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Authors
Seyhan, Emel
Stewart, Jonathan P.

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SITE RESPONSE IN NEHRP PROVISIONS AND NGA MODELS

Emel Seyhan[1], S.M. ASCE and Jonathan P. Stewart[2], PE, F.ASCE

[1]Graduate Student, Civil and Environmental Engineering, University of California, Los Angeles, 90095; eseyhan@ucla.edu
[2]Professor and Vice Chair, Civil and Environmental Engineering, University of California, Los Angeles, 90095-1593; jstewart@seas.ucla.edu

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 factors have discrepancies with respect to the site terms in the 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 of about 1050 m/s, whereas the reference velocity for current application is 760 m/s. We show that the levels of nonlinearity in the NEHRP factors are generally stronger than recent simulation-based models as well as empirically-based models.

INTRODUCTION

The site factors incorporated into ground motion prediction equations (GMPEs) differ from those in the building code, which are presented by BSSC (2009) (typically referred to as *NEHRP Provisions*) (e.g., Huang et al., 2010). These differences create practical difficulties because of caps imposed by regulatory agencies on the levels of ground motion from site specific analysis relative to those developed from prescriptive code procedures. In this paper, we document the differences in site factors and postulate reasons for the discrepancies. This work was performed to provide technical support for possible revisions to the NEHRP site factors, which are being considered for the next cycle of the NEHRP Provisions in 2014. Our conclusions on the factors causing the differences are preliminary because the research is ongoing.

BASIS OF SITE FACTORS IN NEHRP PROVISIONS

Review of NEHRP Site Factors

The NEHRP Provisions and Commentary (BSSC, 2009) 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 US Geological Survey (http://earthquake.usgs.gov/hazards/). In the 2008 version of the maps, the reference site condition is specified as V_{s30}=760 m/s, 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 1, NEHRP site factors are based on site categories 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 >20, and water content > 0.40), for which category 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 categories B and C (V_{s30} = 760 m/s).

Table 1. Site categories 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 1 presents the short- and long-period NEHRP site factors (BSSC 2009) 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).

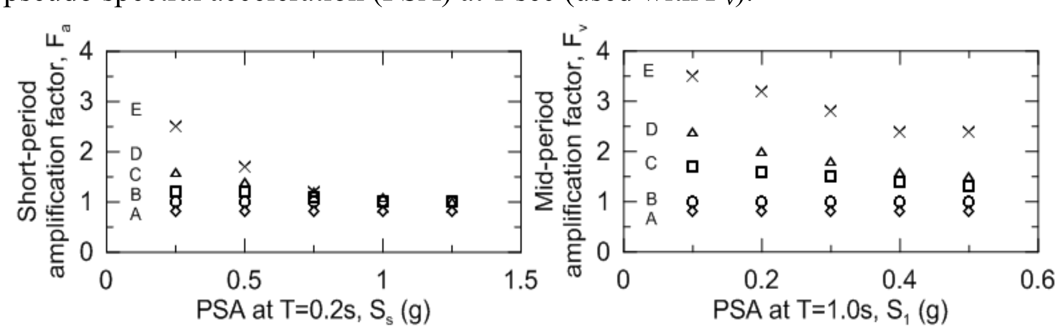

FIG. 1. Site factors F_a and F_v in NEHRP Provisions (BSSC 2009).

Some physical processes underlying the trends in the NEHRP site factors shown in Figure 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 Category E and is less significant for stiffer sites.

3. Site factor F_a (short periods) attenuates more rapidly with increasing S_s or S_1 than does F_v. 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 ground response simulations and empirical approaches. Existing NEHRP site factors were developed empirically for relatively low input rock ground motions (peak accelerations or S_l near 0.1 g) and have levels of nonlinearity derived from simulations. Additional details on the development of NEHRP factors utilizing empirical and simulation-based methods are given in the following sections.

Empirical Basis for Weak Motion NEHRP Site Factors

The empirical basis for the relatively weak motion NEHRP site factors was developed by Borcherdt (1994), 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 shows a map of the rock and soil sites considered by Borcherdt and Glassmoyer (1994) (BG). For a particular period T and rock-soil site pair, the site factor determined by this method is:

$$F\left(T\right)=\frac{FA_{Vs30}\left(T\right)}{FA_{ref}\left(T\right)} \tag{1}$$

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 (these sites generally have V_{s30} > 760 m/s). Fourier amplitude spectral ratios were computed at frequency intervals of 1/40.96 sec in the frequency domain. Period-specific spectral ratios calculated from Eqn. (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 corresponding linear regression curves are presented in BG (1994) and Borcherdt (1994b), and the Borcherdt (1994b) results are reproduced in Figure 3. The reference rock motions used by BG (1994) and Borcherdt (1994b) have bedrock peak ground accelerations that range from 0.075 to 0.11 g, with an average of about 0.1 g.

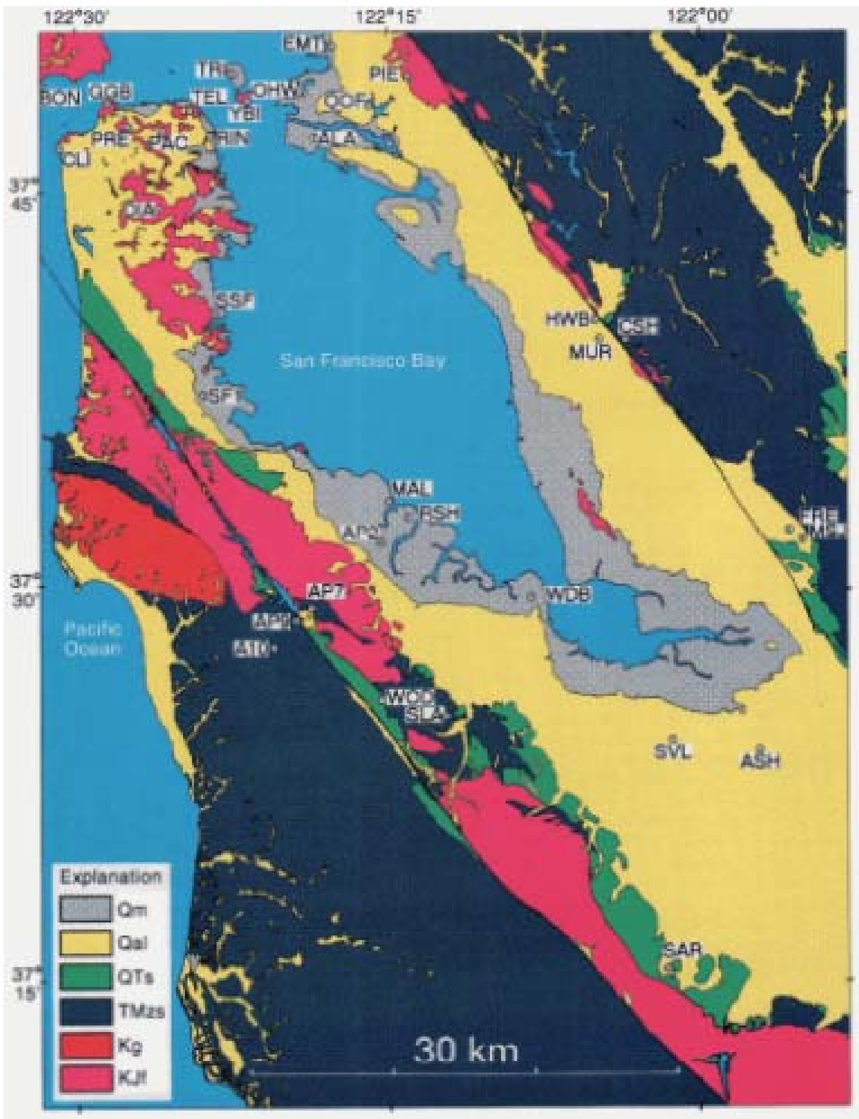

FIG. 2. Map of San Francisco Bay region, showing locations of 34 of 37 free-field stations that recorded 1989 Loma Prieta earthquake and generalized geologic units. KJf corresponds to Franciscan formation bedrock of Cretaceous and Jurassic age that was taken as reference rock. Borcherdt and Glassmoyer (1994).

Figure 3 shows the F_a and F_v factors presented by Borcherdt (1994b) for each station pair plotted as a function of V_{s30} along with linear regression results, 95% confidence intervals for the ordinate to the true population regression line, and the limits for two standard deviations above and below the estimate. The relatively narrow confidence intervals indicate that the scaling of the site terms with V_{s30} is statistically significant. It is apparent from the trends in Figure 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.

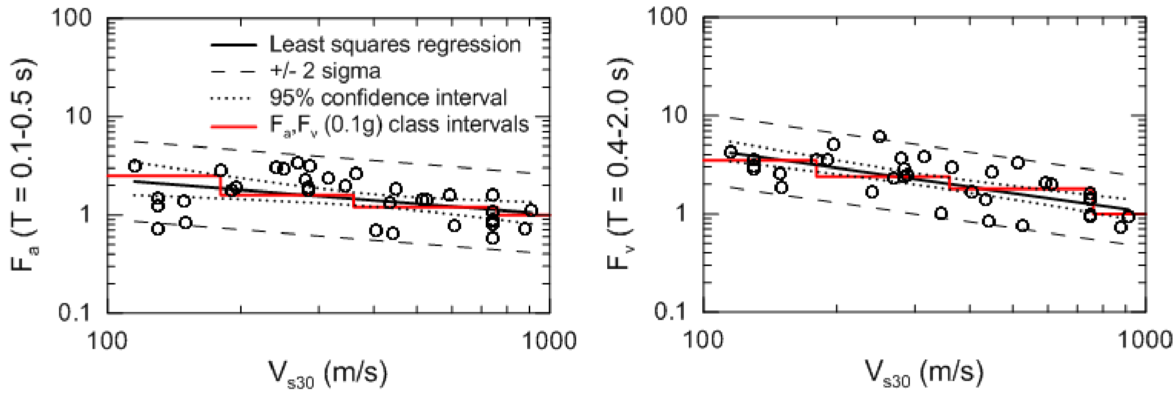

FIG. 3. Site factors F_a and F_v evaluated from reference site approach from recordings of 1989 Loma Prieta earthquake as function of V_{s30} (data from Borcherdt, 1994b). The reference motion amplitude for the data is PGA_r = 0.1g. Red stepped lines correspond to site factors in site class intervals.

The reference sites used by Borcherdt (1994b) 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/s, but the linear trend line through the data in Figure 3 reaches unity at V_{s30} = 1050 m/s.

In Figure 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 3, the NEHRP F_a and F_v factors are consistent with the trend of the regression lines. The stepped site factors in Figure 3 are slightly different from those presented by Borcherdt (1994b), which match the lines at V_{s30} = 150, 270, 560 and 1050 m/s. 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. As seen from Figure 3, the NEHRP factors match the regression lines at V_{s30} = 120, 290, 600 and 1050 m/s (for F_a) and at 160, 290, 450 and 1050 m/s (for F_v).

With regard to the V_{s30} = 1050 m/s 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 US (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/s), 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 are referenced to firm rock (V_{s30} = 1050 m/s). 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/s (e.g., Frankel et al., 1996, p 5 & 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.

Simulation-Based Nonlinearity in NEHRP Site Factors

Ground response simulations generally model the stratigraphy as one-dimensional 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) shear wave velocity profiles utilized for analysis should be representative of the application region, (2) 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 regional seismicity. Similar considerations apply for nonlinear ground response analysis.

Borcherdt (1994b) and Dobry et al. (2000) describe the process by which equivalent linear and nonlinear ground response simulations were used to supplement the linear site factors in Figure 3. Suites of profiles were analyzed by Seed et al. (1994) and Dobry et al. (1994) for categories C-E using velocity profiles from sites in California and Mexico City. The empirical amplification values shown in Figure 3 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 0.1g, 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 4 and given by the following expressions:

$$F_a = \left(V_{ref} / V_{s30}\right)^{m_a} \quad (2)$$

$$F_v = \left(V_{ref} / V_{s30}\right)^{m_v} \quad (3)$$

where V_{ref} is the reference V_{s30} = 1050 m/s 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 4 (Borcherdt, 1994b; Dobry et al., 2000). The black line in Figure 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 4 that these expressions for site factors are referenced to a common V_{s30} = 1050 m/s. For the NEHRP site factors (Figure 1), the input motion ground motion amplitude was re-expressed as S_s and S_1 in lieu of PGA according to S_s=2.5PGA and S_1=PGA.

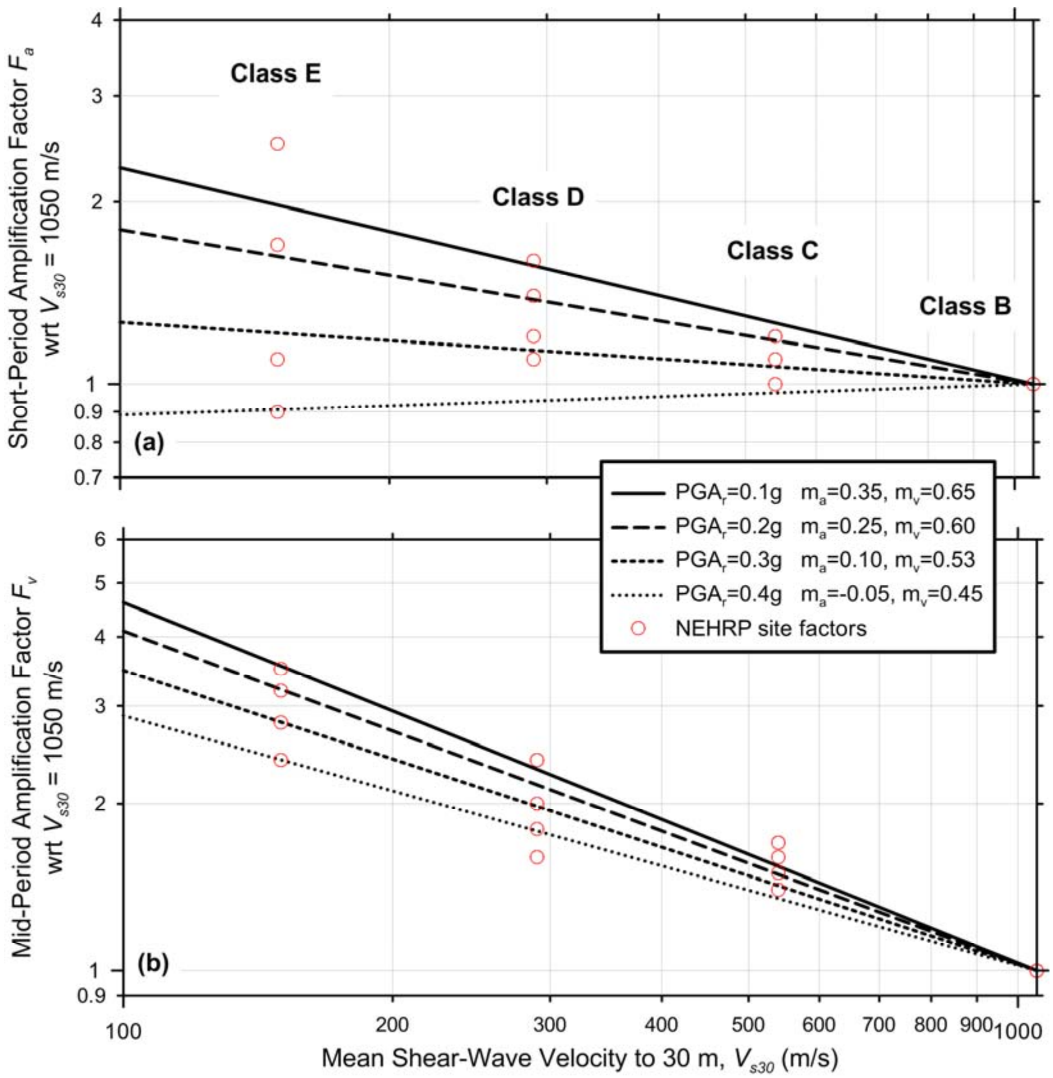

FIG. 4. Relationships between V_{s30} and (a) Short-period F_a and (b) mid-period F_v amplification factors used in the development of NEHRP factors. Figure adapted from Borcherdt (1994b) and Dobry et al. (2000). Parameters m_a and m_v are slopes of the amplification factors with V_{s30} in log-log space as given in Eqn. (2)-(3) with slopes originally from Borcherdt (1993, 1994a,b); PGA$_r$ corresponds to the input ground motion level on rock.

Figure 5 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.

SITE FACTORS IN NGA RELATIONS

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 AS, BA, CB, CY and Idriss are applied. The models are based on analyses of the PEER-NGA empirical strong ground motion database, which contains 3,551 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:

$$\ln Y = f_1(M) + f_2(R) + f_3(F) + f_4(HW) + f_5(S) + \varepsilon_T \tag{4}$$

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

$$\sigma = \sqrt{\phi^2 + \tau^2} \tag{5}$$

where ϕ 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 AS, CB, and CY relations, a basin depth term as well. Different NGA developers used different methods to obtain site factors. AS and CB set coefficients describing the linear site response empirically and constrain the nonlinearity in site response based on simulations by Walling et al. (2008). BA and CY 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 BG, 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:

$$F(T) = \frac{\left(S_a^{rec}(T)\right)}{\left(S_a^{r}(T)_{GMPE}\right)} \qquad (6)$$

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:

$$\ln F(T) = \ln\left(S_a^{rec}(T)\right) - \ln\left(S_a^{r}(T)_{GMPE}\right) \qquad (7)$$

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

As noted previously, the AS and CY GMPEs utilize site amplification models whose nonlinear component is set from the results of 1D ground response simulations. The simulation methodology and model building process are described in Walling et al. (2008). 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 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/ s was computed. Example site factors for V_{s30}=270 m/s and 560 m/s, obtained at T=0.2s from this process, are plotted against PGA for V_{s30}=1100 m/s (i.e. PGA1100) in Figure 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).

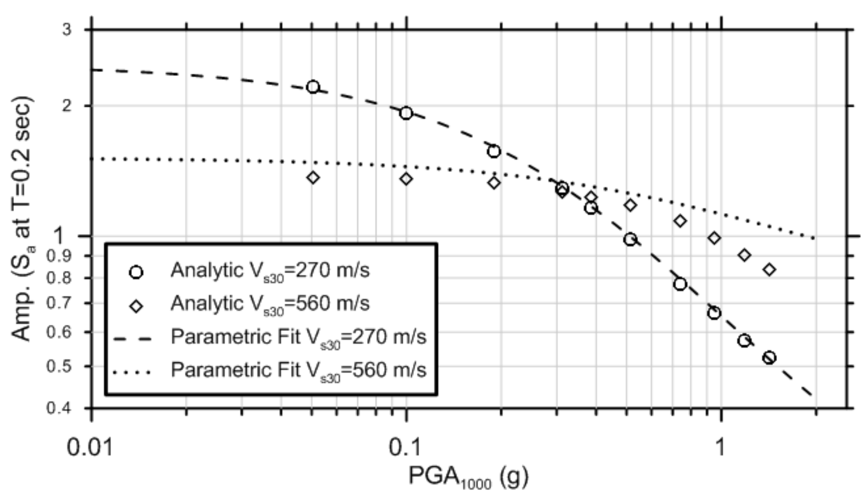

FIG. 5. Examples of the site factors computed by Walling et al. (2008) and parametric fits to the analysis results. Adapted from Walling et al. (2008).

DIFFERENCES BETWEEN NEHRP AND NGA SITE FACTORS

Site Factors Comparisons

In this section we compare the NEHRP site factors with NGA site factors derived from the four 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.

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 AS, BA and CB and as spectral acceleration at the period of interest for CY. 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 $V_{s30}=x$. Reference motion amplitude A_x is a median PGA for AS, BA, CB and an event-term adjusted median S_a at the period of interest for CY. 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
- AS: V_{s30}, Median PGA_{1100} (PGA for V_{s30}=1100 m/s)
- BA: V_{s30}, Median PGA_{760} (PGA for V_{s30}=760 m/s)
- CB: V_{s30}, Median PGA_{1100} (PGA for V_{s30}=1100 m/s)
- CY: V_{s30}, Median + η_i $(S_a)_{1130}$ (S_a for V_{s30}=1130 m/s)

To facilitate comparisons between the NGA and NEHRP site factors, we compute site terms relative to the V_{s30}=760 m/s 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/s reference. 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 (8)

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

We define the reference site motion amplitude as A_x = median PGA for V_{s30} = 760 m/s, which is denoted PGA_r in the following text. Site factors are evaluated for PGA_r = 0.01-0.9g. The CY 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:

$$S_a\left(T = 0.2\sec, V_{ref} = 760m/s\right) = 2.2PGA_r \qquad (9a)$$

$$S_a\left(T = 1.0\sec, V_{ref} = 760m/s\right) = 0.7PGA_r \tag{9b}$$

The factors of 2.2 and 0.7 in Eqn. 9a and 9b are based on differences in the median spectral ordinates (e.g., 0.2 sec S_a on rock vs PGA for Eqn. 9a) from the NGA GMPEs for rock site conditions and various ranges of M_w (5-8) and distance (0-50 km). 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, which are normalized by medians for V_{s30} = 760 m/s. They take the ratio of median S_a at V_{s30} to median S_a at 760 m/s as a period-dependent site factor. Huang et al. (2010) average these values across three GMPEs (i.e. BA, CB and CY) and across period ranges to develop recommendations for F_a and F_v site factors.

We use the NGA site models at representative V_{s30} values for each NEHRP category. The representative velocities are evaluated from medians within the various categories B-E using the site database being compiled for the NGA-West2 project (http://peer.berkeley.edu/ngawest2/). That database contains 804 CA and international sites with measured V_{s30} values distributed as shown in Figure 6. The median V_{s30} values for each site category are indicated in Figure 6. More detailed histograms within the relatively well populated C and D categories are given in Figure 7. The representative category velocities given in Figure 7 are generally similar to those used by Borcherdt (1994b) to set the empirical site factors (i.e., 153 vs 150 m/s for E; 265 vs 290 m/s for D; 488 vs 540 m/s for C; 911 vs 1050 m/s for B).

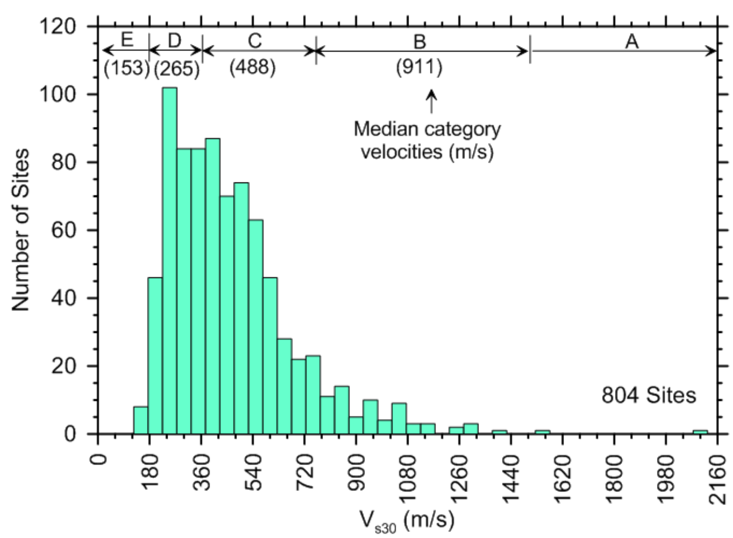

FIG. 6. Histogram of measured V_{s30} values for strong motion sites in NGA-West2 site database used to estimate representative category velocities.

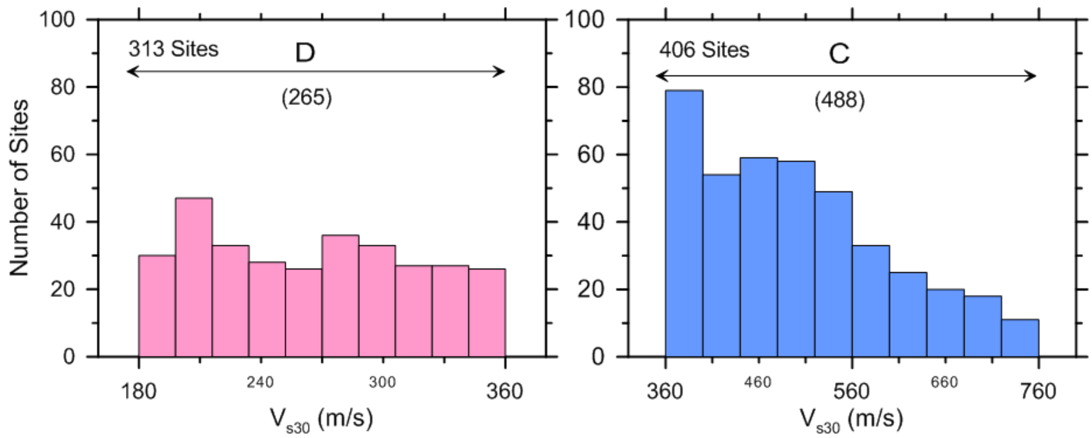

FIG. 7. Histogram of V_{s30} values within Categories C-D from NGA-West2 site database.

Figure 8 compares the discrete NEHRP site factors (black solid symbols) with NGA 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/s. Adjustments to the NEHRP factors are also shown in Figure 8 (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 8 are the 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 Eqn. (9), which are compatible with the magnitude and distance range selected by Huang et al. (2010).

The spread of NGA site factors in Figure 8 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. 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 8 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/s. The Huang et al. (2010) site factors are generally similar to the NGA factors shown in Figure 8 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).

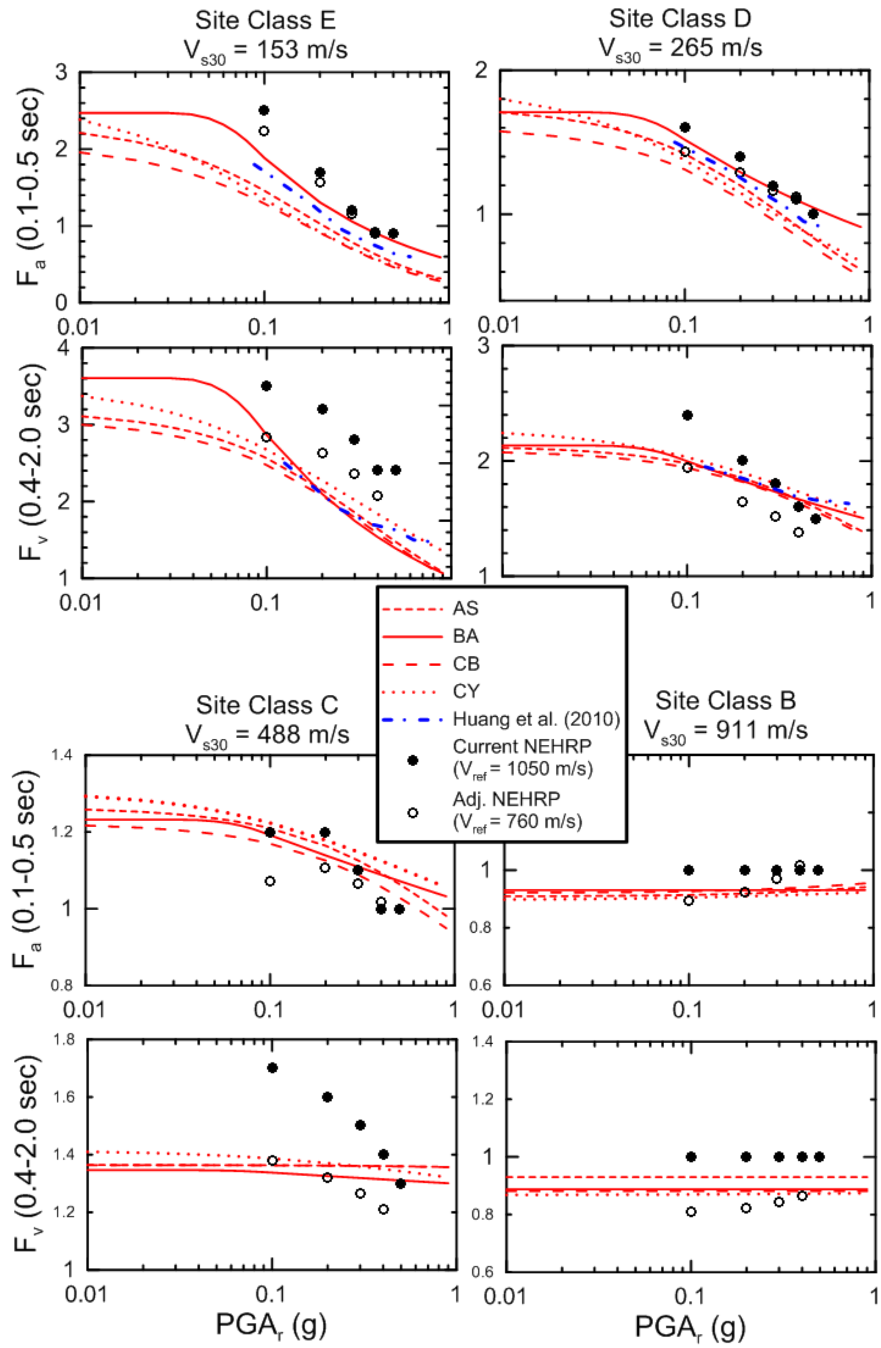

FIG. 8. Comparison of original and adjusted NEHRP site factors to site factors from NGA relationships averaged across corresponding period ranges (0.1-0.5 sec for F_a; 0.4-2.0 sec for F_v) and to those from Huang et al. (2010) (Classes D and E only).

As mentioned previously, adjusted NEHRP factors are also shown in Figure 8. The adjustment is computed to re-normalize the NEHRP factors from a reference velocity of 1050 m/s to 760 m/s as follows:

$$F_a^N = F_a \left(\frac{V_{ref}}{760} \right)^{-m_a} \quad (10a)$$

$$F_v^N = F_v \left(\frac{V_{ref}}{760} \right)^{-m_v} \quad (10a)$$

where superscript '*N*' indicates re-normalization, F_a and F_v are the original, published NEHRP factors, V_{ref} = 1050 m/s per Borcherdt (1994b) and Dobry et al. (2000), and m_a and m_v are taken from Borcherdt (1994b) and Dobry et al. (2000) (shown in Figure 4). No adjustments are made at PGA_r = 0.5g due to a lack of published m_a and m_v values in Figure 4.

Shown with the open black symbols in Figure 8, the re-normalized NEHRP site factors are generally in better agreement with NGA site factors. The re-normalization essentially removes most of the misfit for Class D; significant misfits for other classes remain but are generally reduced. We wish to emphasize that the 'adjusted' NEHRP factors in Figure 8 are not being proposed for adoption in NEHRP, but are merely presented to demonstrate the reduction in site factors discrepancies that is possible through the use of a consistent reference rock condition (i.e. V_{s30}=760 m/s).

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 9 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 153 m/s, 265 m/s, 488 m/s, and 911 m/s, correspond to categories E, D, C and B, respectively.

The results in Figure 9 indicate consistent slopes of the F_a and F_v vs 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 BG (1994) 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 largely due to the 1050 m/s reference condition in the NEHRP factors. For larger PGA_r values, significant differences in site factors occur for V_{s30} < ~500 m/s, which encompasses conditions at most soil sites. Those differences arise principally from different levels of nonlinearity, which is addressed further in the following section.

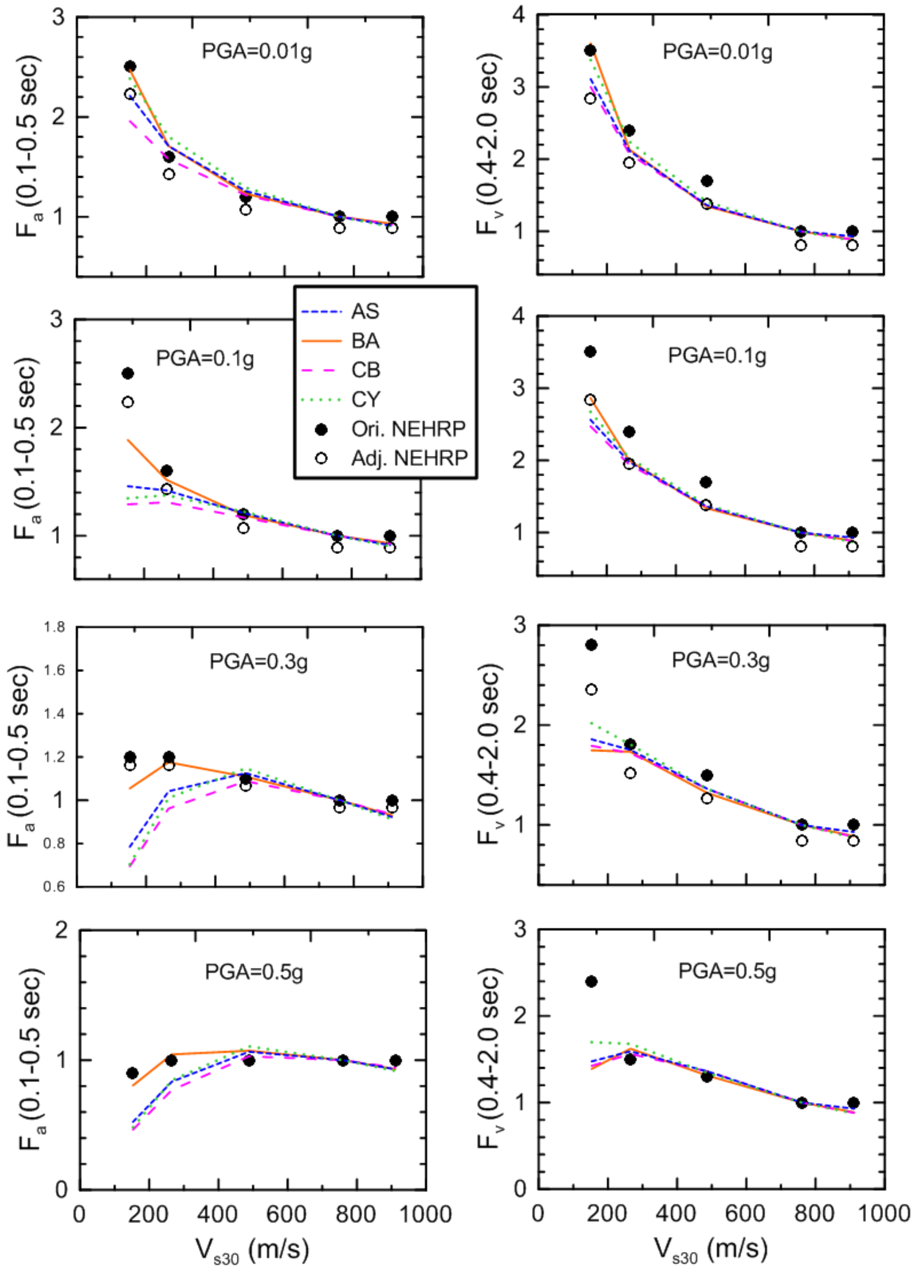

FIG. 9. Variation of site amplification with V_{s30}.

Evaluation of Nonlinearity in Simulation-Based Site Factors

Figure 10 compares the results of analytical studies presented by Dobry et al. (2000) (Fig. 4) with the site factors derived from more comprehensive equivalent-linear analyses by Walling et al. (2008), in which the "Peninsular Range" modulus reduction and damping (MRD) curves (i.e. PEN model) were used. Results are shown for 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 Walling et al. (2008) and Dobry et al. (2000) relations (not necessarily the vertical position of the curves). For instance, whereas the slopes for V_{s30} = 270 m/s are similar, the slopes for faster velocities are flatter in the more recent work.

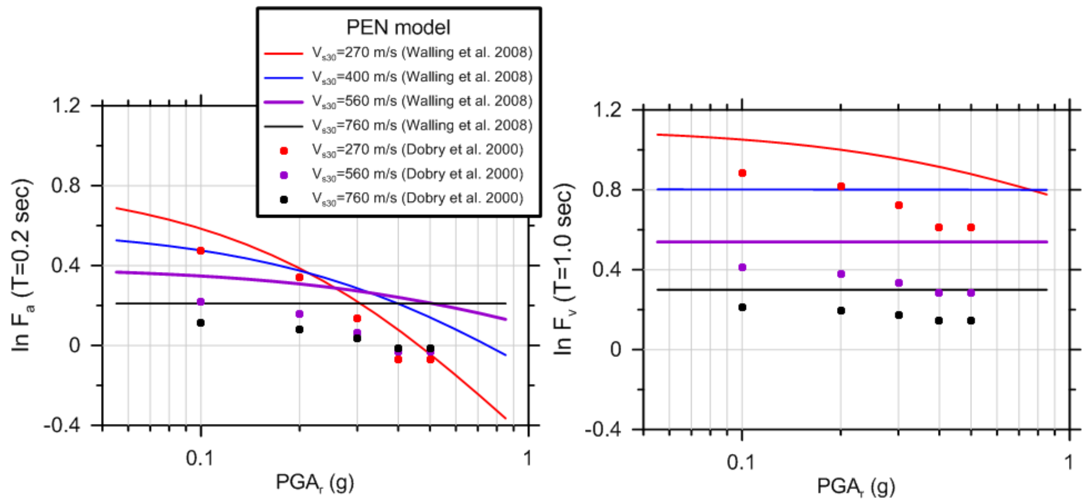

FIG. 10. Comparison of short-period F_a (0.2 sec) and mid-period F_v (1.0 sec) amplification factors between Dobry et al. (2000) and Walling et al. (2008) (PEN model). Results show flatter nonlinear relationship in the Walling et al. model for V_{s30} > 270 m/s.

Figure 11 illustrates the same type of comparison, but the results derived from the PEN model by Walling et al. (2008) 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/s; the Walling slopes are flatter for faster velocities.

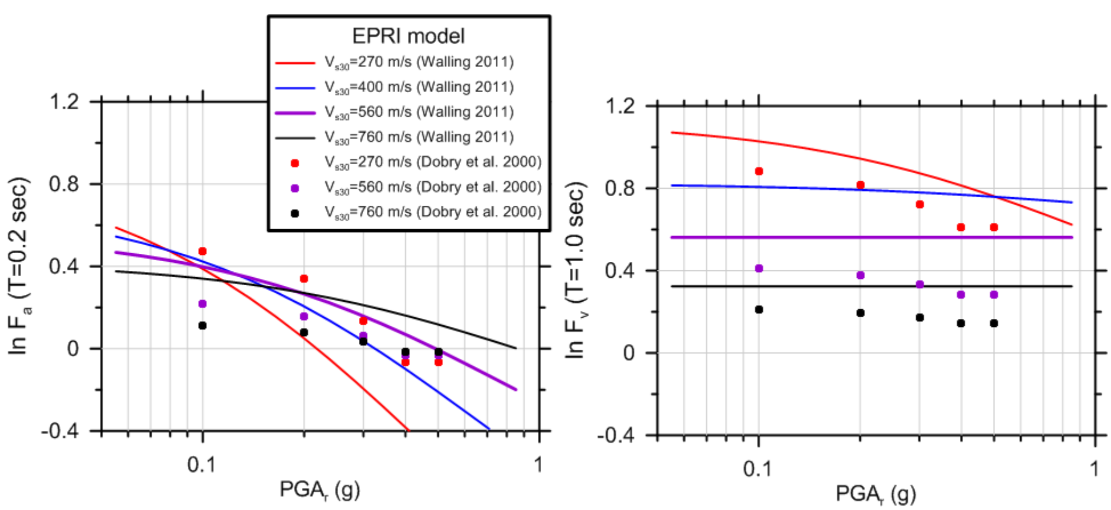

FIG. 11. Comparison of short-period F_a (0.2 sec) and mid-period F_v (1.0 sec) amplification factors between Dobry et al. (2000) and Walling (personal communication, 2011) (EPRI model).

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 12 compares the PEN curves from Walling et al. (2008) 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.

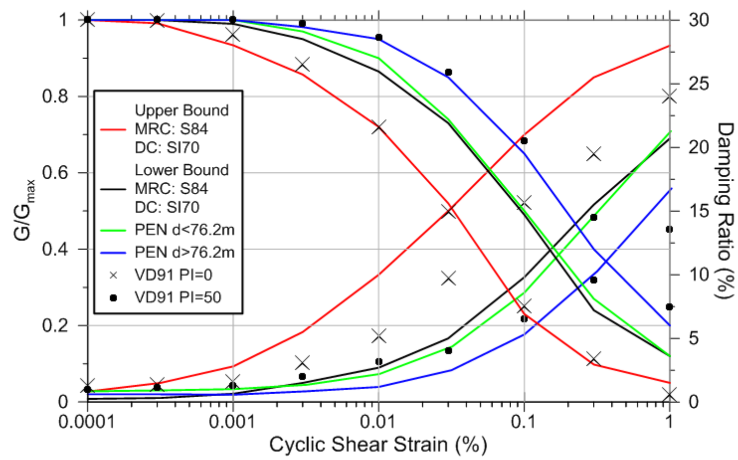

FIG. 12. Comparison of modulus reduction and damping curves from Dobry et al. (1994), Seed et al. (1984) and Walling et al. (2008) (PEN model). S84 = Seed et al. (1984), SI70 = Seed and Idriss (1970) and VS91 = Vucetic and Dobry (1991).

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 Walling et al. (2008) 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 Walling et al. (2008). Residuals were calculated in a manner similar to Eqn. (7), but with the rock GMPE median modified with the theoretical site factor and event term η. An example result is shown in Figure 13, which shows no trend in residuals vs 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 Walling et al. (2008) and used in several of the NGA site terms.

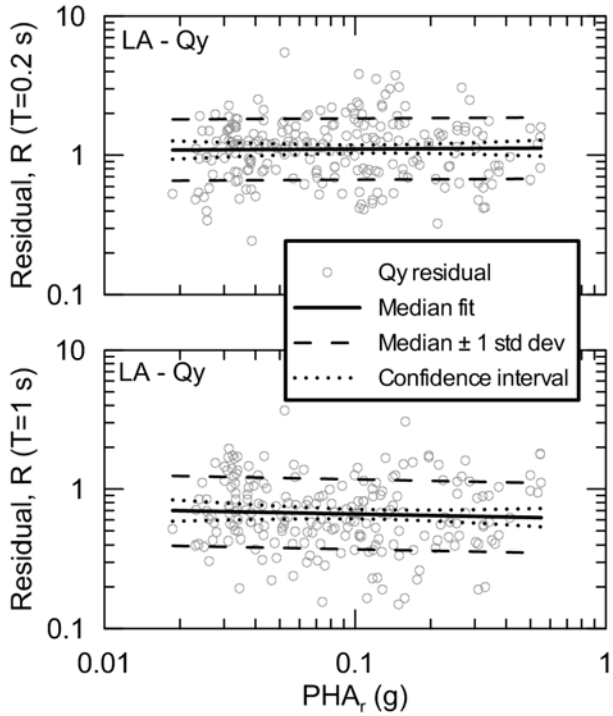

FIG. 13. Trend of residuals with PHA$_r$. From Kwok and Stewart (2006).

CONCLUSIONS

NGA and NEHRP site factor 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≤0.1 g) 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/s, whereas their current application is relative to V_{s30} = 760 m/s. When re-normalized to V_{s30} = 760 m/s, 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 (Walling et al, 2008) 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.

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