IM, μ_r is the mean (in natural log units) of the BEA14 GMPE for rock conditions (including regional corrections for apparent anelastic attenuation, as applicable), η_i is the event term for earthquake i, and $\varepsilon_{i,j}$ is the within-event residual. The rock site condition used in the computations was V_{S30}=760 m/sec. Nonlinearity was evaluated by regressing R_{ij} against PGA_r (median peak acceleration on rock) within bins of V_{S30} (< 200, 200–310, 310–520, 520–760, > 760 m/sec) using Equation (4.3). This analysis is expanded in this report (Section 4.3.1) to examine regional variations of nonlinearity.

Stage 2 of model building was to evaluate the linear term, F_{lin}. This analysis operates on residuals R_{ij} [Equation (4.5)] that are adjusted by removing nonlinear effects as predicted by the F_{nl} model [Equation (4.1)]:

$$R_k^{lin} = R_{i,j} - \ln\left(F_{nl}\right)_{i,j} \tag{4.6}$$

The modified residual, R_k^{lin}, applies for linear (small strain) conditions. Subscript k in R_k^{lin} is an index spanning across all available data points; we drop the event and within-event subscripts (i and j, respectively) because of the removal of event terms in the computation of R_{ij}, which allows all data points to be weighted equally. The c coefficient in Equation (4.2) is evaluated as the slope in a linear regression between the natural log of R_k^{lin} against the natural log of V_{S30} for $V_{S30} < V_c$. In Section 4.3.2 we investigate regional variations of the c parameter and its dependence on data selection criteria.

4.2 CONSTRAINT OF PARAMETERS USING SIMULATION-BASED MODEL

As described in Section 2.2, nonlinear site amplification models can be derived on the basis of equivalent-linear ground response simulations, which were undertaken by WEA08 for the original NGA project. The nonlinearity in these relations is driven by the shear modulus reduction and damping versus shear strain relations. The WEA08 study used judgment-driven modulus reduction and damping curves known as the peninsular range curves (PEN) and curves presented by EPRI (1993)

As part of the NGA-West 2 project, KEA14 re-analyzed a larger set of ground motion simulations that includes additional site profiles and input motions relative to those utilized by WEA08, but the same PEN and EPRI nonlinear curves. Similar to WEA08, the results are presented as period-dependent nonlinear amplification models for a discrete number of mean V_{S30} values (five for WEA08; six for KEA14). The resulting KEA14 model uses the functional form for site amplification from WEA08, which has a similar structure to Equation (4.3) but which is considerably more complex such that the coefficients' physical meaning is not the same as the f_1, f_2, and f_3 parameters in Equation (4.3). Accordingly, as shown in Figure 4.1, we use the KEA14 equations to compute site amplifications and then fit the computed points using Equation (4.3). Because the KEA14 function has a closed-form expression for the equivalent of the f_3 parameter that is V_{S30}-dependent, we apply that function in advance so that the fitting process matches f_1 and f_2 only for a constrained value of f_3. Table 4.1 shows the resulting f_2 values for the discrete V_{S30} values and various periods.

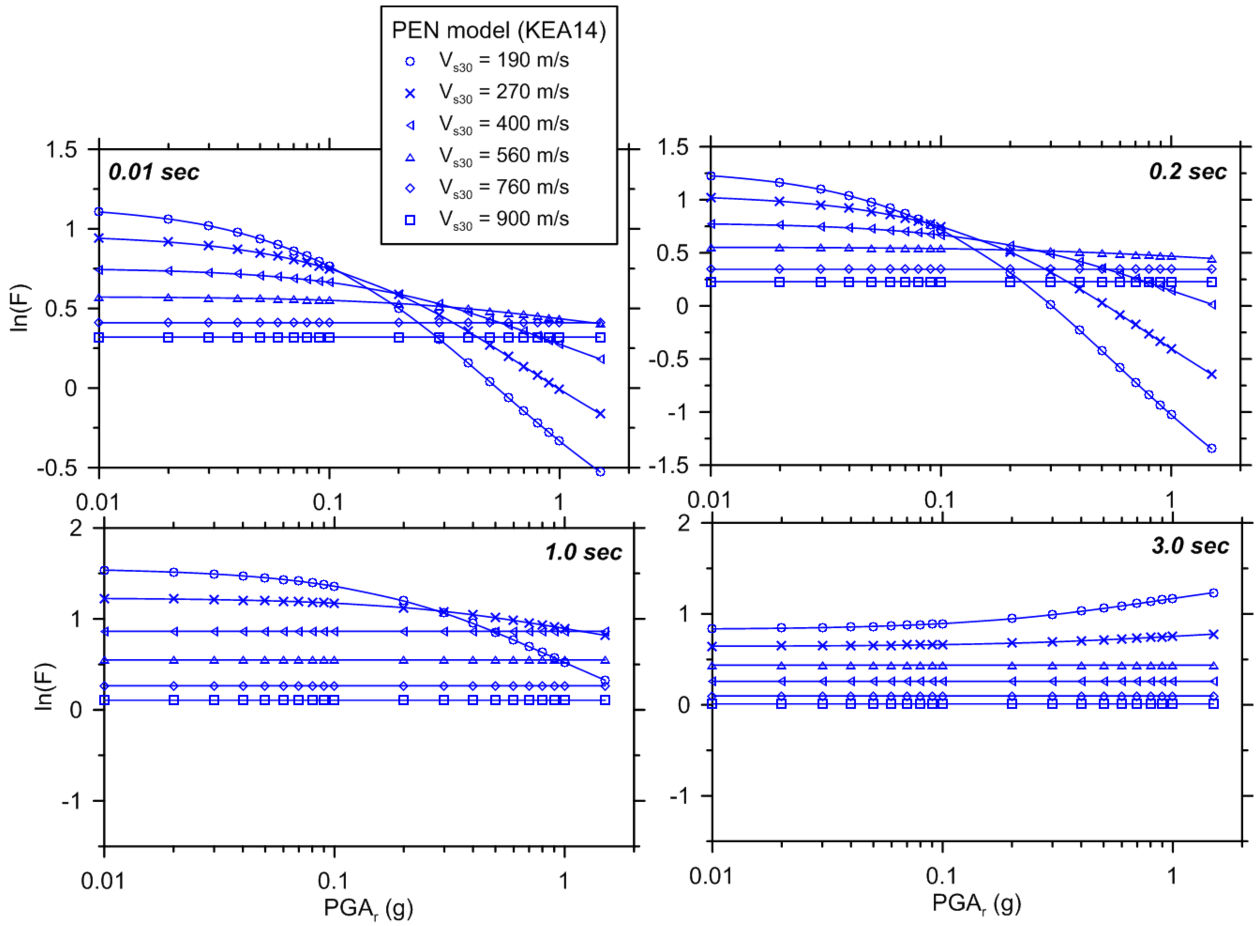


Figure 4.1(a) Site amplification as function of V_{S30}, period, and PGA_r from simulation-based model of KEA14; PEN modulus reduction and damping curves.

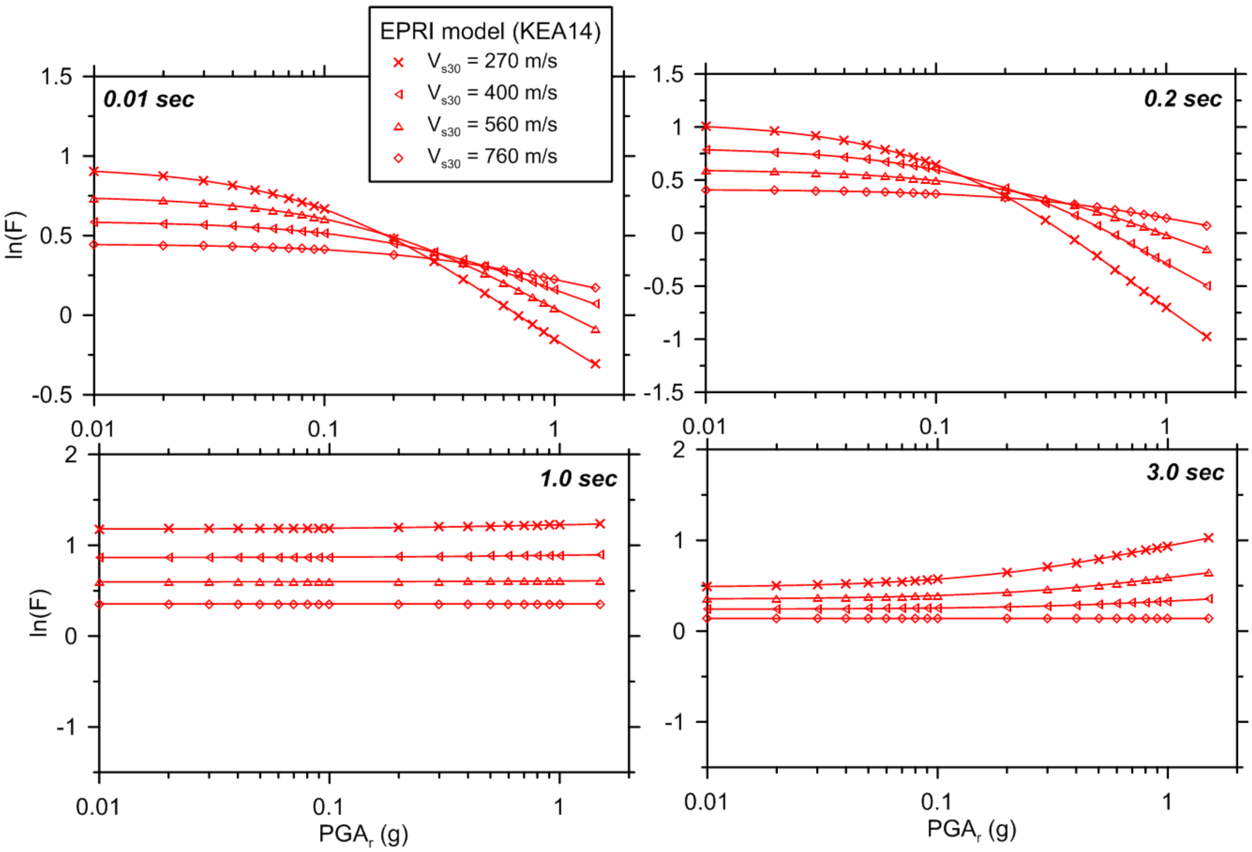


Figure 4.1(b) **Site amplification as function of V_{S30}, period, and PGA_r from simulation-based model of KEA14; EPRI modulus reduction and damping curves.**

Table 4.1 **Values of f_2 for KEA14 model based on fit using Equation (4.3).**

Period (sec)	*PEN as PGA input (V_{S30} in m/s)*					
	190	***270***	***400***	***560***	***760***	***900***
0.01	-0.48±0.008	-0.34±0.011	-0.17±0.010	-0.05±0.021	0.00±0.000	0.00±0.000
0.2	-0.77±0.012	-0.52±0.013	-0.23±0.015	-0.03±0.001	0.00±0.000	0.00±0.000
1	-0.38±0.015	-0.13±0.017	0.00±0.000	0.00±0.000	0.00±0.000	0.00±0.000
3	0.14±0.000	0.05±0.03	0.00±0.000	0.00±0.000	0.00±0.000	0.00±0.000
	EPRI as PGA input (V_{S30} in m/s)					
		270	***400***	***560***	***760***	
0.01		-0.36±0.017	-0.27±0.014	-0.17±0.002	-0.09±0.046	
0.2		-0.60±0.018	-0.39±0.021	-0.23±0.014	-0.10±0.058	
1		0.02±0.042	0.00±0.000	0.00±0.000	0.00±0.000	
3		0.16±0.058	0.09±0.083	0.03±0.062	0.00±0.002	

Values of nonlinear parameter f_2 from simulations are shown in Figure 4.2 along with the non-regional empirical results of SS14 and the proposed model. The simulation-based slopes are comparable to the data-based slopes, except for PSA at $T = 0.5–3.0$ sec where the data exhibits more nonlinearity than is evident from the simulations.

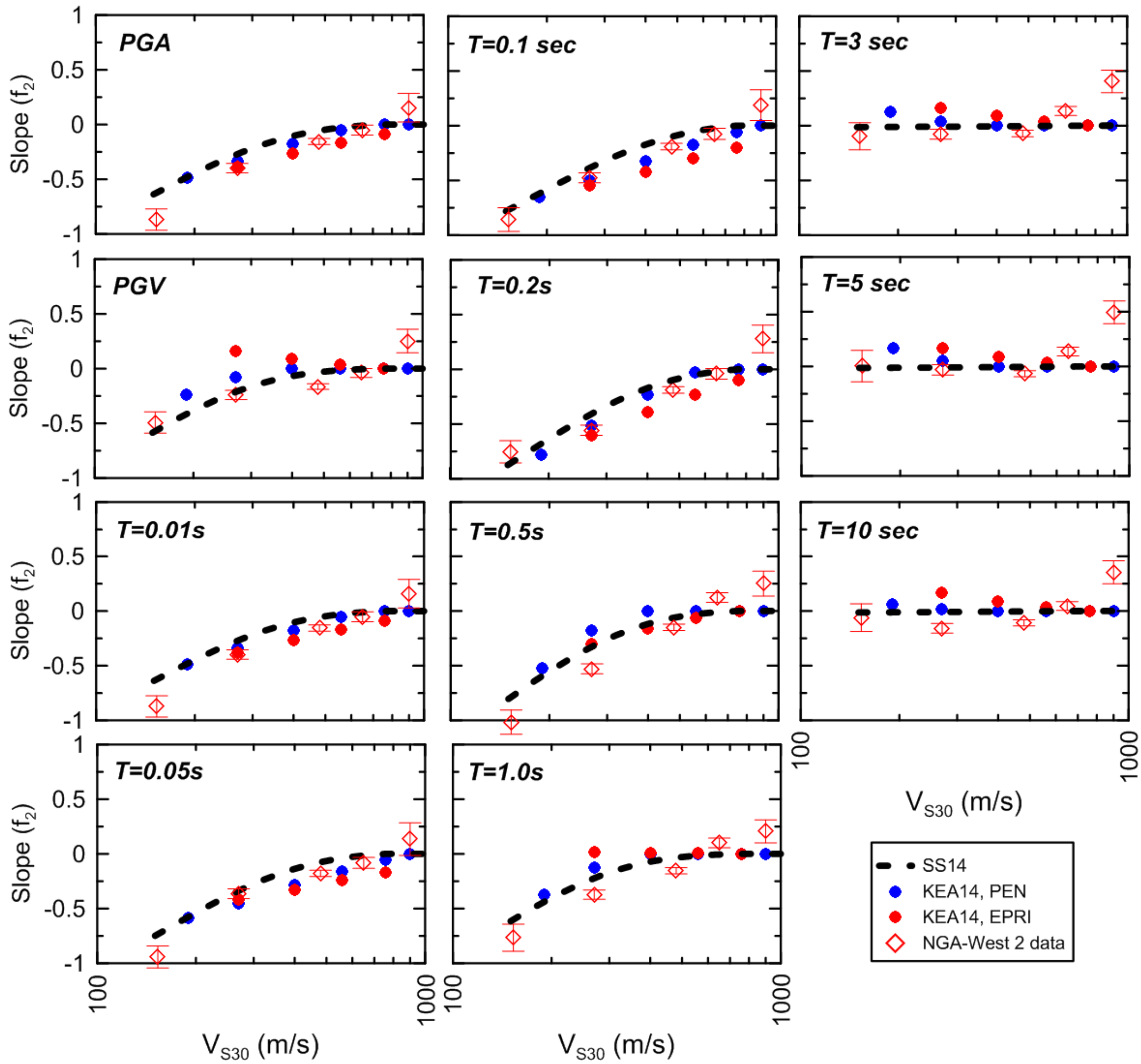


Figure 4.2 Variation of slope f_2 with V_{S30} from NGA-West 2 data, KEA14 simulation results (using modulus reduction curves labeled PEN for Peninsular range and EPRI), and SS14 model.

4.3 REGIONAL VARIATIONS OF SITE AMPLIFICATION

4.3.1 Nonlinear Component of Model

SS14 examined trends of R_{ij} against PGA_r within V_{S30} bins using a large portion of the NGA-West 2 data set drawn from many regions, which forms the basis for the empirical f_2 values shown in Figure 4.2 (data selection criteria are described in BEA14). A least-squares regression using Equation (4.3) was performed using data in each period and V_{S30} bin to estimate f_1 and f_2. Additive parameter f_3, which produces saturation of site amplification for input motion amplitudes with $PGA_r << f_3$, was fixed at 0.1g in these regressions because the three coefficients cannot be reliably computed simultaneously.

The fixed value of f_3=0.1g was selected by repeating regressions using Equation (4.3) with variable fixed values of f_3 and finding the value that minimizes dispersion for data in the V_{S30} bins of < 200 and 200–310 m/sec. Figure 4.3 shows the resulting values of f_3, which do not exhibit trends with period. Note that values of f_3 implied from the simulation-based model of KEA14 are also shown in Figure 4.3.

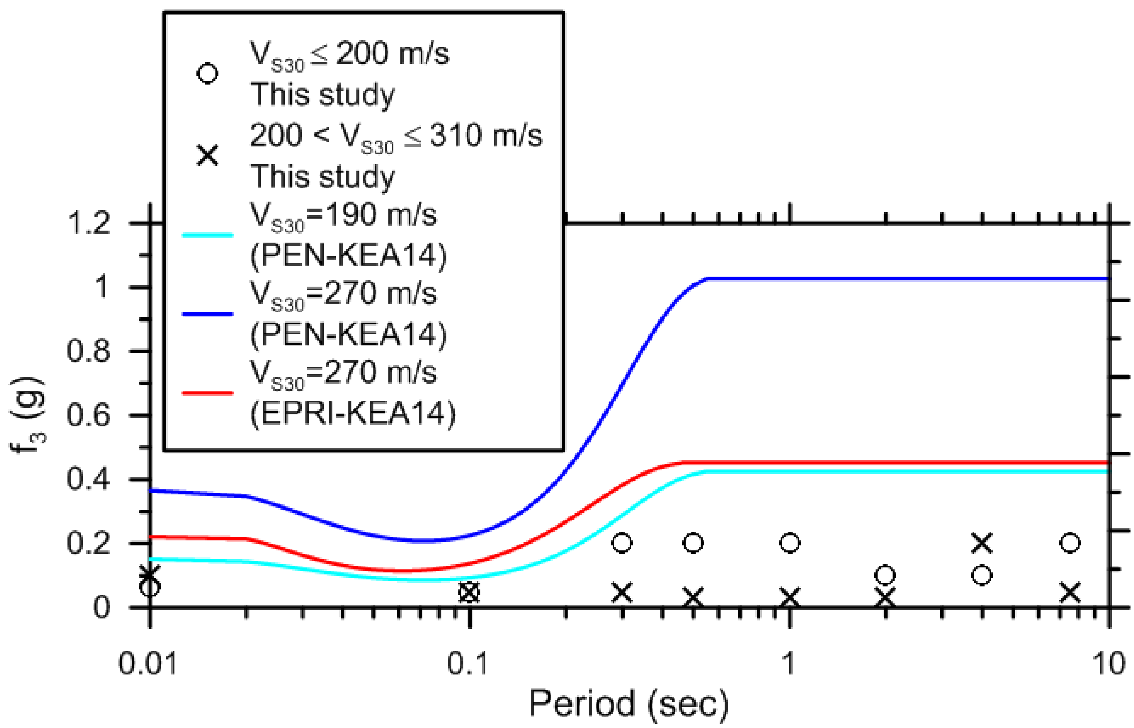


Figure 4.3 Variation of additive term f_3 in site amplification function with period from empirical data analysis (to minimize residuals) and from model of KEA14.

Because the empirical data analysis performed to support the development of the nonlinear component of the site amplification model utilized a combined global data set, it is of interest to evaluate possible regional dependencies in the f_2 parameter. This was not formally investigated by BEA13 or SS14 and is presented here.

In Figures 4.4 to 4.6, we plot R_{ij} against PGA_r by region. The data used for these plots are subsets of the dataset considered by BEA13 and SS14 within California, Japan, and Taiwan. The plots show fits to the data in the respective V_{S30} bins using Equation (4.3) (with f_3 set to 0.1g) along with the fit for the overall (global) data from SS14. Nonlinearity is manifest in the plots by non-zero values of slope parameter f_2 that are statistically significant, which is judged to be the case when the value of f_2 is larger than its standard error (values of f_2 by region and their standard errors are shown in Table 4.2). There are two major trends in the plots, both of which have been observed previously [e.g., Choi and Stewart (2005)]: (1) nonlinearity decreases with increasing V_{S30}, generally becoming statistically insignificant for relatively stiff site categories (V_{s30}>310 m/sec); and (2) nonlinearity decreases as period increases, being statistically significant only for $T \leq \sim 1$ sec except for the softest soil sites (V_{S30} <200 m/sec).

In Figure 4.7, we plot f_2 values against V_{S30} from the regional regressions, with the SS14 model also shown for comparison. The aforementioned trends of decreasing nonlinearity with increasing V_{S30} and increasing period are evident in Figure 4.7. While there are substantial between-region variations in f_2, we do not observe specific regional trends in nonlinearity that are considered sufficiently important to carry forward into an amplification model. Therefore, regionalization of f_2 was not incorporated into the site amplification model of SS14.

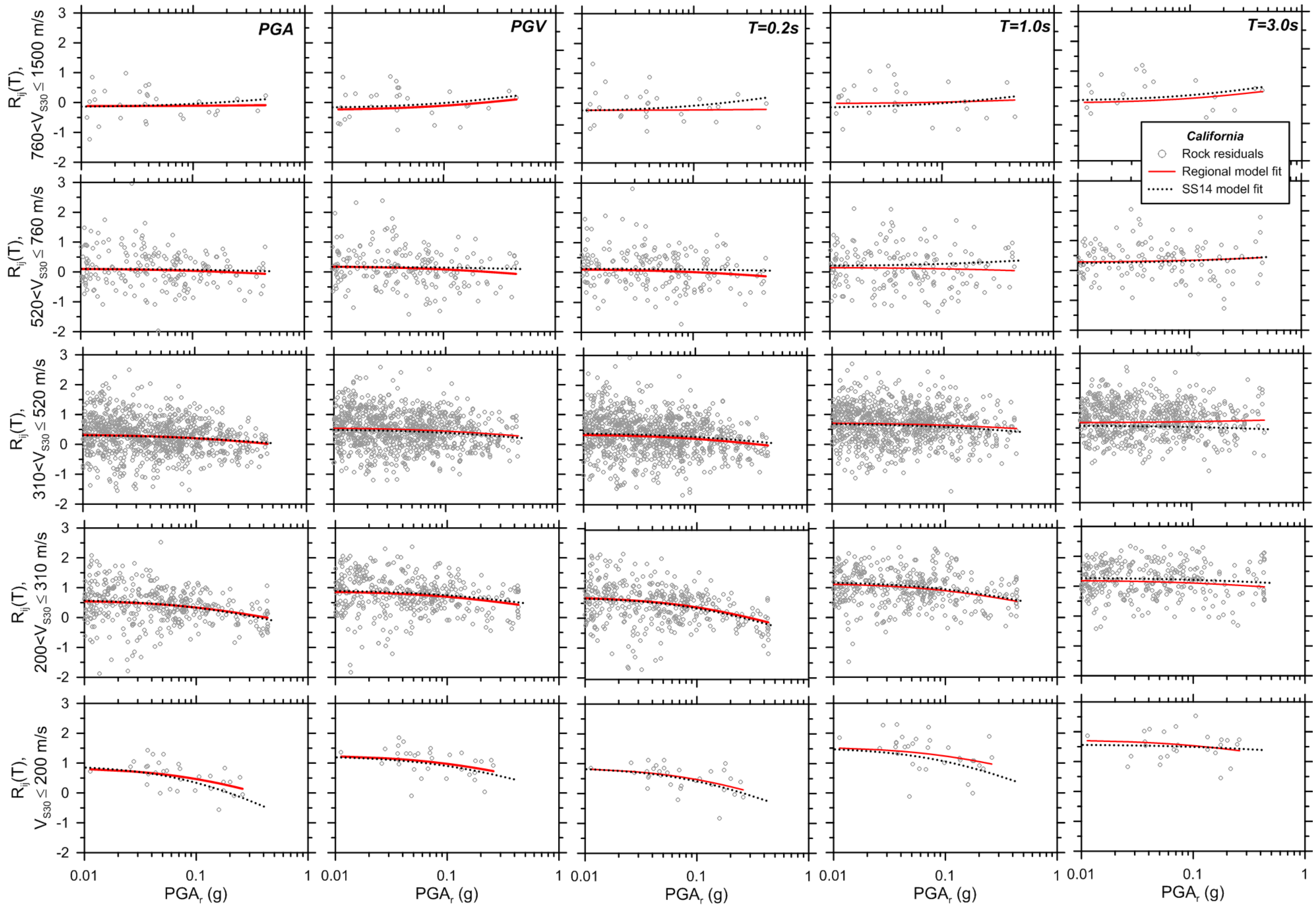


Figure 4.4 Variation of site amplification factors with PGA_r within site categories for California portion of data set. Discrete symbols are within-event residuals [R_{ij}, Equation (4.5)], solid lines are nonlinear regional fit from Equation (4.3), dotted lines are global fit from SS14.

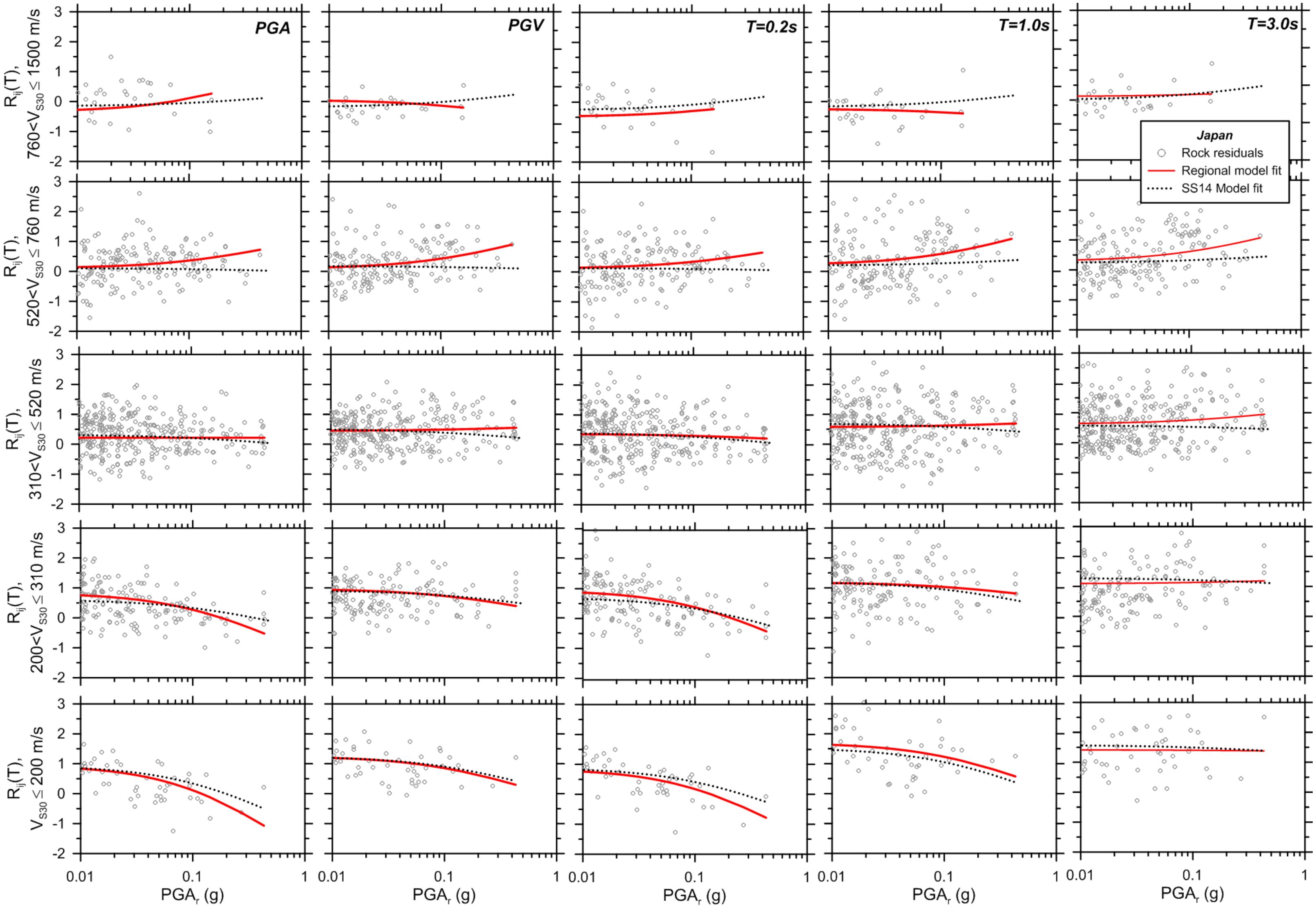


Figure 4.5 **Variation of site amplification factors with *PGA_r* within site categories for Japan. See Figure 4.4 caption for further explanation of symbols.**

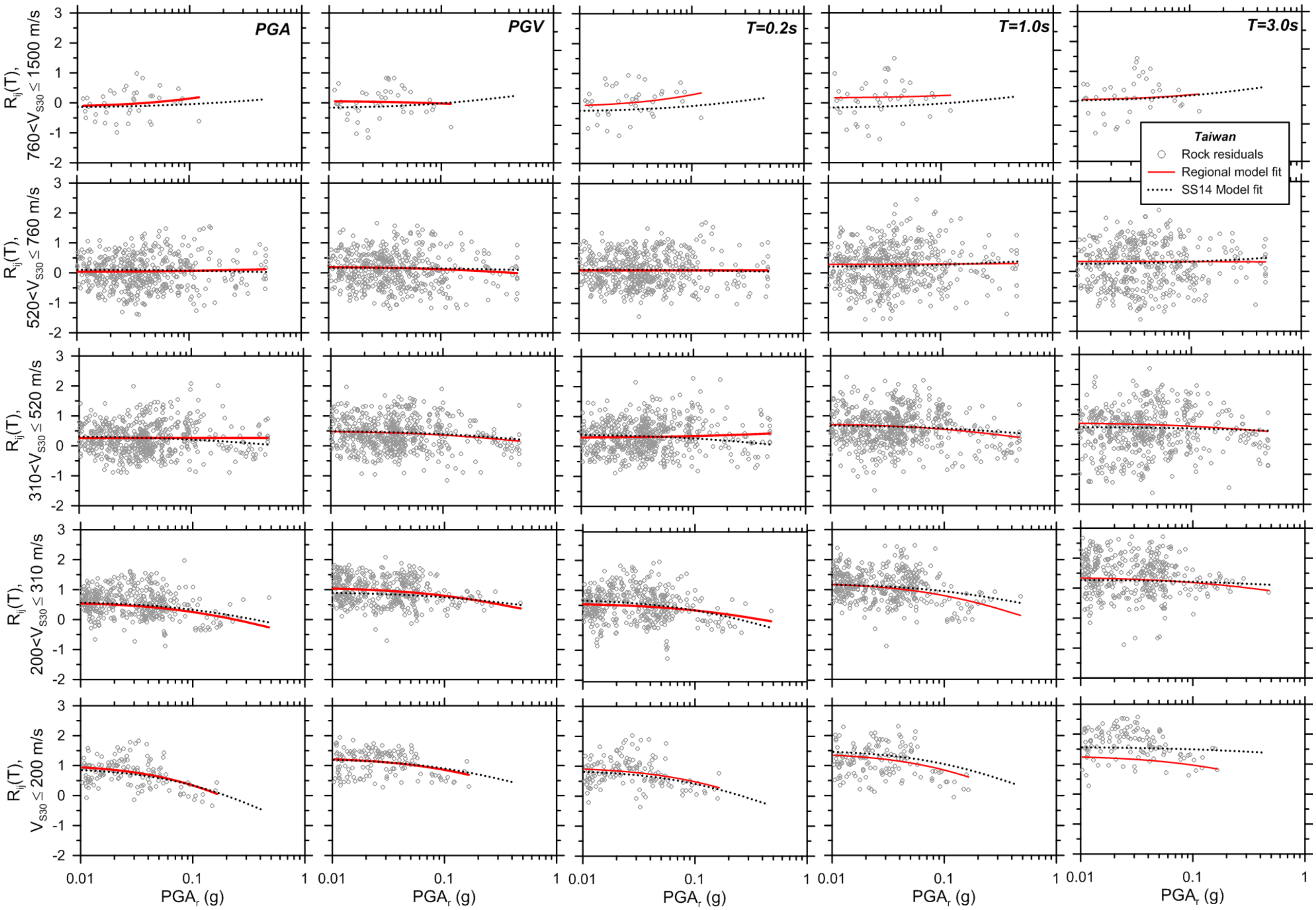


Figure 4.6 **Variation of site amplification factors with *PGA_r* within site categories for Taiwan. See Figure 4.4 caption for further explanation of symbols.**

Table 4.2 **Nonlinear parameter f_2 as established from regressions of regional data using Equation (4.3).**

Site Class	*IM/Period (sec)*	*California*		*Japan*		*Taiwan*	
		f_2	***Std. Dev.***	***f_2***	***Std. Dev.***	***f_2***	***Std. Dev.***
$V_{S30} \le 200$ m/s	PGA	-0.57 ± 0.17	0.53	-1.21 ± 0.17	0.60	-1.01 ± 0.17	0.42
	PGV	-0.42 ± 0.16	0.47	-0.57 ± 0.18	0.57	-0.59 ± 0.17	0.39
	0.2	-0.59 ± 0.16	0.50	-0.98 ± 0.18	0.59	-0.71 ± 0.20	0.46
	1	-0.47 ± 0.18	0.54	-0.67 ± 0.22	0.68	-0.83 ± 0.20	0.48
	3	-0.23 ± 0.17	0.47	-0.02 ± 0.24	0.71	-0.45 ± 0.23	0.49
$200 < V_{S30} \le$ 310 m/s	PGA	-0.35 ± 0.06	0.62	-0.81 ± 0.09	0.57	-0.48 ± 0.10	0.43
	PGV	-0.27 ± 0.05	0.59	-0.34 ± 0.09	0.57	-0.40 ± 0.10	0.42
	0.2	-0.51 ± 0.06	0.67	-0.82 ± 0.10	0.66	-0.34 ± 0.12	0.50
	1	-0.36 ± 0.05	0.54	-0.22 ± 0.09	0.73	-0.63 ± 0.14	0.48
	3	-0.13 ± 0.05	0.50	0.05 ± 0.13	0.77	-0.25 ± 0.14	0.62
$310 < V_{S30} \le$ 520 m/s	PGA	-0.02 ± 0.04	0.62	-0.00 ± 0.07	0.59	0.00 ± 0.06	0.48
	PGV	-0.16 ± 0.04	0.57	0.06 ± 0.07	0.56	-0.19 ± 0.06	0.49
	0.2	-0.22 ± 0.04	0.65	-0.09 ± 0.09	0.71	0.08 ± 0.06	0.51
	1	-0.11 ± 0.04	0.60	0.07 ± 0.09	0.75	-0.26 ± 0.07	0.57
	3	0.05 ± 0.04	0.58	0.19 ± 0.09	0.72	-0.16 ± 0.09	0.70
$520 < V_{S30} \le$ 760 m/s	PGA	-0.10 ± 0.09	0.72	0.37 ± 0.11	0.63	0.05 ± 0.07	0.53
	PGV	-0.15 ± 0.08	0.64	0.48 ± 0.10	0.57	-0.12 ± 0.08	0.55
	0.2	-0.14 ± 0.09	0.77	0.32 ± 0.13	0.70	0.00 ± 0.07	0.53
	1	-0.06 ± 0.07	0.59	0.06 ± 0.14	0.77	0.02 ± 0.09	0.68
	3	0.09 ± 0.07	0.55	-0.02 ± 0.11	0.62	-0.01 ± 0.10	0.72
$760 \le V_{S30} <$ 1500 m/s	PGA	0.02 ± 0.20	0.69	0.64 ± 0.381	0.69	0.41 ± 0.39	0.43
	PGV	0.21 ± 0.16	0.56	-0.27 ± 0.24	0.43	-0.12 ± 0.43	0.47
	0.2	0.02 ± 0.19	0.66	0.27 ± 0.38	0.68	0.60 ± 0.44	0.48
	1	0.07 ± 0.15	0.52	-0.16 ± 0.34	0.61	0.12 ± 0.55	0.60
	3	0.23 ± 0.16	0.51	0.09 ± 0.29	0.51	0.27 ± 0.51	0.56

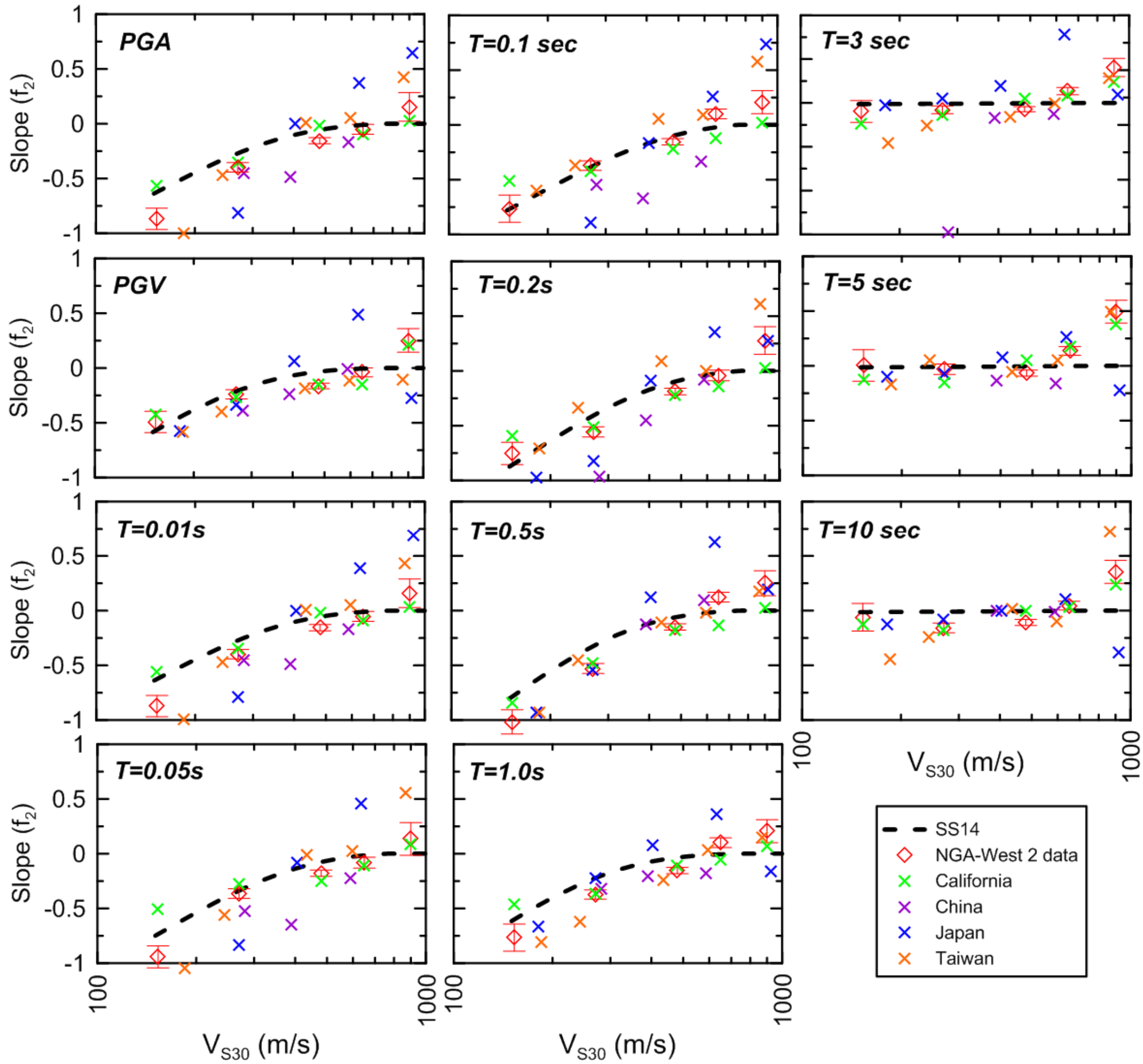


Figure 4.7 **Dependence of slope (f_2) with V_{S30} for various regions along with SS14 model.**

4.3.2 Linear Component of Model

Linear site amplification is evaluated by subtracting the nonlinear term from the total residual to obtain R_k^{lin}, as shown in Equation (4.6). Whereas the analysis of nonlinearity places a premium on close-distance sites likely to have been subject to nonlinear soil behavior, the analysis of linear site amplification tends to be weighted towards the large number of sites at greater distance where amplitudes of shaking are low and site response is more likely linear. This places the empirical analysis of linear site response somewhat in tension with regional variations of anelastic attenuation, which can introduce systematic bias in GMPEs at large distance for specific events. If not accounted for, this bias could be mistakenly mapped into site amplification using the data analysis procedures described in Section 4.1.

This problem has previously been addressed by truncating the data set used for analysis of site response at site-source distances sufficiently small (approximately 80 km) that anelastic attenuation effects are unlikely to be significant [e.g., Campbell and Bozorgnia (2013); Stewart et al. (2013)]. As mentioned in Section 4.1, the approach adopted by BEA13 and BEA14 is different, opting instead to correct for regional anelastic attenuation effects, verify the efficacy of such corrections, and then extend the distance range much further (up to approximately 400 km).

Figure 4.8(a-b) show the dependence of site amplification (represented by R_k^{lin}) with V_{S30} for various periods for the five regions contributing most of the NGA-West 2 data: California, Japan, Taiwan, Mediterranean (Greece, Italy, Turkey), and China. Two data selection criteria were applied: (1) the criteria used in BEA13 and BEA14 (e.g., Section 2.1 of BEA13), which include data up to $R_{jb} \approx 400$ km; and (2) data truncation at $R_{jb} \leq 80$ km (these residuals were computed without regional anelastic attenuation corrections). Residuals R_k^{lin} were sorted by region and regressed using Equation (4.2) to obtain slope parameter c. These regressions are performed with V_{ref} left as a free parameter so as to obtain the most accurate slope. This causes the regression to be non-zero at 760 m/sec, which is the desired reference velocity. That offset from zero at 760 m/sec is subtracted on a regional basis for the plots shown in Figure 4.8 (and similar diagrams in SS14). Note that parameter c represents the V_{S30}-scaling in that it quantifies the slope of the relationship between site amplification and V_{S30} in log-log space.

The slopes in Figure 4.8(a-b) are negative, which is expected, as this indicates stronger ground motion for softer sites. Slopes also tend to increase with period over the range considered, which is also consistent with past experience [e.g., Boore et al. (1997) and the NGA-West 1 models]. Note that the results from California in Figure 4.8 indicate a break in the V_{S30} scaling for fast velocities and longer periods (as seen in the results for T = 1.0 sec). It is this break in slope that motivated the use of the corner velocity V_c in the linear portion of the site amplification function [Equation (4.2)].

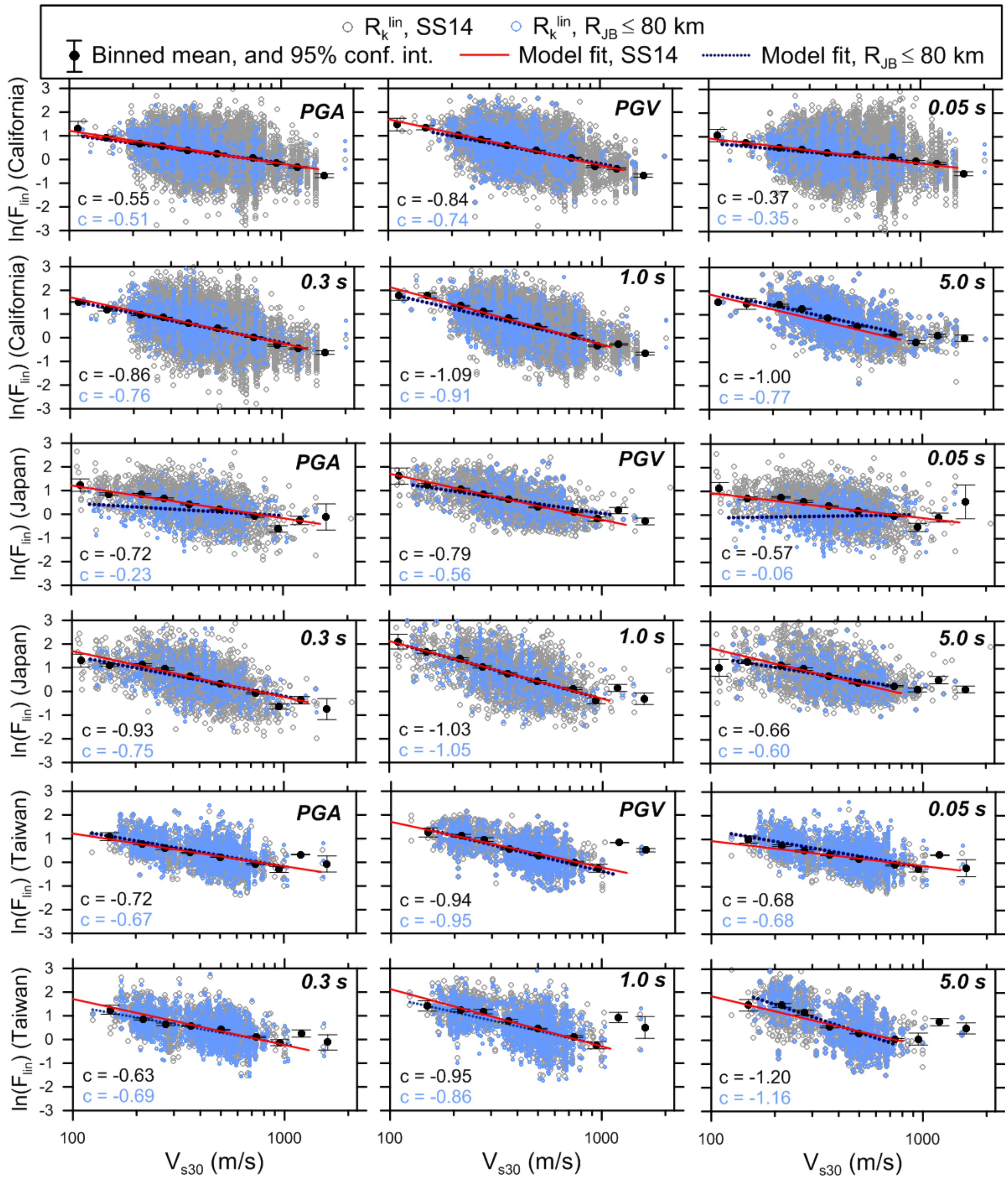


Figure 4.8(a) **Variation of linearized site amplification [Equation (4.6)] with V_{S30} and their binned means (and 95% confidence intervals) for subsets of data from California, Japan, and Taiwan. Trend lines for global data set shown for $V_{S30} < V_c$ and marked as SS14. Data points selected using more restrictive criteria (R_{JB} < 80 km) also shown. Slope values (c) listed for linear fit through grey (all points) and blue (more restrictive) data sets.**

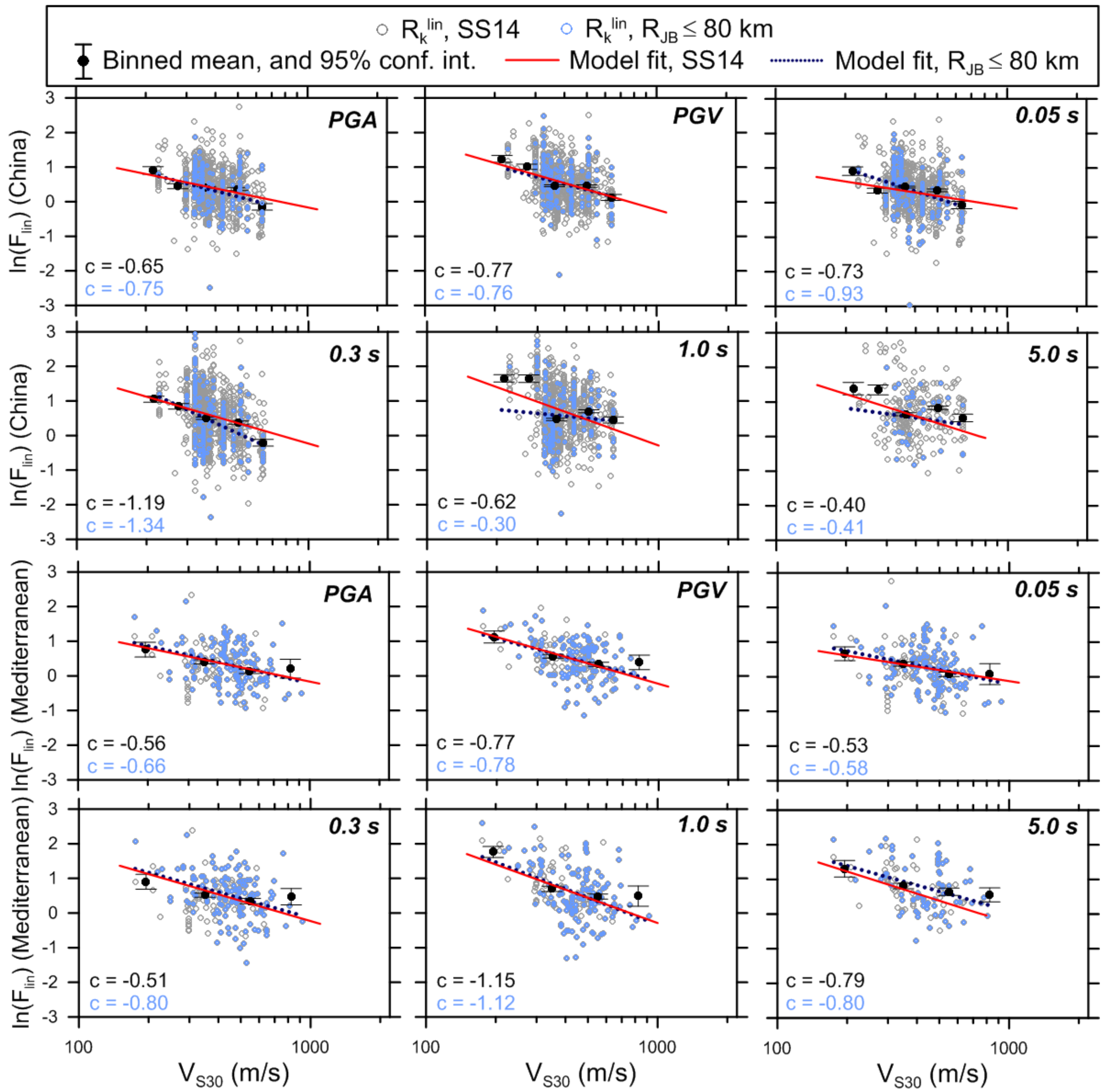


Figure 4.8(b) **Variation of linearized site amplification [Equation (4.6)] with V_{S30} for subsets of data from Medeteranean regions and China.**

Figure 4.9 shows the resulting c values plotted against period for the two data selection criteria. Figure 4.9a shows the values obtained using the SS14 criteria in which the data extend to large distance, whereas Figure 4.9b shows the values obtained with the 80-km cutoff distance. Using the SS14 data selection criteria (inclusive of large distances), we find modest variations of c between regions. As shown in Figures 4.8 and 4.9, the two data selection criteria produce similar slopes in most regions and periods. A notable exception is Japan, where the 80-km truncated data set slopes are significantly different, being much flatter at short periods. Similar sensitivites of the V_{S30} slope parameter to data selection criteria have been observed previously by Chiou and Youngs (2012) for the Japanese data. There are slope differences at some periods for the Mediterranean and China regions as well, although these are relatively poorly constrained due to relatively sparse data (and limited V_{S30} range). Until the cause of these differences in slopes are better understood, we consider it prudent to use slopes derived from the global data set. BEA14 and SS14 used that relatively complete data set and elected to not regionalize the *c* parameter due to the relatively modest between-region variations evident in Figure 4.9a.

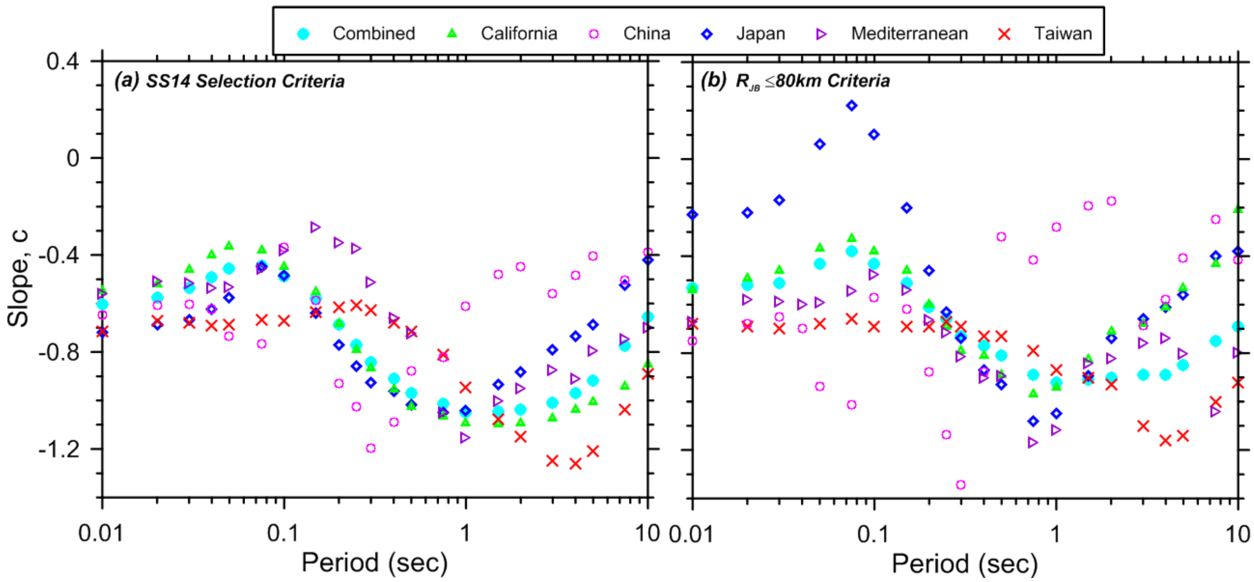


Figure 4.9 **Variation of slope (*c*) with spectral periods for combined data set and various regions using (a) SS14 data selection criteria and (b) restricting data sites with R_{JB} < 80 km.**

The data shown in Figure 4.8 include sites with V_{S30} values both from measurements and inferred from proxy relationships. As requested by members of the Task 8 wording group, we investigated whether the trends shown in Figure 4.8 are preserved when data are considered only from sites with measurement-based V_{S30} values. Figure 4.10 shows the V_{S30}-scaling using only measured V_{S30} for the combined data sets and those from three regions. There are some changes in the slope coefficients, particularly at shorter periods. The largest changes occur in the California and Japan results. The use of proxies aggregate at a series of individual V_{S30} values that would otherwise be a continuous spread of data points. Particularly for slow V_{S30}-values, this aggregation has the effect of underestimating the level of the nonlinear correction because that correction increases substantially in magnitude as V_{S30} decreases. Indeed, regressions of the type shown in Figures 4.8 and 4.10 without removal of nonlinear effects (not shown here) indicate almost no change as a result of screening the data to consider only measured sites. Despite this potential pitfall of using proxies, particularly for soft sites, in subsequent analyses in this report we utilize data from sites with V_{S30} from measurements and proxy estimates so as to not overly restrict the size of the data set.

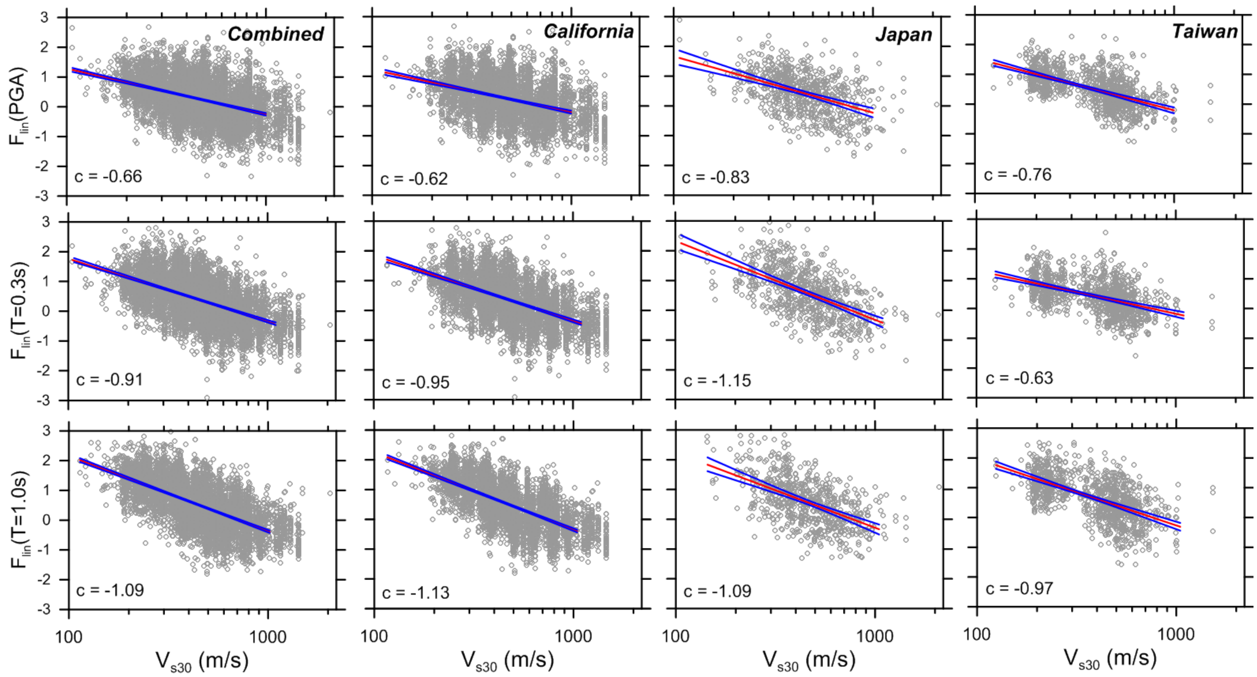


Figure 4.10 Variation of site amplification factors with V_{S30} (measured only) for combined data set and subsets from California, Japan, and Taiwan. Blue solid line: ± 95% CI, red solid line: Median fit for $V_{S30} < V_c$.

The Taiwan data set is somewhat unique in that it has a substantial volume of data from aftershocks, along with a smaller amount of mainshock data. This is of some concern because aftershocks are treated differently than mainshocks in the development of some GMPEs. We segregate events into two types: (1) 1999 Chi Chi mainshock (CL1) and (2) subsequent Chi Chi Class 2 (CL2) events (considered as aftershocks). The aftershocks are the largest in number (970 recordings) for this region. The results are shown in Figure 4.11. The Chi-Chi CL2 data (orange dots) dominate the data set and hence the trends shown previously for Taiwan in Figure 4.8. The aftershocks produce stronger V_{S30}-scaling than the mainshocks. It is possible that these differences result in part from nonlinearity. Recall that the nonlinear correction applied to the data represents an apparoximate global average as inferred from data analysis and simulations. Individual regions can exhibit different trends, which is indeed the case for Taiwan. As shown in Figure 4.6, the Taiwan data exhibit higher than average nonlinearity for soft sites and less than average nonlinearity for stiff sites. If the nonlinear correction were modified to consider those apparent regional effects, the mainshock slopes would steepen, making them closer to aftershock slopes. Despite these differences in behavior, we retain the use of data from aftershocks in our work because we see no reason for the physical processes causing site response to be biased for one event type versus another, provided the effects of nonlinearity are taken into account.

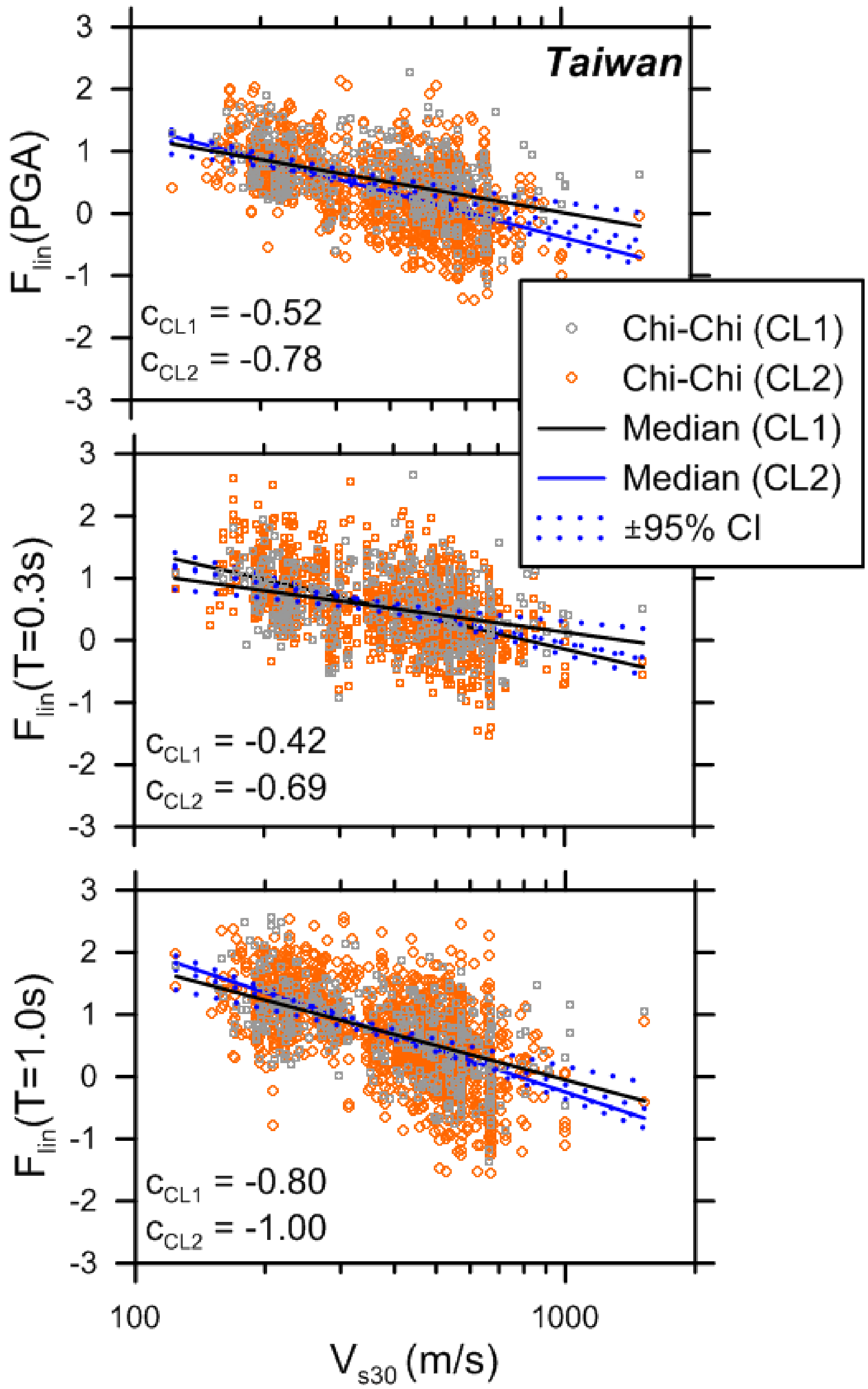


Figure 4.11 Variation of site amplification with V_{S30} for Chi Chi, Taiwan, Class 1 (CL1) events (mainshocks) and Class 2 (CL2) events (aftershocks).

4.4 COMPARISON TO SITE TERMS IN OTHER NGA-WEST 2 GMPES

In Section 2.2 we described the site terms in the NGA-West 1 GMPEs and showed how they compared to the NEHRP site factors. Each set of site factors has been updated for NGA-West 2 in papers by Abrahamson et al. (2014: ASK14), BEA14, Campbell and Bozorgnia (2014: CB14), and Chiou and Youngs (2014: CY14). A fifth NGA-West 2 GMPE by Idriss (2014) now includes a site term (which was not included in the 2008 version of this GMPE), but the data used in the analysis does not include most soil sites, so that study is not considered further here.

Other than BEA14, the general form of the site term equations has remained the same from NGA-West 1 to NGA-West 2. All site terms are based on empirical data analysis for V_{S30}-scaling terms, whereas nonlinear terms are evaluated from a hybrid of data analysis and simulation results from WEA08 and KEA14 in a manner very similar to that described in Section 2.2. Other than BEA14, the main change was that ASK14 now use PSA at the period of interest as the parameter driving nonlinearity (similar to CY08) in lieu of PGA_r.

Figure 4.12 shows the site terms for the four aforementioned NGA-West 2 GMPEs: ASK14, BEA14 (SS14), CB14, and CY14. The site terms were all normalized to a reference condition of V_{ref} = 760 m/sec using procedures described in Section 3.1 of this report. The GMPE site factors are computed at equally-spaced periods on a log scale and averaged (in arithmetic units) for the plot in Figure 4.12.

For soil site classes C and D, the ASK14 factors are typically highest and CB14 lowest, with BEA14 and CB14 values generally being intermediate. Overall, the differences between the site factors for site classes C and D is relatively modest.Variations among models are more pronounced for site class E, with the ASK14 factors having the strongest nonlinearity. The current NEHRP factors are also shown on the plot for reference purposes. The misfits between the NGA-West 2 factors and NEHRP factors follow similar trends to those identified earlier for NGA-West 1 factors in Section 3.1.

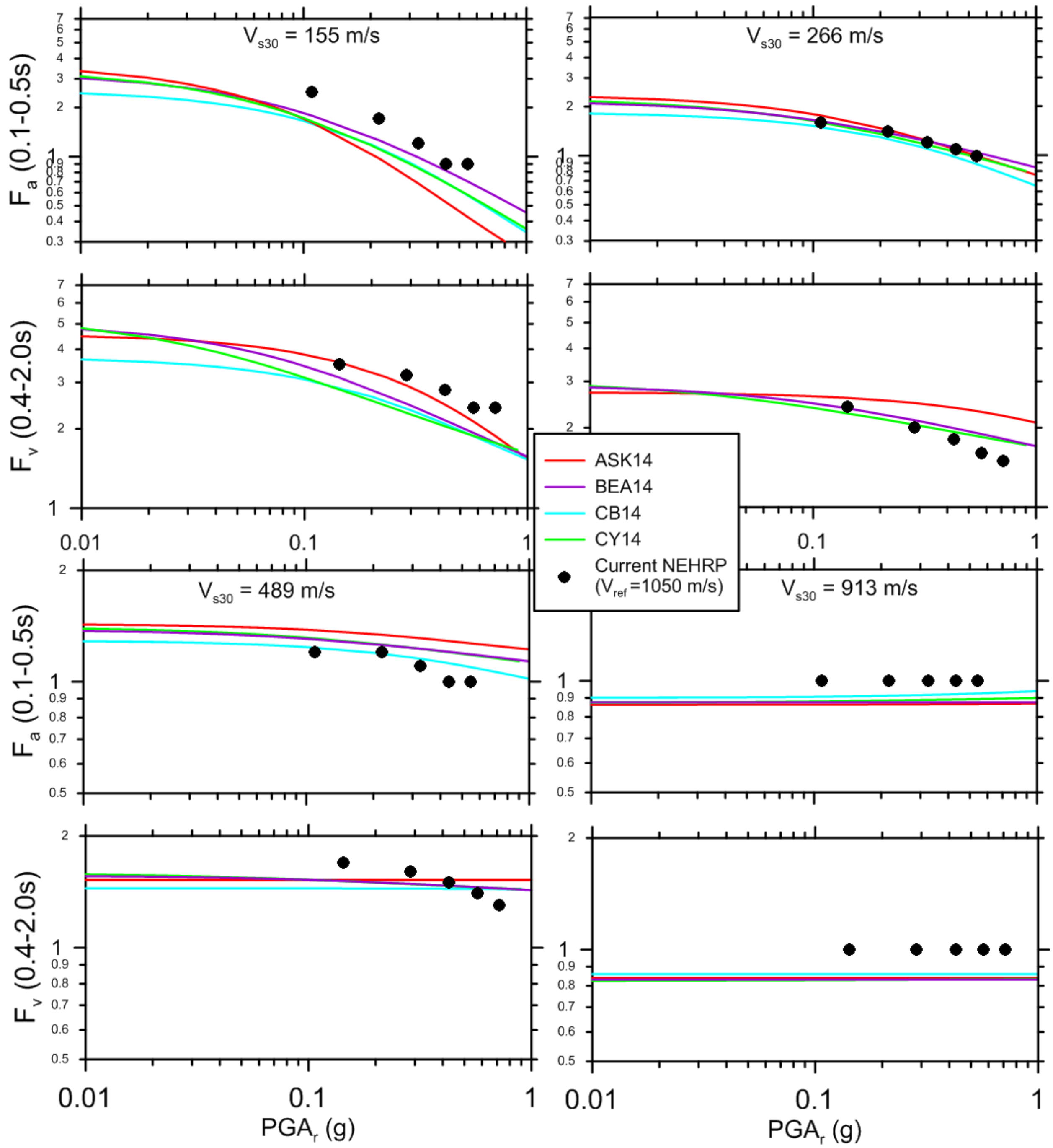


Figure 4.12 **Comparison of site terms in NGA-West 2 GMPE normalized to a common reference site condition of V_{ref} = 760 m/sec along with current NEHRP site factors, which have a reference condition of 1050 m/sec. Site factors from NGA relationships are averaged across corresponding period ranges (0.1–0.5 sec for F_a; 0.4–2.0 sec for F_v) using equally spaced periods on a log scale.**

5 Development of Revised NEHRP Site Factors

5.1 THE PROCESS

The Task 8 Working Group described in Chapter 1.1 was assembled principally to support the development of a proposal to modify the NEHRP site factors. Many working group members have experience as past members of the Building Seismic Safety Council (BSSC) Provisions Update Committee (PUC), which meets on approximately four-year intervals to hear and vote on proposals to revise the *NEHRP Recommended Provisions for New Buildings and Other Structures* (BSSC 2003).

One member of the Task 8 Working Group, C.B. Crouse, is a current member of the PUC. Early in this project, we sought and received PUC approval to prepare a proposal to revise the NEHRP site factors. The PUC requested that the Task 8 working group prepare a proposal and that the group members vote on it. A unanimous or nearly unanimous Task 8 vote was considered essential for a proposal to be favorably evaluated at the PUC level.

The Task 8 working group met in person and via phone meetings on five occasions between March 2010 and June 2012. The purpose of the initial meetings was to define specific scope items that would enable the issues with the current NEHRP site factors to be clearly defined. The outcomes of this work are described principally in Chapters 2 and 3 of this report, and were publically presented in a keynote presentation at the 2012 GeoCongress in Oakland California (Seyhan and Stewart 2012). Subsequent meetings involved the review of data and analysis results developed by the authors and other committee members, much of which is included in Chapter 4 of this report.

In the course of these meetings, different views of some key issues were identified and discussed in some detail, as described further in the next section. Aside from those specific issues, the Task 8 group was able to reach consensus relatively easily on other matters. A proposal was submitted to PUC in October 2012. Following several round of review, revision, and balloting, the proposal was approved unanimously by the PUC in September 2013. Accordingly, the new site factors are expected to appear in the 2015 version of the NEHRP *Provisions*.

The principal technical issues that were discussed and debated within the Task 8 working group and PUC are described in the following section.

5.2 DECISION POINTS IN COMMITTEE DELIBERATIONS

Several issues have direct influence on nonlinear site factors having a functional dependence on the site parameter V_{S30}. These include the region from which the data is derived, the value of V_{S30} that site factors are referenced to, the manner by which nonlinearity in site amplification is evaluated and parameterized, and whether best-estimate or deliberately biased site factors should be used in building code applications.

Of these issues, the reference value of V_{S30} presented the most difficulty in reaching consensus within the Task 8 working group. One opinion, expressed principally by one working group member, was that the reference velocity (V_{ref}) should be taken as 1050 m/sec. The rationale for this choice was that this approximate value was obtained from reference site regressions using the Loma Prieta earthquake data (Borcherdt 1994b), as described further in Chapter 2 (Section 2.1.1). The second opinion was that V_{ref} should be taken as the value used in the USGS national hazard maps, so that site amplification from the factors would be expressed relative to the mapped ground motion levels. The committee ultimately came to the view (in a June 2012 meeting) that the second approach was preferred as it is more in keeping with how the national maps and site factors are currently configured and used. The PUC ultimately approved site factors derived using the second approach as well.

A second issue requiring a decision drawn from the collective judgment of the Task 8 group concerned the regionalization of site amplification described in Chapter 4, which affects the slope of log amplification – log (V_{S30}) relations. Two approaches were considered. The first was to base the site factors on slopes derived from California data, since much of the U.S. seismic hazard lies in California, and hence the impact of the NEHRP *Provisions* is particularly strong there. The second approach was to base the slope on a global site amplification model (i.e., the model by SS14 and adopted by BEA14), since the NEHRP factors are applied broadly and the diversity of regions contributing data to NGA-West 2 comes closer to capturing the range of conditions in application regions than the use of solely California data. The second (non-regionalized) approach was selected, which had the benefit of changing the NEHRP factors in most site categories by amounts less than 20% (the amount of change would have been larger in some cases using V_{S30}-scaling specific to California).

The issue of nonlinearity, while important, was non-controversial. The nonlinear model of SS14 was considered by the Task 8 group to represent a reasonable combination of results obtained from simulation-based and empirical studies.

The issue of bias in the NEHRP site factors was raised in discussions with the PUC. There was general consensus that site factors for Classes B-D should be unbiased (median values), but that Class E factors should be biased high. The rationale for introducing this bias was to not produce a large change from the current Class E values and to incentivize site-specific analyses, which in most cases should produce reduced levels of site amplification relative to code values. The PUC also requested that we compute site factors for a stronger shaking level ($S_s > 1.5$, $S_1 > 0.6$), which has been provided.

In a June 29 2012 meeting, the following resolution was put forward to the Task 8 working group:

> *Should revised NEHRP factors be derived from a site amplification model derived from residuals analysis using full NGA-West 2 data set and cast relative to a reference site condition of V_{ref}=760 m/sec?*

The Task 8 working group voted unanimously "yes" to the resolution. NEHRP site factors derived in consideration of this approach are described in the following section.

A complication that arose after the June 2012 meeting was that one committee member dis-avowed support for the above approach and put forward a proposal formulated differently from what is described in the following section. That proposal maintains a reference velocity for the site factors of 1050 m/sec. The rationale for this alternative proposal is described by Borcherdt (2012). The basis of the argument is essentially that the empirical site factors from Borcherdt (1994b) were developed relative to rock sites having an average shear wave velocity that is near the B-C boundary (795 m/sec). Therefore, although the equation fit to the data passes through unity at 1050 m/sec, the site factors in an overall sense are relative to something near the B-C boundary. We do not dispute this interpretation of the Borcherdt (1994b) results. Where we disagree is in the supposition that the 1050 m/sec velocity, or something near it, should be maintained as the reference condition when site factors are evaluated using a non-reference site approach (i.e., the approach used in GMPE development and SS14). Based on the results of the June 2012 meeting and subsequent correspondence, all but one of the Task 8 working group members recognize that using a reference velocity different from 760 m/s would introduce bias to the site factors that is not appropriate. As mentioned previously, the PUC also agreed unanimously with the use of a reference velocity of 760 m/s for the derivation of the new NEHRP site factors.

5.3 UPDATED NEHRP FACTORS

The site amplification model described by SS14 and in Chapter 4 is utilized to generate site amplification factors within the V_{S30} bins, and at the PGA_r values, currently used in the NEHRP *Provisions*. Recall that the NEHRP site factors are specified for Categories A-E with the V_{S30} limits given in Table 2.1. We select representative V_{S30} values for each category from the distribution of measured data in the NGA-West 2 site database (Seyhan et al. 2014).

Table 5.1 presents these within-category median V_{S30} values along with the recommended V_{S30} values from Borcherdt (1994b, Table 2, marked as 'B94'). Site amplification within each category is computed using the NGA-West 2 median V_{S30} values in Table 5.1. The rationale behind this selection is that the NEHRP factors are evaluated for the 50th percentile V_{S30} value within the category. The resulting factors are not substantially different if they are evaluated at alternate velocities selected by Borcherdt (1994b) or at the geometric mean of the category limits (see Section 3.1 for discussion).

The NEHRP site factors are developed using the model represented by Equation (4.1). The ln(F_{lin}) term is computed using Equation (4.2) by averaging slope (c) values across period ranges of 0.1–0.5 sec (for F_a) and 0.4-2.0 sec (for F_v). The averaging is not done across all NGA periods within those ranges, because they are not evenly sampled in log space. Rather, we selected 20 periods per log cycle that were (roughly) evenly sampled. The corresponding c values are -0.73 for F_a and -1.03 for F_v. As described in Section 5.2, V_{ref} is taken as 760 m/sec.

The ln(F_{nl}) term is computed using Equation (4.3), in which slope f_2 is computed using Equation (4.4) from averaged f_4 and f_5 values for the respective period ranges computed as described above and for the V_{S30} values shown in Table 5.1, f_1 is zero, and f_3 is taken as 0.1g independent of period.

Table 5.1 Representative median V_{S30} values in NEHRP categories.

NEHRP Site Class	*NGA-West 2 Median V_{S30} (m/s)*	*Mid-Range V_{S30} (m/s) from B94*	*Geometric Mean of Class Limits (m/s)*
E (V_{S30} ≤ 180 m/s)	155	150	180
D (180 < V_{S30} < 360 m/s)	266	290	255
C (360 ≤ V_{S30} < 760 m/s)	489	540	523
B (760 ≤ V_{S30} < 1500 m/s)	913	1050	1068
A (V_{S30} ≥ 1500 m/s)	1620 [a]	1620	1500

[a] Adopted from Borcherdt (1994)

Coefficients for c, f_4 and f_5 that were used in the above calculations are given in the Appendix of BEA14.

Since reference site ground motion amplitudes are specified in the NEHRP *Provisions* in terms of spectral ordinates instead of PGA_r, we apply the following conversions:

$$\begin{aligned} S_S &\approx 2.3 \times PGA_r \\ S_1 &\approx 0.7 \times PGA_r \end{aligned} \tag{5.1}$$

Site factors are computed at PGA_r = 0.11, 0.22, 0.33, 0.43, 0.54, and 0.65g (for F_a) and PGA_r = 0.14, 0.29, 0.43, 0.57, 0.71, and 0.86g (for F_v), which is consistent with the tabulated S_s and S_1 values in the current NEHRP *Provisions* (except for the newly added highest shaking levels.

We compute period-averaged site amplification for the specified ranges of V_{S30} and PGA_r. The results are given in Figure 5.1 and Table 5.2. For the case of Site Class A, we maintain the current values of 0.8, which are generally consistent with amplification for $V_{S30} > V_c$ in SS14. For Site Class E, median estimates of site amplification were computed using the complete model as with the other classes. However, the recommended factors for Site Class E are increased above the median by one-half of the within-event standard deviation derived as given by BEA14, which increases site factors by approximately a factor of 1.3-1.4. This introduces a conservative bias to the Class E factors that is considered desirable due to the relatively modest amount of data for this site condition. A conservative bias was applied in the original site factors for Class E as well (Dobry et al. 2000). As shown in Figure 5.1., other than Class E, the recommended site factors are consistent with those in the NGA-West 2 models.

Figure 5.2 shows the recommended site factors as a function of V_{S30} for the levels of excitation (specified as values of S_S and S_1) given in the NEHRP tables (Table 5.2). Trends in the plot show the expected patterns of relative V_{S30}-scaling (stronger for F_v than F_a) and nonlinearity (strong for soft soil, decreasing effects for stiff soil and rock; stronger for F_a than F_v).

Table 5.2 compares the current and proposed site factors. Values for F_{PGA} are also shown in the table. The proposed site factors are generally smaller than original values due to the change in reference velocity from 1050 to 760 m/sec. For stronger shaking levels and Class C-D soils, the recommended site factors become close to, or slightly greater than, original values because of reduced levels of nonlinearity, especially at long period (i.e., in the F_v parameter).

As noted previously, the nonlinear model, described in Section 4.1, has a substantial effect on the computed factors for Class E. There are relatively large epistemic uncertainties in this model for soft soils. Our introduction of conservatism in the Site Class E factors, as described above, is intended to approximately account for this epistemic uncertainty.

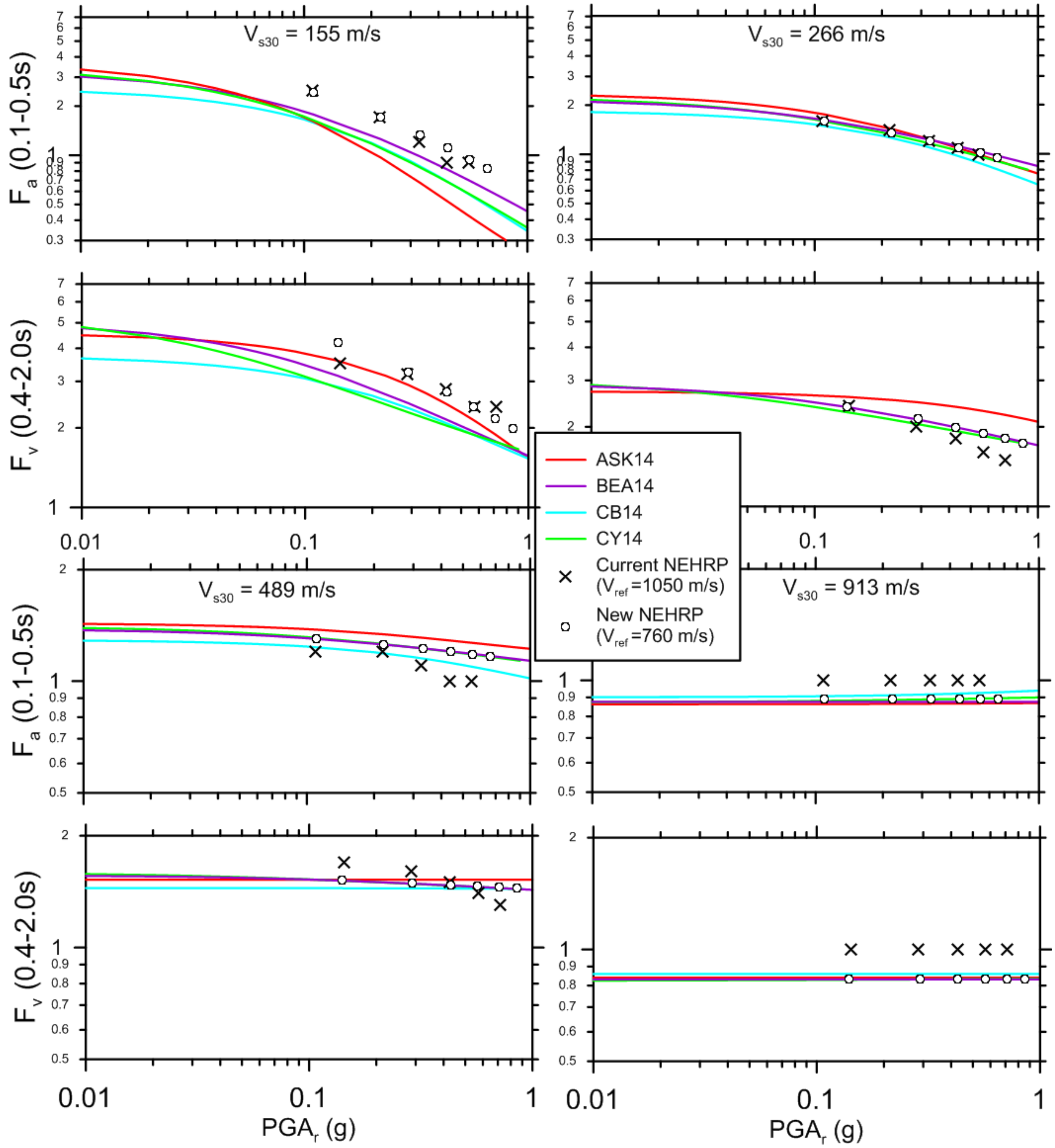
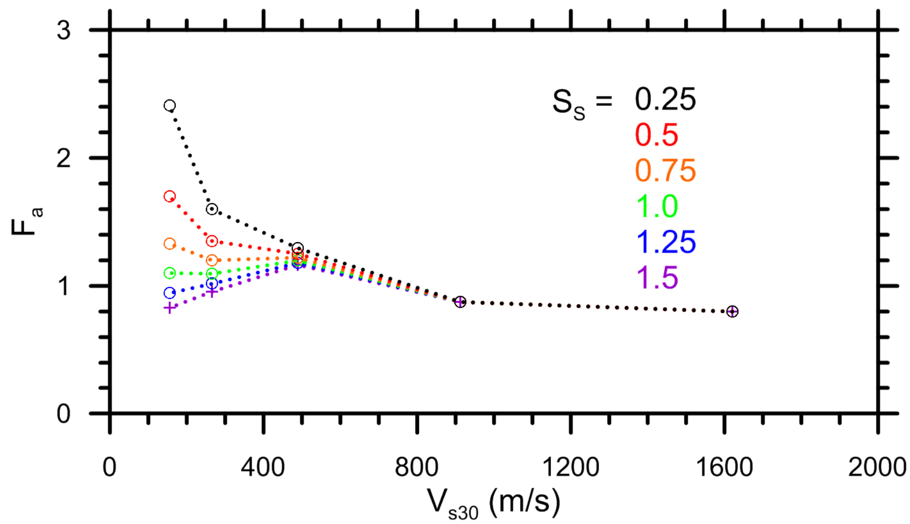


Figure 5.1 **Comparison of proposed and current NEHRP site factors with site terms in NGA-West 2 GMPEs normalized to a common reference site condition of V_{ref} = 760 m/sec.**



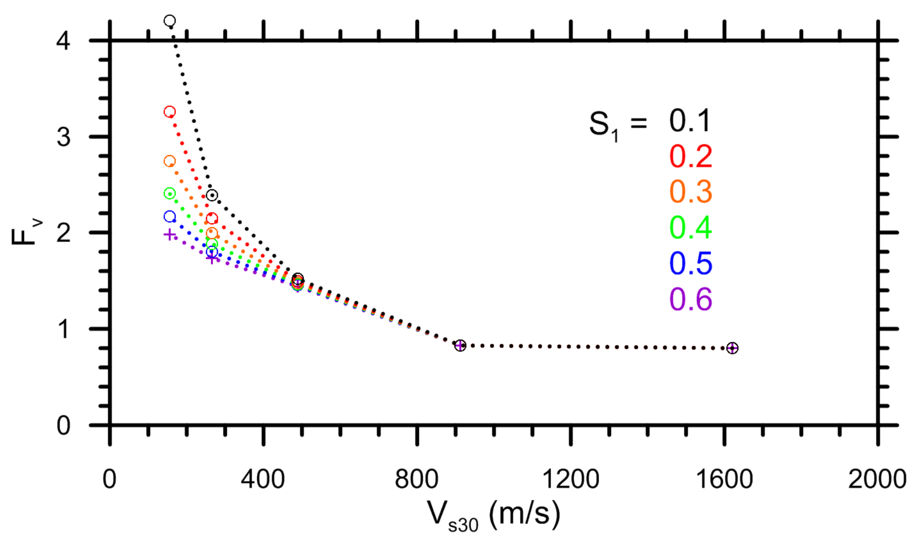


Figure 5.2 Recommended NEHRP site factors for F_a and F_v as function of V_{S30}.

Table 5.2 **Original (ASCE) and updated (PEER) site amplification factors F_a, F_v, and F_{PGA}. PEER values are rounded to the nearest 0.1 for application in the NEHRP *Provisions*.**

F_a

Site	$S_s < 0.25$		$S_s = 0.5$		$S_s = 0.75$		$S_s = 1.0$		$S_s = 1.25$		$S_s > 1.5$	
Class	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*
A	0.8	**0.8**	0.8	**0.8**	0.8	**0.8**	0.8	**0.8**	0.8	**0.8**	0.8	**na**
B	0.9	**1.0**	0.9	**1.0**	0.9	**1.0**	0.9	**1.0**	0.9	**1.0**	0.9	**na**
C	1.3	**1.2**	1.3	**1.2**	1.2	**1.1**	1.2	**1.0**	1.2	**1.0**	1.2	**na**
D	1.6	**1.6**	1.4	**1.4**	1.2	**1.2**	1.1	**1.1**	1.0	**1.0**	1.0	**na**
E	2.4	**2.5**	1.7	**1.7**	1.3	**1.2**	1.1	**0.9**	0.9	**0.9**	0.8	**na**

F_v

Site	$S_1 < 0.1$		$S_1 = 0.2$		$S_1 = 0.3$		$S_1 = 0.4$		$S_1 = 0.5$		$S_1 > 0.6$	
Class	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*
A	0.8	**0.8**	0.8	**0.8**	0.8	**0.8**	0.8	**0.8**	0.8	**0.8**	0.8	**na**
B	0.8	**1.0**	0.8	**1.0**	0.8	**1.0**	0.8	**1.0**	0.8	**1.0**	0.8	**na**
C	1.5	**1.7**	1.5	**1.6**	1.5	**1.5**	1.5	**1.4**	1.5	**1.3**	1.4	**na**
D	2.4	**2.4**	2.2	**2.0**	2.0	**1.8**	1.9	**1.6**	1.8	**1.5**	1.7	**na**
E	4.2	**3.5**	3.3	**3.2**	2.8	**2.8**	2.4	**2.4**	2.2	**2.4**	2.0	**na**

F_{PGA}

Site	*PGA < 0.1*		*PGA = 0.2*		*PGA = 0.3*		*PGA = 0.4*		*PGA = 0.5*		*PGA > 0.6*	
Class	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*	*PEER*	*ASCE*
A	0.8	**0.8**	0.8	**0.8**	0.8	**0.8**	0.8	**0.8**	0.8	**0.8**	0.8	**na**
B	0.9	**1.0**	0.9	**1.0**	0.9	**1.0**	0.9	**1.0**	0.9	**1.0**	0.9	**na**
C	1.3	**1.2**	1.2	**1.2**	1.2	**1.1**	1.2	**1.0**	1.2	**1.0**	1.2	**na**
D	1.6	**1.6**	1.4	**1.4**	1.3	**1.2**	1.2	**1.1**	1.1	**1.0**	1.1	**na**
E	2.4	**2.5**	1.9	**1.7**	1.6	**1.2**	1.4	**0.9**	1.2	**0.9**	1.1	**na**

6 SUMMARY AND CONCLUSIONS

6.1 RESEARCH OBJECTIVES AND SCOPE

The project reported in this documented (Task 8 of NGA-West2) had as its objectives the development of a proposal for revising the NEHRP site amplification factors and supporting work for NGA-West2 GMPE developers related to site terms and site amplification modeling. As described in Chapter 1, the scope of work undertaken to realize those objectives included:

- Review of the technical basis of the NEHRP factors and NGA site factors
- Comparisons of site amplification factors from NEHRP provisions and the NGA-West 1 models, including interpretation of the principal causes of differences
- Enhancement and development of the site database used to support the NGA-West 2 flatfile [details in Ancheta et al. (2013)]
- Development of a site amplification model using NGA-West 2 data and simulation results
- Producing a proposal for revision of NEHRP site factors and engaging with the NEHRP Provisions Update Committee to see the approval process through to fruition

6.2 PRINCIPAL FINDINGS

The NGA and NEHRP site factors are consistent in certain respects (e.g., the scaling of linear site amplification with V_{S30}), but have discrepancies in linear site amplification (applicable for $PGA_r \leq 0.1g$) for site Classes B to E and in the levels of nonlinearity for Classes C and D. The amount of these discrepancies ranges from up to 50% for Class E to amounts ranging from about 0 to 20% for Classes B-D. Previous work has identified similar discrepancies in NEHRP and NGA site factors (Huang et al. 2010), but the discrepancies were not clearly associated with differences in linear site amplification levels and nonlinearities. Such associations are useful to understand causes of misfits and to formulate revisions to NEHRP factors.

A major cause of the weak motion amplification misfit is that the NEHRP factors are normalized relative to a reference site condition of V_{ref} =1050 m/sec, whereas their current application is relative to V_{S30} = 760 m/sec. When re-normalized to V_{S30} = 760 m/sec, the NEHRP factors are much closer to NGA factors (especially for Class D), although misfits remain for Classes B, C, and E.

We find that the nonlinearity in F_a and F_v from simulation-based work in the 2008 NGA project (WEA08) is smaller than the nonlinearity in the NEHRP factors (Dobry et al. 2000).

Those reduced levels of nonlinearity are consistent with trends from empirical ground motion data from the 2008 NGA project.

Examining the NGA-West 2 data, we find the V_{S30}-scaling to follow regional trends, but the significance of the regional differences is strongly sensitive to the method of data selection. When regional anelastic attenuation effects are considered in the data analysis and the data is extended to large distances, regional site response effects are relatively modest. On the other hand, when a relatively short cut-off distance is used to minimize anelastic attenuation effects (less than approximately 80 km), regional effects are much stronger, especially for Japanese data at short periods. The nonlinearity in site amplification does not show strong evidence of regional variability.

We developed a semi-empirical site amplification model for shallow crustal regions in which V_{S30}-scaling is parameterized using the NGA-West 2 data. The development of that site amplification model is described by SS14; this report presents supporting work that guided model development relative to regional variations in site amplification and levels of nonlinearity implied by simulations. The nonlinear component of the model is constrained jointly by NGA-West 2 data and simulation results.

The complete model (for V_{S30}-scaling and nonlinearity) is used to derive new NEHRP site factors using a reference velocity of 760 m/sec. For relatively weak levels of shaking, the recommended NEHRP site factors are generally smaller than current values due to the change in reference velocity from 1050 to 760 m/sec. For stronger shaking levels and Class C and D soils, the recommended site factors become close to, or slightly greater than, those used currently because of reduced levels of nonlinearity, especially at long period (i.e., in the F_v parameter). Factors for soft soil (Class E) were set conservatively, as were the original NEHRP site factors, to account for larger epistemic uncertainty in the nonlinearity for this site class as compared to others. The new site factors have been approved by the Provisions Update Committee of the Building Seismic Safety Council and are expected to appear in the 2015 version of the NEHRP *Provisions*.

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The topic of site amplification in GMPEs would benefit from additional research. A few issues raised in this study deserve particular attention. One general area of inquiry would be on the use of site parameters other than V_{S30} to improve site amplification functions (e.g., depth and site period). Such parameters may well be able to explain some of the unresolved questions related to regional variations in site terms, which almost certainly are associated with between-region variations in geologic conditions. Current simulation-based modeling techniques are not able to provide a theoretical justification for the nonlinearity that is observed empirically (e.g., at 3.0 sec period). Further data analysis will also help to clarify whether those observations are robust.

There will always be an element of epistemic uncertainty in site response. Additional research is needed to define methodologies to better capture the range of viable models for site amplification at long periods, including possible nonlinear effects.

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