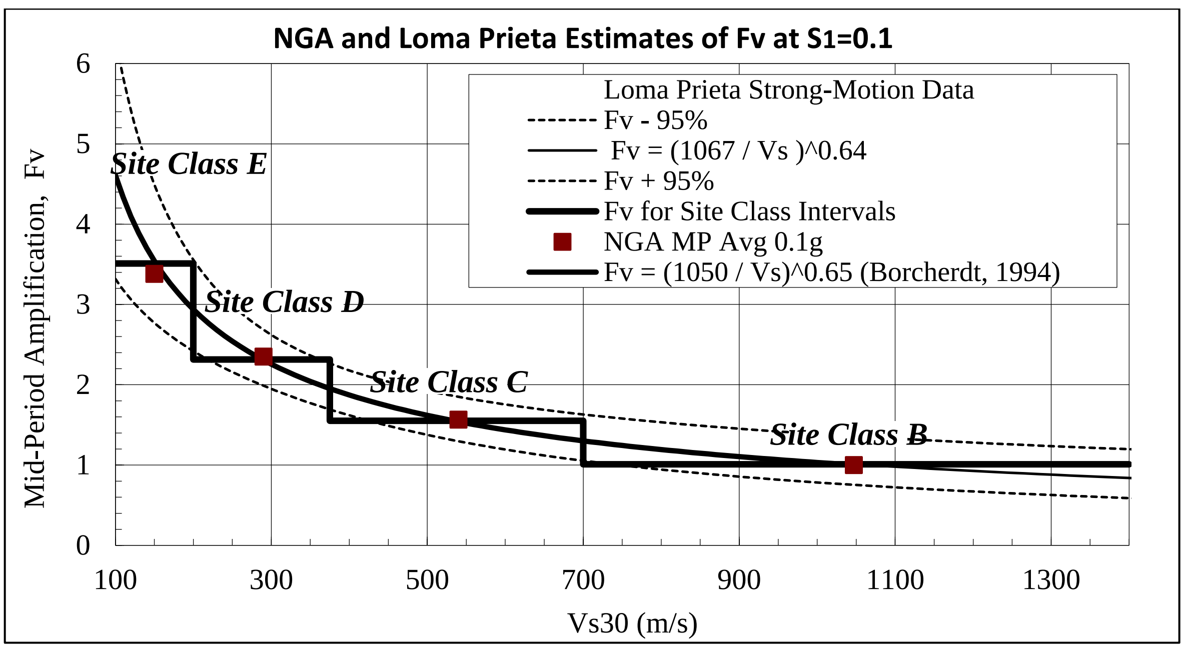
Implications of NGA for NEHRP Site Coefficients

By Roger D. Borcherdt



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Implications of NGA for NEHRP Site Coefficients

Roger D. Borcherdt

ABSTRACT

Three proposals are provided to update tables 11.4–1 and 11.4–2 of Minimum Design Loads for Buildings and Other Structures (7-10), by the American Society of Civil Engineers (2010) (ASCE/SEI 7–10), with site coefficients implied directly by NGA (Next Generation Attenuation) ground motion prediction equations (GMPEs). Proposals include a recommendation to use straight-line interpolation to infer site coefficients at intermediate values of $\bar{v}_S$ (average shear velocity).

Site coefficients are recommended to ensure consistency with ASCE/SEI 7-10 MCE_R (Maximum Considered Earthquake) seismic-design maps and simplified site-specific design spectra procedures requiring site classes with associated tabulated site coefficients and a reference site class with unity site coefficients. Recommended site coefficients are confirmed by independent observations of average site amplification coefficients inferred with respect to an average ground condition consistent with that used for the MCE_R maps. The NGA coefficients recommended for consideration are implied directly by the NGA GMPEs and do not require introduction of additional models.

INTRODUCTION

The proposals provided here are based on NGA (Next Generation Attenuation) site coefficients provided by each NGA developer as part of a comprehensive review of the implications of NGA for site coefficients as specified in Tables 11.4-1 and 11.4-2 of Minimum Design Loads for Buildings and Other Structures (7–10), by the American Society of Civil Engineers (2010) (ASCE/SEI 7–10). That review (Task Committee 8, NGA West 2) was coordinated by the Pacific Earthquake Engineering Research Center (PEER) as part of a larger initiative to improve the NGA GMPEs capabilities for earthquake-resistant design (Bozorgnia, 2010). Analysis and review of the NGA data for Task 8 was conducted by Stewart and Seyhan (2012) with review meetings of the Steering Committees organized under the auspices of PEER (Pacific Earthquake Engineering Research Center). The results reported here were derived from spreadsheets summarizing NGA results as reported by each NGA developer and provided by Stewart and Seyhan (written commun, 2011).

BACKGROUND FOR PROPOSALS

The current procedure adopted in ASCE/SEI 7-10 for estimation of site-specific design spectra uses a simplified procedure to account for site conditions. The simplified procedure is based on the concept of six site classes with an associated set of discrete tabulated site coefficients for five of the classes (Tables 11.4-1 and 11.4-2). The simplified procedure implies that a reference site class be chosen such that the amplification factor for the reference site class is unity and those for the other classes specified with respect to that for the reference site class. For consistency, the uniform ground condition chosen to specify the input ground motion level should be the same as that of the reference site class.

In addition, the simplified procedure as implemented with site classes implies that the tabulated set of site coefficients represent the average amplification across the entire site class. For consistency with the definition of the site classes in terms of $\bar{v}_S$ intervals and amplification factors expressed as a function of $\bar{v}_S$, the simplified procedure implies that the short- and mid-period site coefficients, F_a and F_v, represent the amplification at the mid-point of each site class interval. In addition, the simplified procedure uses MCE_R maps (Maximum Considered Earthquake ground-motion Response maps) prepared by the U.S. Geological Survey (2010) to estimate the input ground-motion level for a uniform ground condition specified by $\bar{v}_S = 760\, m/s$. Sites with $\bar{v}_S = 760\, m/s$ are classified as site-class B sites, which implies that the reference site class is site class B and the associated site coefficients for site class B must be unity in order to maintain consistency with the MCE_R maps.

The proposals included herein provide a set of coefficients consistent with the simplified procedure adopted in ASCE/SEI 7-10 and consistent with those as initially adopted in the 1994 edition of the NEHRP Recommended Seismic Provisions for New Buildings (1994). The proposed coefficients provide average amplification factors at the $\bar{v}_S$ mid-point for each site class referenced to the corresponding $\bar{v}_S$ midpoint for the reference site class B. This procedure previously reviewed and adopted in numerous versions of the codes provides unity amplification factors for the reference site class B, and hence unity amplification factors for the uniform ground condition specified in the MCE_R design maps. This procedure provides site coefficients consistent with those inferred from strong motion data for the Loma Prieta earthquake (Seed, 1992; Seed et al., 1994; Borcherdt, 1992, 1994; Joyner et al., 1992, 1994; Dobry et al, 1992, 1994).

The proposals recommend that if site coefficients are desired as a continuous function of site conditions ($\bar{v}_S$) as opposed to discrete values as specified for the five site classes, then the site coefficients should be inferred by straight-line interpolation using the site coefficients as specified at the mid-point of each site class interval. This procedure yields results that agree with site coefficients adopted in Tables 11.4-1 and 11.4-2 and those proposed herein.

Three proposals for adjustments to Tables 11.4.-1 and 11.4-2 are provided for consideration. The first proposal suggests minimal changes based on adjusting only those site coefficients that exceed the 95% confidence limits for the NGA predictions. The second proposal replaces each coefficient with the corresponding mean NGA value for site classes C and D. The third proposal replaces each coefficient with the corresponding mean NGA value for site classes C, D, and E. No changes are proposed for the reference site class B or for site class A.

PROPOSAL I

Proposal I provides changes as shown in parenthesis for those F_a and F_v coefficients exceeding 95% NGA confidence limits with the exception to that for site class E for Ss <0.25 (see Figures 5, 6, and 7). The proposed changes are the mean NGA value.

Table 1a) Proposal I changes to Table 11.4-1 ASCE/SEI 7-10.

Table 11.4-1 Site Coefficient, F_a

Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at Short Period

Site Class	$S_s < 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	(1.37) 1.2	(1.33) 1.2	(1.31) 1.1	(1.29) 1.0	(1.27) 1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	see Section 11.4.7				

Notes: 1) Use straight-line interpolation for intermediate values of S_S.
2) Use straight-line interpolation for intermediate values of $\overline{v}_S$ using site class mid-point value for $\overline{v}_S$ from chapter 20.

Table 1b) Proposal I changes to Table 11.4-2 ASCE/SEI 7-10.

Table 11.4-2 Site Coefficient, F_v

Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at 1-s Period

Site Class	$S_1 < 0.1$	$S_l = 0.20$	$S_l = 0.30$	$S_l = 0.40$	$S_l \geq 0.50$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	(1.48) 1.3
D	(2.35) 2.4	(2.25) 2.0	(2.19) 1.8	(2.14) 1.6	(1.97) 1.5
E	3.5	3.2	2.8	2.4	2.4
F	see Section 11.4.7				

Notes: 1) Use straight-line interpolation for intermediate values of S_1.
2) Use straight-line interpolation for intermediate values of $\overline{v}_S$ using site class mid-point value for $\overline{v}_S$ from chapter 20.

PROPOSAL II

Proposal II provides changes for site class C and D coefficients with corresponding mean NGA values. A large epistemic uncertainty in the NGA results and a limited amount of data for site class E suggests that until these uncertainties are better resolved, changes to only the site coefficients for site classes C and D may be warranted.

Table 2a) Proposal II changes to Table 11.4-1 ASCE/SEI 7-10.

Table 11.4-1 Site Coefficient, F_a

Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at Short Period

Site Class	$S_s < 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	(1.37) 1.2	(1.33) 1.2	(1.31) 1.1	(1.29) 1.0	(1.27) 1.0
D	(1.68) 1.6	(1.47) 1.4	(1.34) 1.2	(1.24) 1.1	(1.16) 1.0
E	2.5	1.7	1.2	0.9	0.9
F	see Section 11.4.7				

Notes: 1) Use straight-line interpolation for intermediate values of S_S.
2) Use straight-line interpolation for intermediate values of $\overline{v}_S$ using site class mid-point value for $\overline{v}_S$ from chapter 20.

Table 2b) Proposal II changes to Table 11.4-2 ASCE/SEI 7-10.

Table 11.4-2 Site Coefficient, F_v

Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at 1-s Period

Site Class	$S_1 < 0.1$	$S_l = 0.20$	$S_l = 0.30$	$S_l = 0.40$	$S_l \geq 0.50$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	(1.57) 1.7	(1.56) 1.6	(1.56) 1.5	(1.55) 1.4	(1.48) 1.3
D	(2.35) 2.4	(2.25) 2.0	(2.19) 1.8	(2.14) 1.6	(1.97) 1.5
E	3.5	3.2	2.8	2.4	2.4
F	see Section 11.4.7				

Notes: 1) Use straight-line interpolation for intermediate values of S_1.
2) Use straight-line interpolation for intermediate values of $\overline{v}_S$ using site class mid-point value for $\overline{v}_S$ from chapter 20.

PROPOSAL III

This proposal provides options for changes in the site coefficients for site classes C, D, and E with corresponding mean NGA values. However, a large epistemic uncertainty in the NGA results and a limited amount of data for site class E suggests that until these uncertainties are better resolved, revision of only the site coefficients for site classes C and D may be warranted (see Proposal II)..

Table 3a Potential NGA changes to Table 11.4-1 ASCE/SEI 7-10.

Table 11.4-1 Site Coefficient, F_a

Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at Short Period

Site Class	$S_s < 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	(1.37) 1.2	(1.33) 1.2	(1.31) 1.1	(1.29) 1.0	(1.27) 1.0
D	(1.68) 1.6	(1.47) 1.4	(1.34) 1.2	(1.24) 1.1	(1.16) 1.0
E	(1.87) 2.5	(1.31) 1.7	(1.02) 1.2	(0.84) 0.9	(0.72) 0.9
F	see Section 11.4.7				

Notes: 1) Use straight-line interpolation for intermediate values of S_S.
2) Use straight-line interpolation for intermediate values of $\overline{v}_S$ using site class mid-point value for $\overline{v}_S$ from chapter 20.

Table 3b Potential NGA changes to Table 11.4-2 ASCE/SEI 7-10.

Table 11.4-2 Site Coefficient, F_v

Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at 1-s Period

Site Class	$S_1 < 0.1$	$S_l = 0.20$	$S_l = 0.30$	$S_l = 0.40$	$S_l \geq 0.50$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	(1.57) 1.7	(1.56) 1.6	(1.56) 1.5	(1.55) 1.4	(1.48) 1.3
D	(2.35) 2.4	(2.25) 2.0	(2.19) 1.8	(2.14) 1.6	(1.97) 1.5
E	(3.38) 3.5	(2.83) 3.2	(2.52) 2.8	(2.31) 2.4	(2.08) 2.4
F	see Section 11.4.7				

Notes: 1) Use straight-line interpolation for intermediate values of S_1.
2) Use straight-line interpolation for intermediate values of $\overline{v}_S$ using site class mid-point value for $\overline{v}_S$ from chapter 20.

JUSTIFICATION

The results reported herein were derived from spreadsheets summarizing NGA results provided by each NGA developer and compiled by Stewart and Seyhan (written commun. 2011). (Most of the results presented herein have been previously presented at Task Committee 8 meetings.)

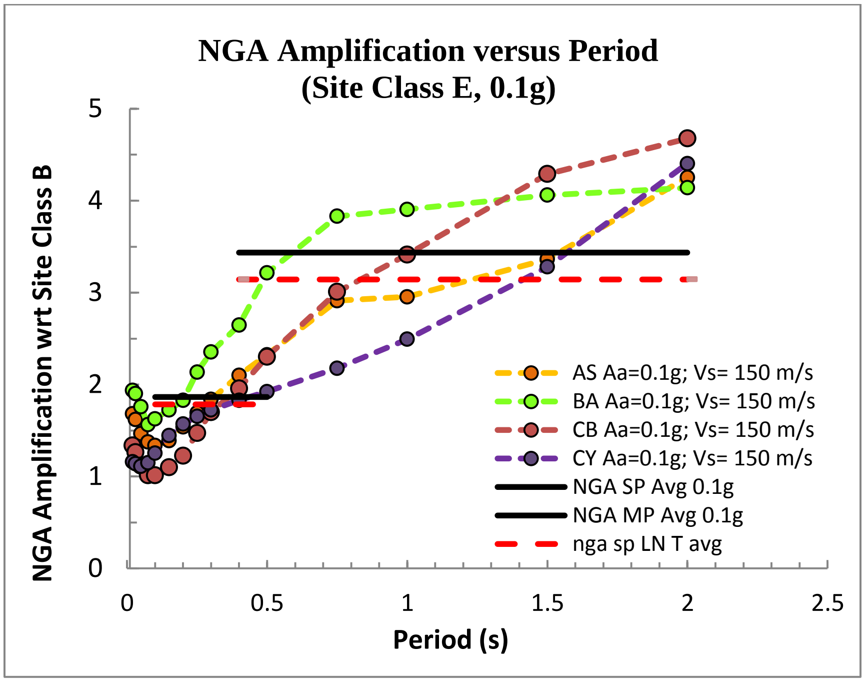
Amplification values were provided by the four developers, Abrahamson and Silva (2008; referred to as AS), Boore and Atkinson (2008; BA), Campbell and Bozorgnia (2008; CB), and Chiou and Youngs (2008; CY)) as a function of period and ground motion level as referenced to 1100 m/s (AS, CB), 1130 m/s (CY), and 760 m/s (BA). The spreadsheets compiled from these values were provided by Stewart and Seyhan (written commun. 2011). In order to maintain consistency with the simplified procedure, that requires site classes and an associated discrete set of site coefficients, all of the amplification factors were normalized to the mid-point $\bar{v}_S$ value for reference site class B. Average short- and mid-period band site coefficients were computed from the NGA factors using equally spaced values of period. ($\bar{v}_S$ is defined as in ASCE/SEI 7-10 chapter 20 as the average shear velocity to a depth of 30 m, which is equivalent to the ratio of 30 m to the travel time for a wave to travel from the surface to a depth of 30 m. $\bar{v}_S$ also is referred to as $v_{S\,30}$ and v_S.)

NGA AMPLIFICATION AS A FUNCTION OF PERIOD

Plots of the NGA amplification factors inferred as a function of period are shown in Figures 1, 2, and 3 for site classes E, D, and C with input ground-motion levels of 0.1g and 0.4g. The plots show the dependence of amplification as a function of period as inferred by each developer for each site class. They also illustrate the epistemic or model uncertainty associated with the four NGA models. They show that the amplification factors for site Class E first decrease with period for periods less than about 0.1 s, then show a well-defined increase with period. The rate of this increase with period decreases for periods greater than about 0.75 s for site class D and about 0.5 s for site class C. The plots show that variation in estimates of amplification for each of the NGA developers increase with period with the largest variations occurring for periods greater than about 0.5 s.

Figures 1, 2, and 3 also show average amplification factors inferred for the short- and mid-period bands from amplification values at equally spaced intervals. In addition, Figure 1 shows average amplification factors inferred using amplification values derived at equally spaced logarithmic periods used by Stewart and Seyhan (2012). Figure 4 shows a comparison of average short- and mid-period amplification factors computed using the equal and logarithmic spacing in period for site class E as a function of PGA. The comparisons (Figs. 1 and 4) show that the averages computed using the two spacings in period differ significantly for the mid-period amplification values.

The average amplification factors computed with logarithmic spacing are biased to smaller values, because more values of amplification at short periods are included in each average than at the longer periods. This unequal spacing in period causes the resultant NGA averages to be biased toward smaller values. This effect is most pronounced for the averages computed for site class E (Fig.4), but also apparent for site classes D and C (not shown). The bias toward smaller values is most apparent for the mid-period amplification factor, where it increases with increasing PGA values. The bias impacts conclusions regarding the comparison of NEHRP and NGA values (e.g. compare Fig 3.3, Stewart and Seyhan, 2012 with Figs. 5-12 herein). The bias incorrectly implies an increase in nonlinearity (see Fig. 4b). It biases the comparison between NGA and NEHRP low



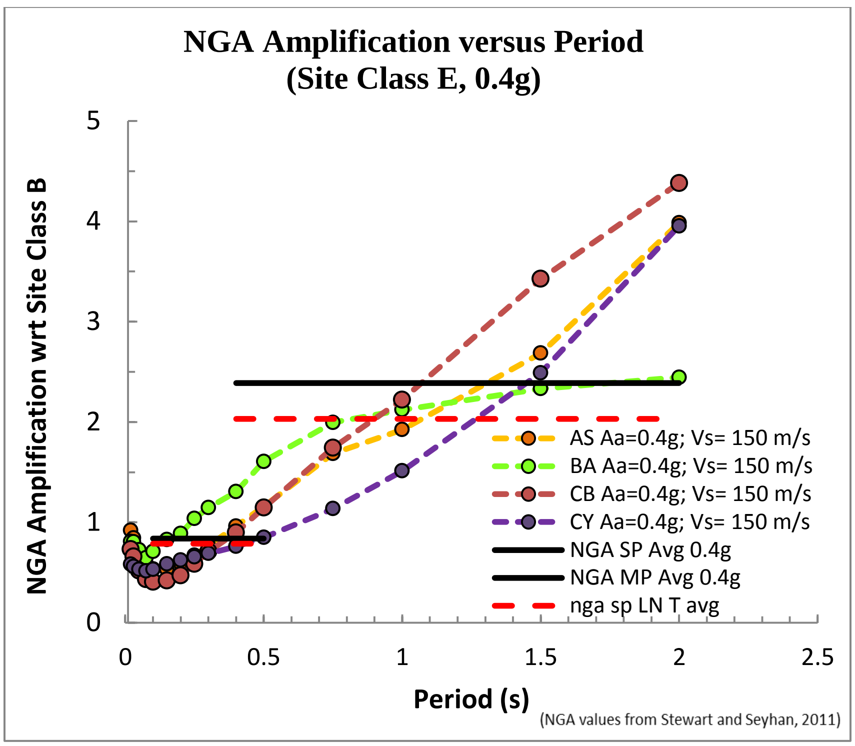
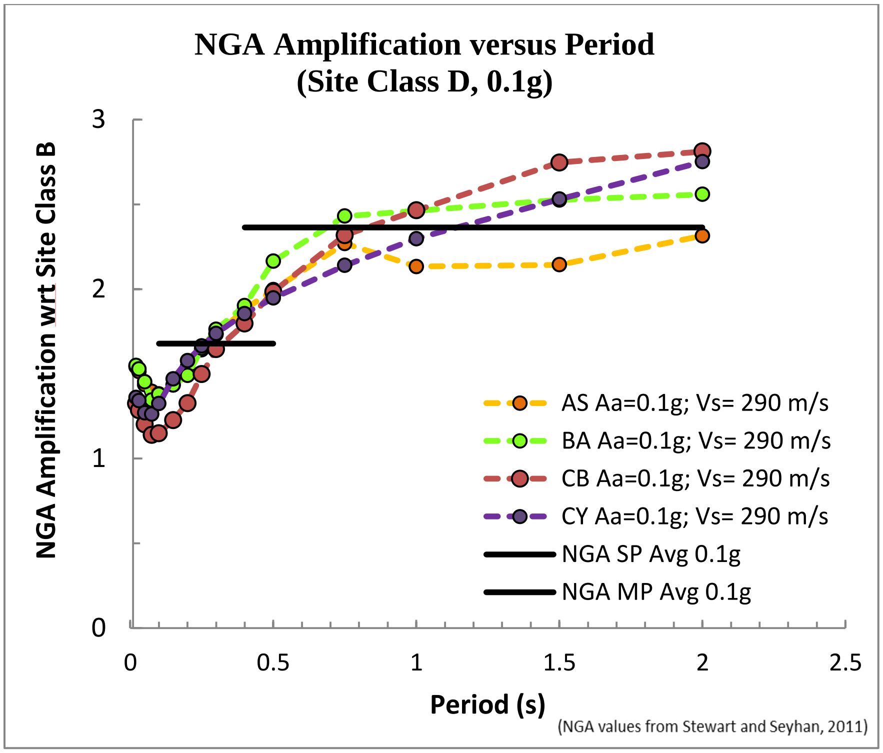


Figure 1. NGA amplification for site class E with respect to mid-point of site class B $\overline{v}_S$ interval versus period for 0.1g (Fig. 1a) and 0.4g (Fig. 1b). Short-period (0.1-0.5 s) and mid-period (0.4-2.0 s) averages inferred from equally-spaced period values (solid black lines) and logarithm-spaced period values (dashed red lines) are shown. The plots show that the logarithm-spaced values (Stewart and Seyhan, 2012) are biased to significantly smaller values for the average mid-period amplification for site class E.



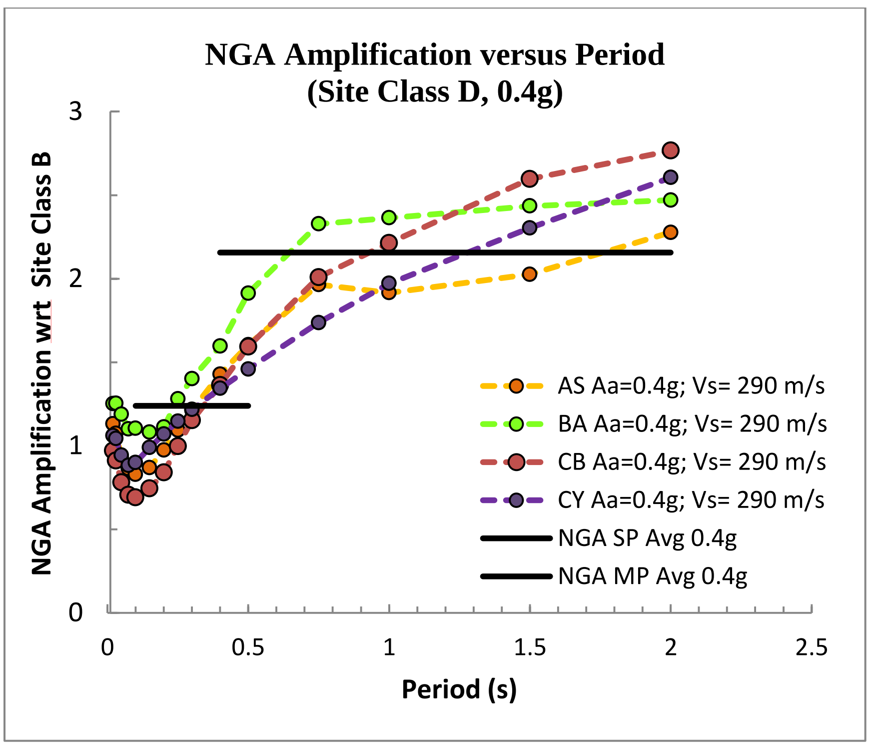
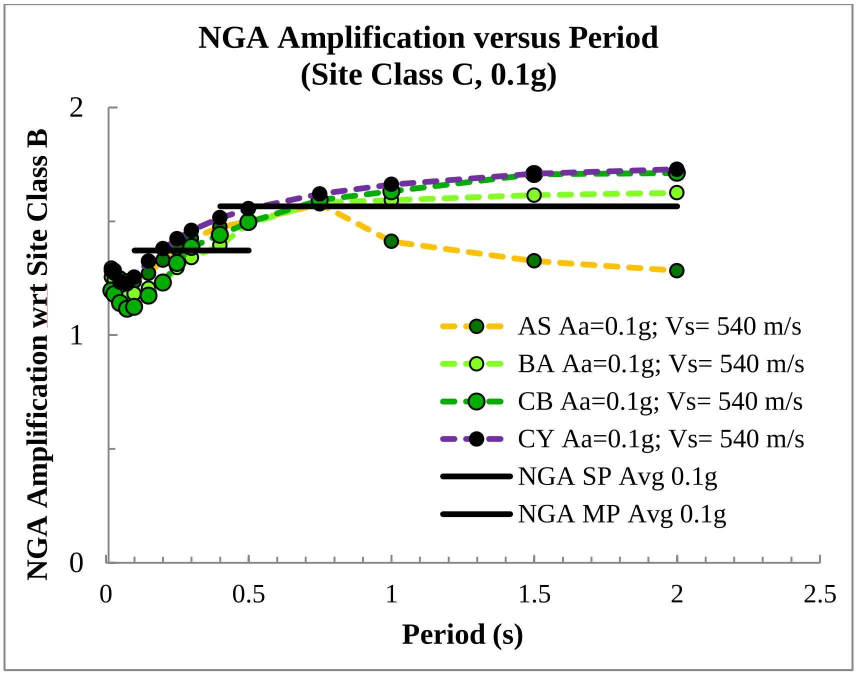


Figure 2. NGA amplification for site class D with respect to mid-point of site class B $\bar{v}_S$ interval versus period for 0.1g (Fig. 2a) and 0.4g (Fig. 2b). Short-period (0.1-0.5 s) and mid-period (0.4-2.0 s) averages inferred from equally-spaced period values (solid black lines) are shown.



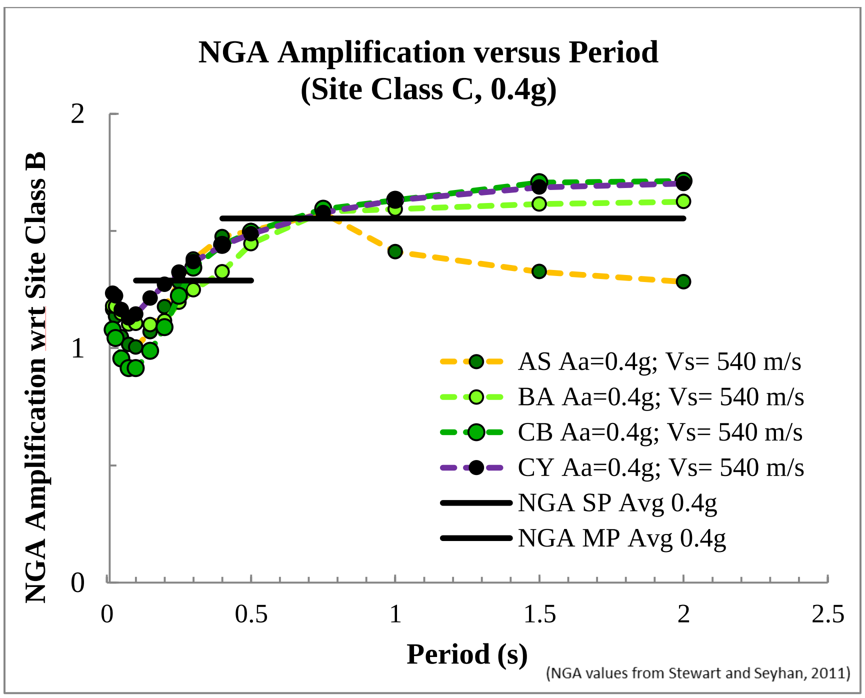
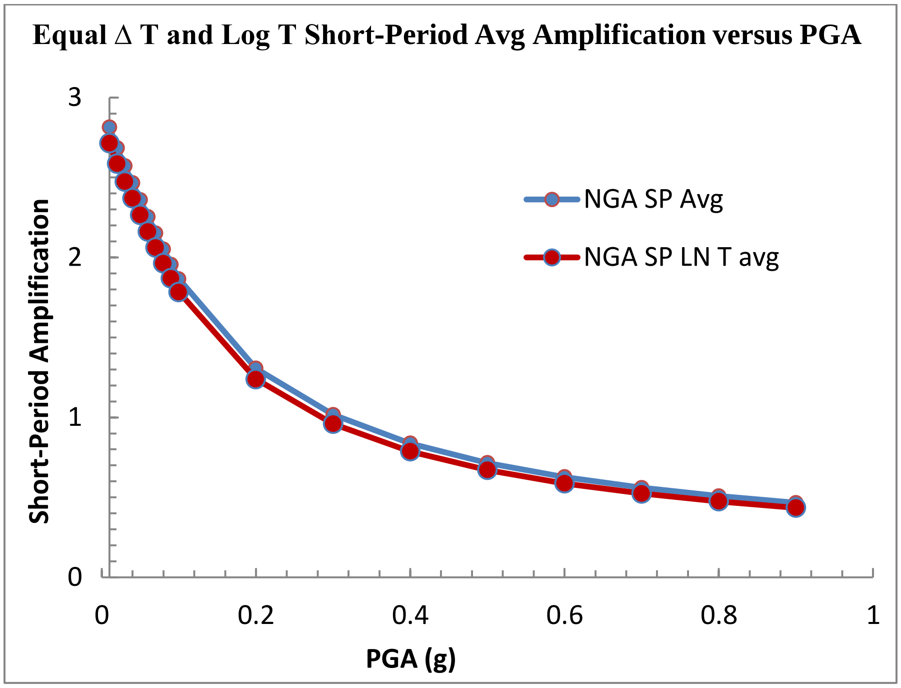


Figure 3. NGA amplification for site class C with respect to mid-point of site class B $\overline{v}_S$ interval versus period for 0.1g (Fig. 3a) and 0.4g (Fig. 3b). Short-period (0.1-0.5 s) and mid-period (0.4-2.0 s) averages inferred from equally-spaced period values (solid black lines) are shown.



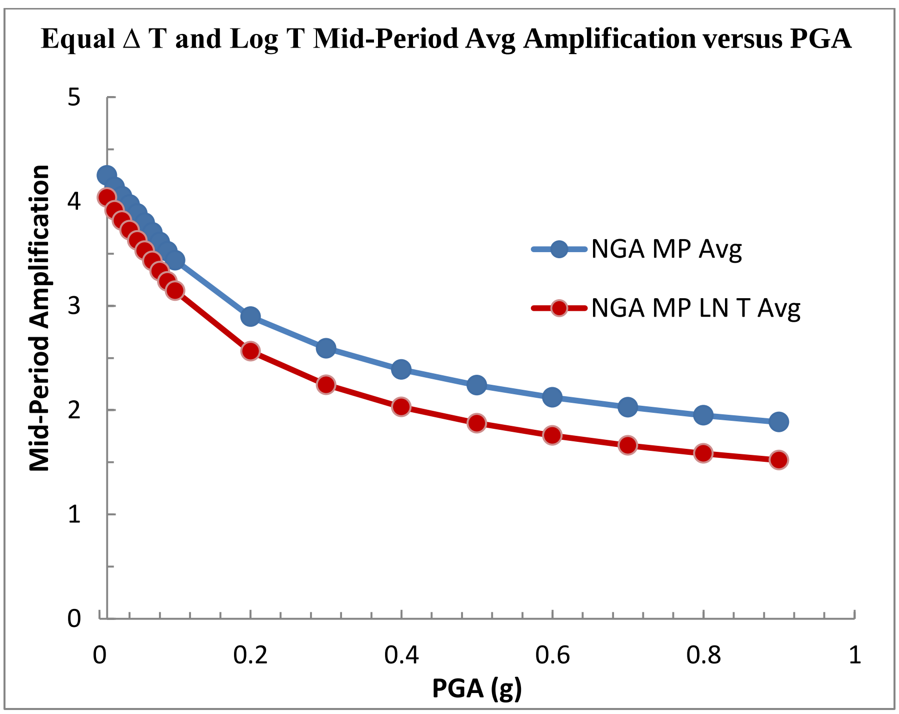


Figure 4. NGA short-period (Fig. 4a) and mid-period average amplification (Fig . 4b) values for site class E inferred from equally-spaced period values (solid blue lines) and those inferred from logarithmic spaced period values (solid red lines) inferred as a function of PGA. The plots show that the logarithm-spaced values (Stewart and Seyhan, 2012) are biased to significantly smaller values, especially for the average mid-period amplification factor.

strain coefficients and, in turn, biases recommendations regarding implications of NGA for proposed changes in ASCE/SEI 7-10 site coefficients (see Stewart and Seyhan, 2012).

COMPARISON OF NGA AND NEHRP AMPLIFICATION FACTORS

Figures 5, 6, and 7 show plots of the short- and mid-period amplification factors as a function of PGA for each site class. Superimposed on each plot are mean values and mean $\pm$ 2 standard deviation (S.D.) values inferred from the sample comprised of the four NGA estimates. For comparison, the NEHRP site coefficients also are plotted. Comparison of the NGA and NEHRP estimates as a function of input ground shaking level (Figs. 5, 6, and 7) show that the majority of the NEHRP values are within the 95 % uncertainty limits implied by the NGA estimates with exceptions as noted:

> *Site Class D*: F_v is less than the NGA mid-period mean – 2 S.D. value at PGA = 0.3g, 0.4g, and 0.5g (S_1= 0.3, 0.4, and 0.5),
>
> *Site Class C*: F_a is less than the NGA mid-period mean – 2 S.D. value at 0.1-0.5g (S_S= 0.25-1.25), F_v is slightly less than the NGA mid-period mean – 2 S.D. value at 0.5g (S_1=0.5).

Proposal I (Tables 1a and 1b) suggests adjustment of Tables 11.4-1 and 11.4-2 of ASCE/SEI 7-10 to ensure that all coefficients for site classes D and C are within the 95% uncertainty limits implied by the NGA GMPEs.

Comparison of the NGA and NEHRP estimates as a function of $\overline{v}_S$ (Figs. 8, 9, 10, 11, and 12) again show that the majority of the NEHRP values are within or near the 95% uncertainty limits implied by the NGA estimates with exceptions as noted above. The plots in Figures 8-12 further emphasize that the uncertainty in the NGA estimates increases with decreasing $\overline{v}_S$ with the largest variation between NGA model predictions clearly being associated with site class E. The large uncertainty in the NGA results for site class E suggests that adjustment of these coefficients may not be warranted until additional consensus is achieved regarding GMPE models for nonlinear soil behavior.

AGREEMENT BETWEEN NGA AND OBSERVED SPECTRAL AMPLIFICATION

Recalling that the NEHRP values for PGA levels near 0.1g were inferred from strong-motion recordings of the Loma Prieta earthquake, it is of interest to compare these inferences of spectral amplification with those derived from the NGA models based on a larger set of strong motion recordings. The Loma Prieta coefficients represent a consensus derived from observed strong-motion data using; response spectra ratios (Joyner, 1992; Joyner et al., 1994; Seed 1992; Seed et al, 1994), Fourier amplitude spectra ratios (Borcherdt, 1992, 1994), and response spectra parametric studies (Dobry et al., 1992, 1994). These coefficients at PGA=0.1g were subsequently adopted in the 1994 edition of the NEHRP Recommended Seismic Provisions for New Buildings, with the exception of the value for F_a, which was increased from a value of 2.0 to 2.5 in order to better account for observed amplification effects of high plasticity clays in Mexico City. The average short- and mid-period amplification coefficients as inferred from the Loma Prieta strong-motion recordings are shown in Figure 13 (black step function). The amplification coefficients were inferred with respect to an average $\overline{v}_S = 795\, m/s$ for rock sites in the San Francisco Bay region (Borcherdt, 1992, 1994). The corresponding $\pm$ 2 S.D. limits derived from the original regression analysis also are shown (Borcherdt, 1994).

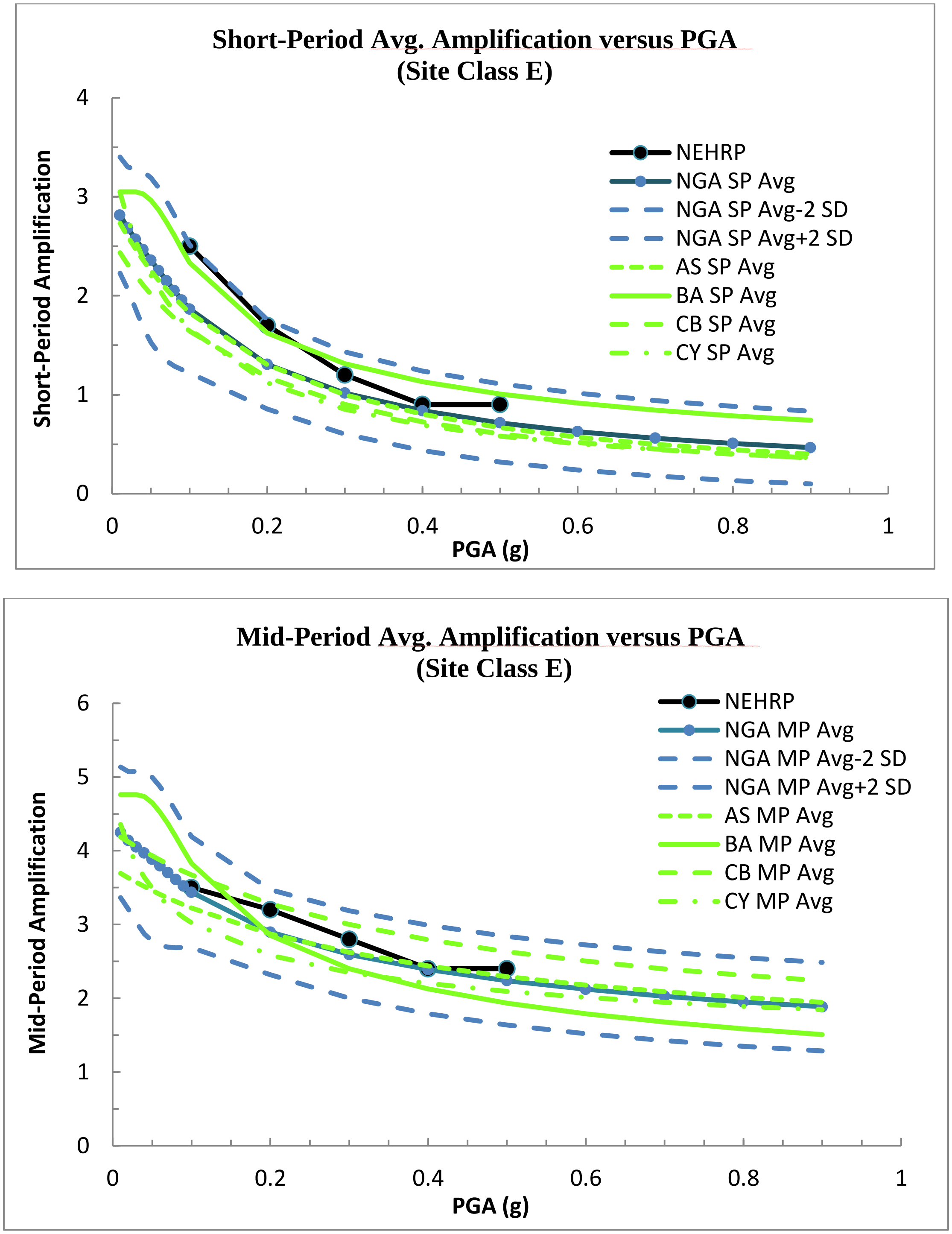
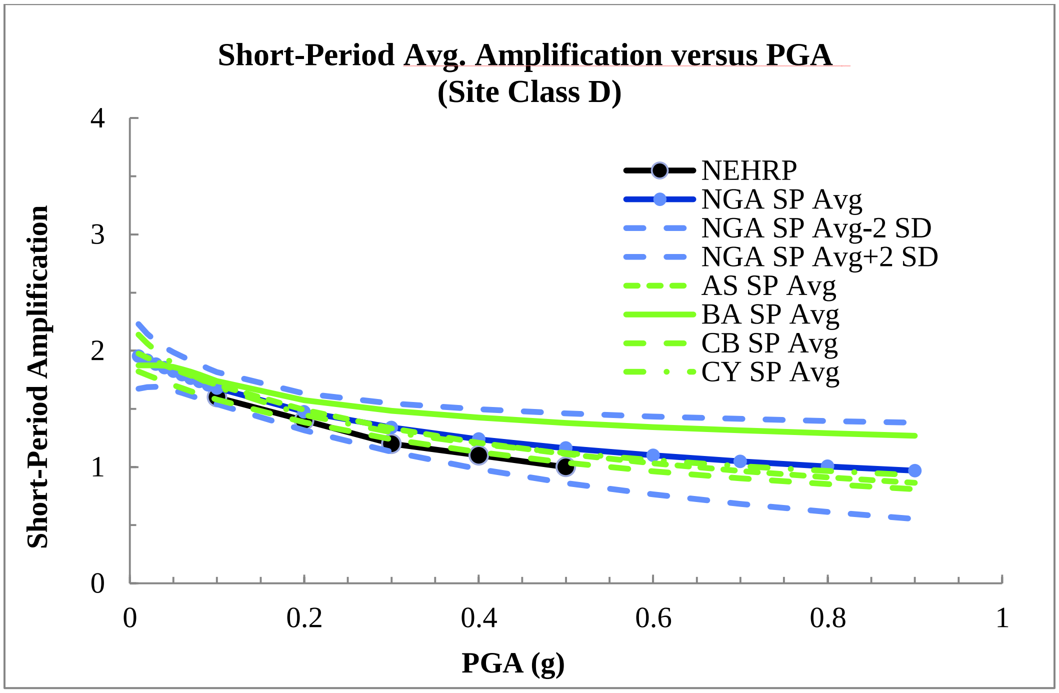


Figure 5. Short-period (Fig. 5a) and mid-period average amplification (Fig. 5b) values for site class E inferred from equally-spaced period values for each NGA developer (green lines), mean and 95% NGA limits (blue lines), and NEHRP site coefficients (black line) as a function of PGA. The plots show that the NEHRP F_a and F_v coefficients are within 95% NGA uncertainty limits for all values except for Fa at PGA=0.1g



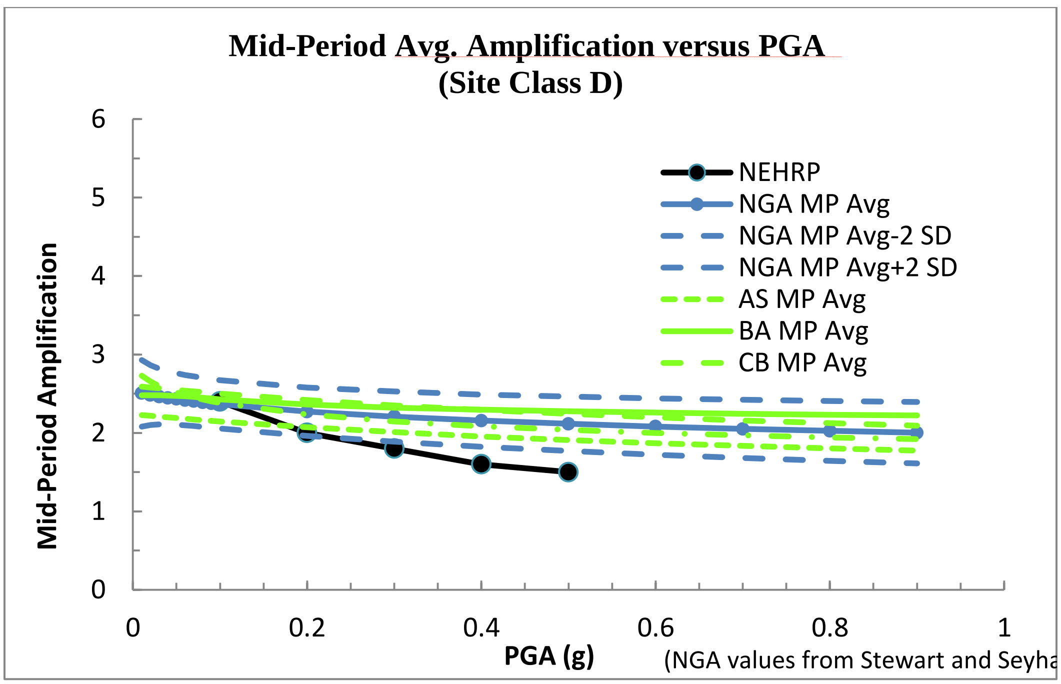
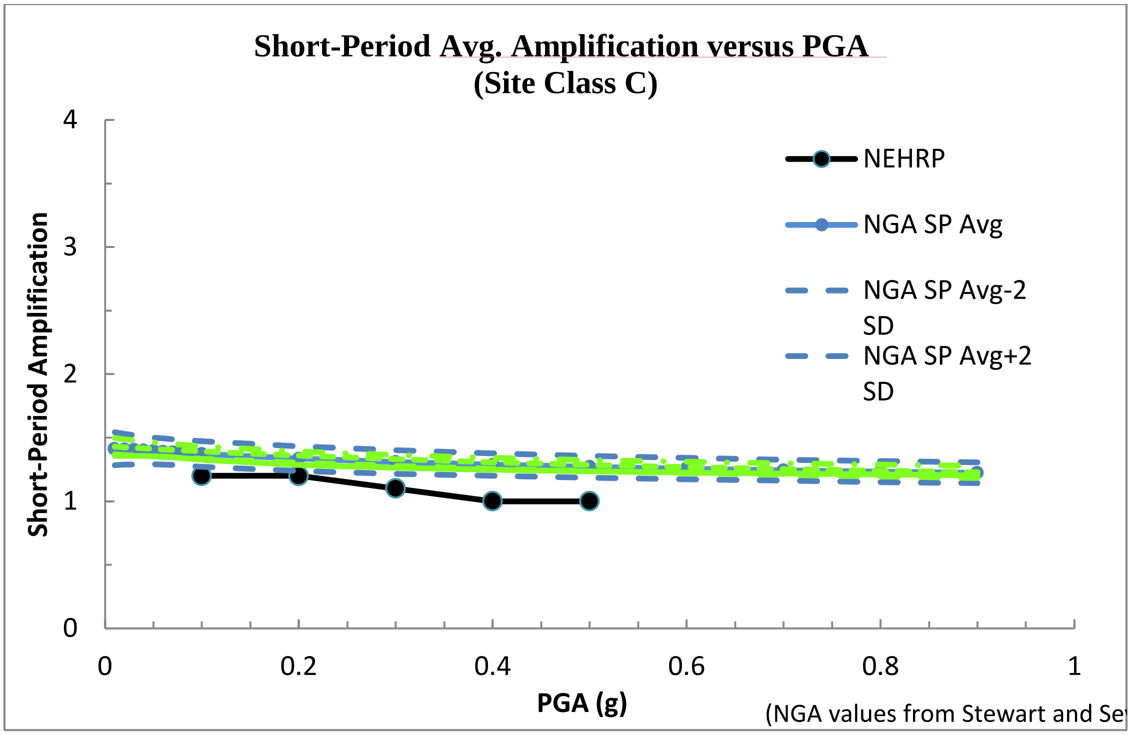


Figure 6. Short-period (Fig. 6a) and mid-period average amplification (Fig. 6b) values for site class D inferred from equally-spaced period values for each NGA developer (green lines), mean and 95% NGA limits (blue lines), and NEHRP site coefficients (black line) as a function of PGA. The plots show that the NEHRP F_a and F_v coefficients are within 95% NGA uncertainty limits for all values except Fv at PGA $\geq$ 0.3g.



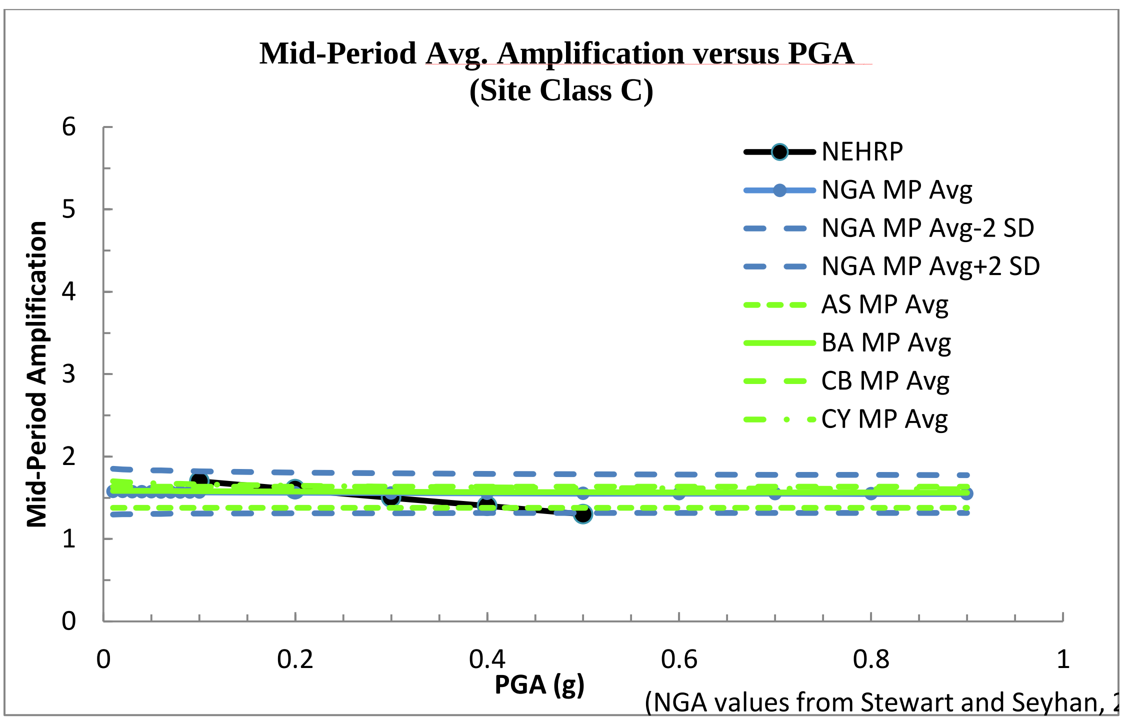
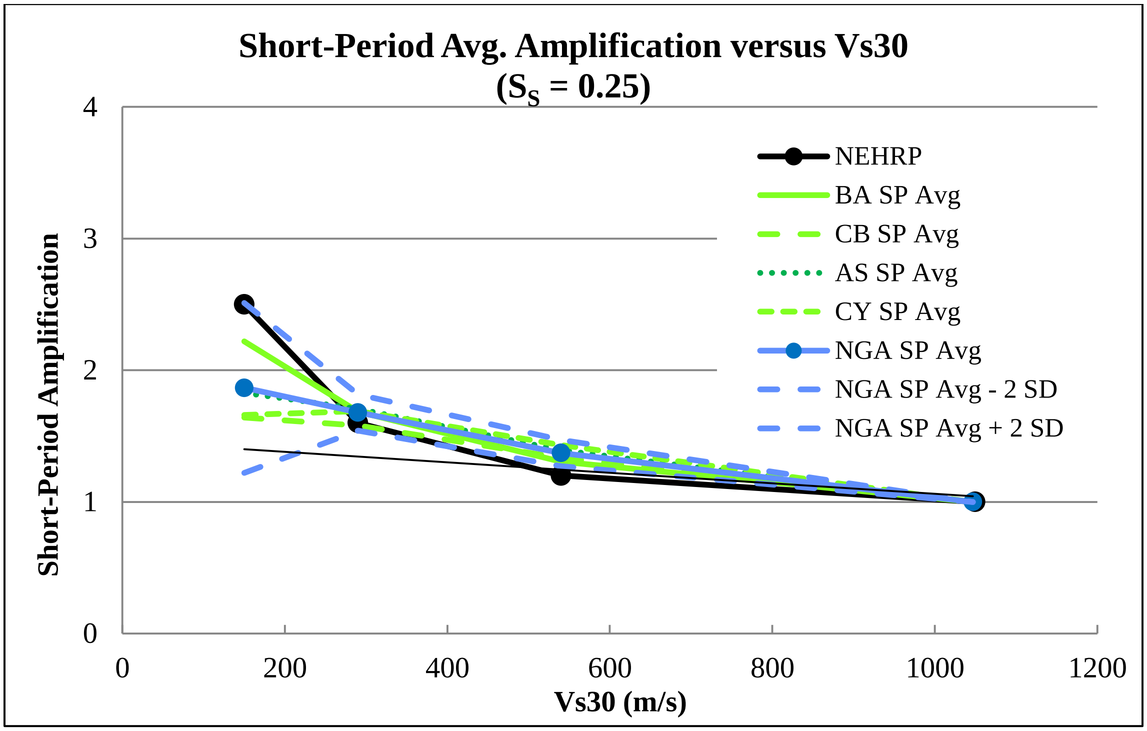


Figure 7. Short-period (Fig. 7a) and mid-period average amplification (Fig. 7b) values for site class C for each NGA developer (green lines), mean and 95% NGA limits (blue lines), and NEHRP site coefficients (black line) as a function of PGA. The plots show that the NEHRP Fa and Fv coefficients are within 95% NGA uncertainty limits for all PGA values except for Fa with PGA $\geq$ 0.1g and for Fv with PGA= 0.5g.



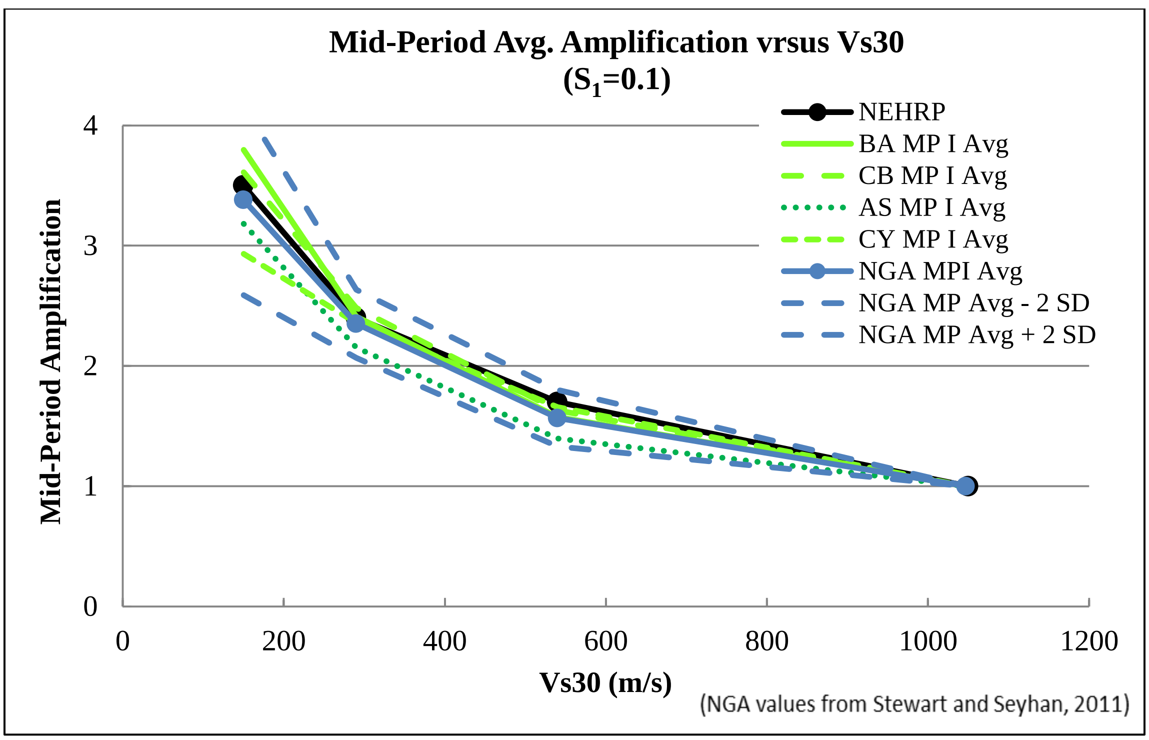
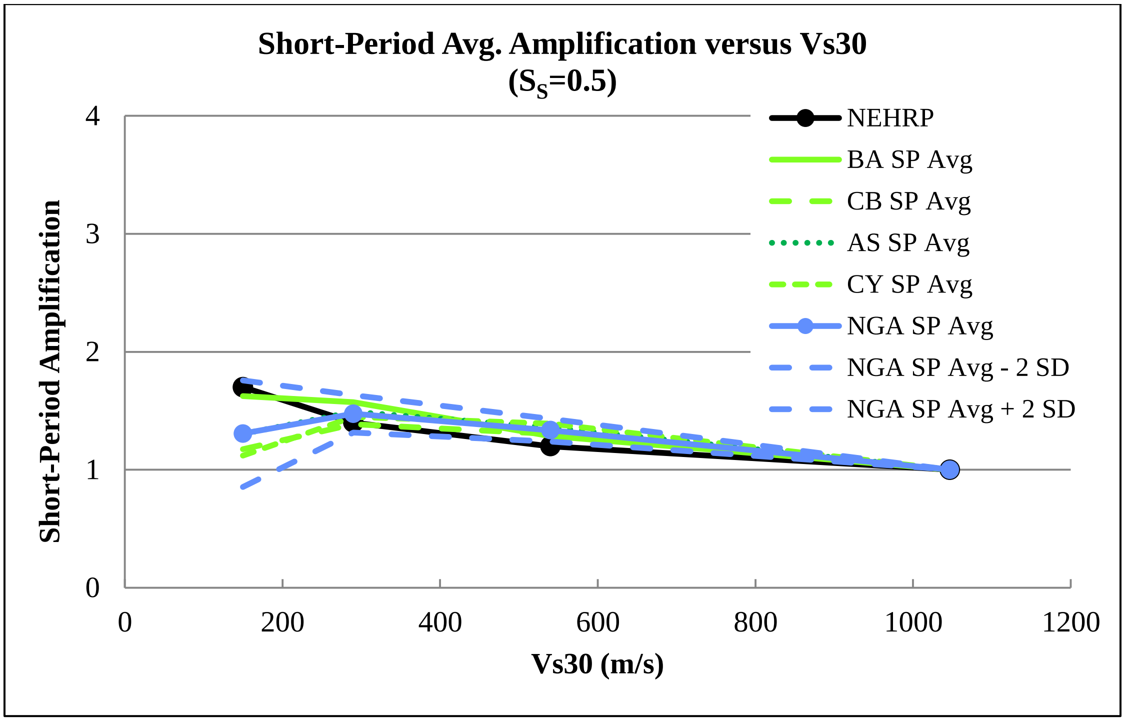


Figure 8. Short-period coefficients at S_S=0.25 (Fig. 8a) and mid-period coefficients at S_1=0.1 (Fig. 8b) as a function of $\overline{v}_S$ for each NGA developer (green lines), mean and 95% NGA values (blue lines), and NEHRP site coefficients (black line). The plots show that the NEHRP F_a and F_v coefficients are within 95% NGA uncertainty limits for all $\overline{v}_S$ values except for F_a with values just beyond the limits for site class E and at indicated ground-motion levels.



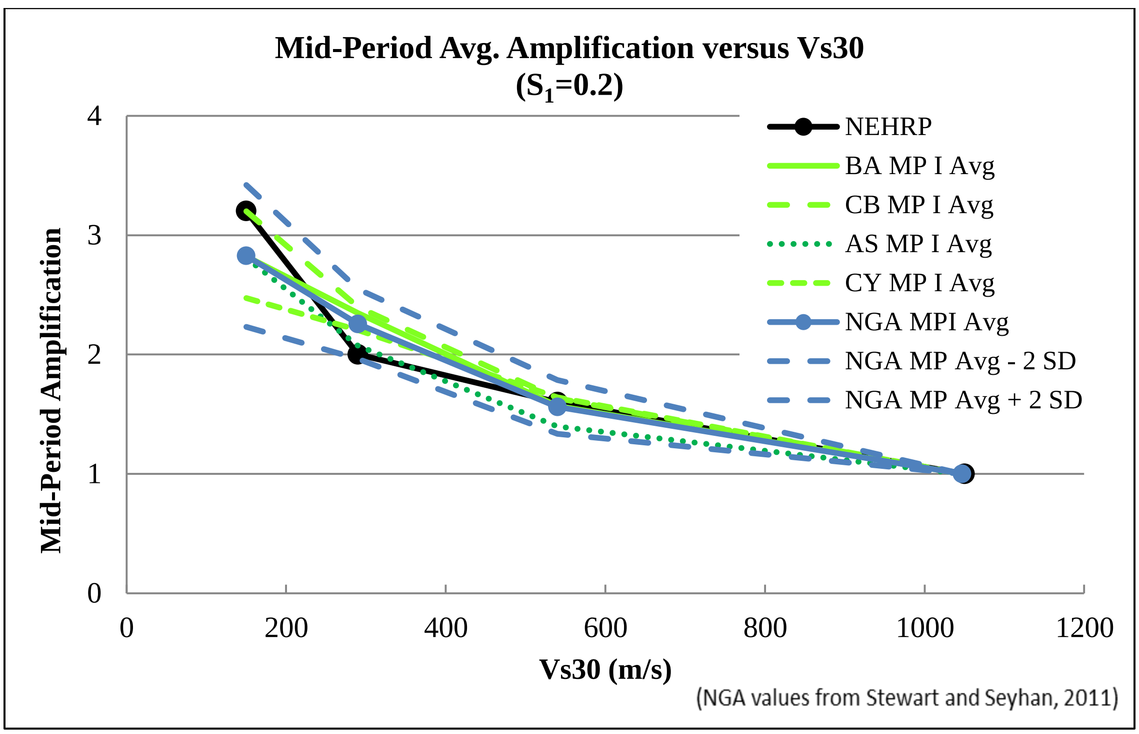


Figure 9. Short-period coefficients at S_S=0.5 (Fig. 9a) and mid-period coefficients at S_1=0.2 (Fig. 9b) as a function of $\bar{v}_S$ for each NGA developer (green lines), mean and 95% NGA values (blue lines), and NEHRP site coefficients (black line). The plots show that the NEHRP F_a and F_v coefficients are within 95% NGA uncertainty limits for all $\bar{v}_S$ values except for F_a with values just beyond the limits for site class C at indicated ground-motion levels.

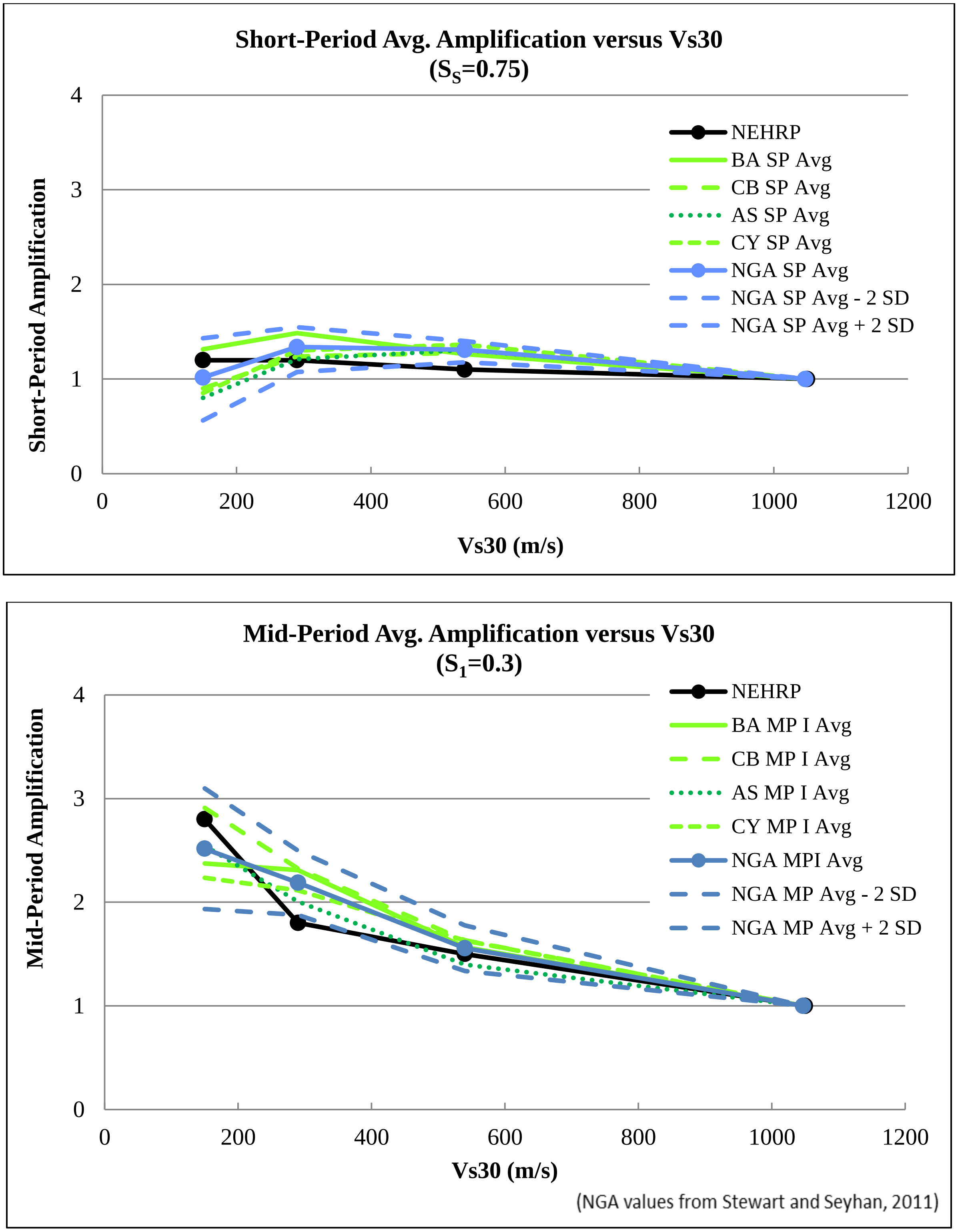


Figure 10. Short-period coefficients at S_S=0.75 (Fig. 10a) and mid-period coefficients at S_1=0.3 (Fig. 10b) as a function of $\overline{v}_S$ for each NGA developer (green lines), mean and 95% NGA values (blue lines), and NEHRP site coefficients (black line). The plots show that the NEHRP F_a and F_v coefficients are within 95% NGA uncertainty limits for all $\overline{v}_S$ values except for F_a with values just beyond the limits for site class C and Fv value for site class D at indicated ground-motion levels.

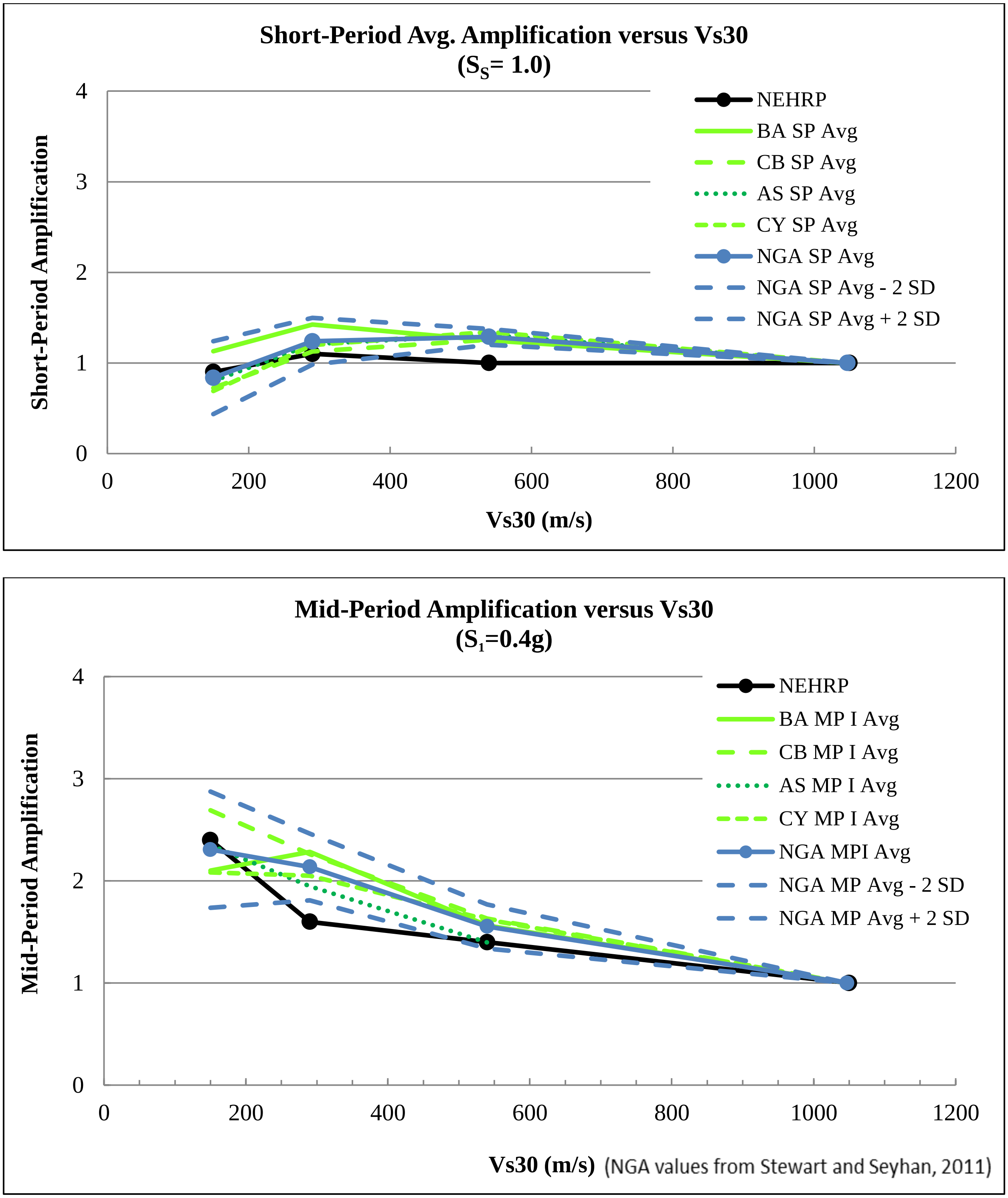


Figure 11. Short-period coefficients at S_S=1.0 (Fig. 11a) and mid-period coefficients at S_1=0.4 (Fig. 11b) as a function of $\overline{v}_S$ for each NGA developer (green lines), mean and 95% NGA values (blue lines), and NEHRP site coefficients (black line). The plots show that the NEHRP F_a and F_v coefficients are within 95% NGA uncertainty limits for all $\overline{v}_S$ values except for F_a for site class C and Fv value for site class D at indicated ground-motion levels.

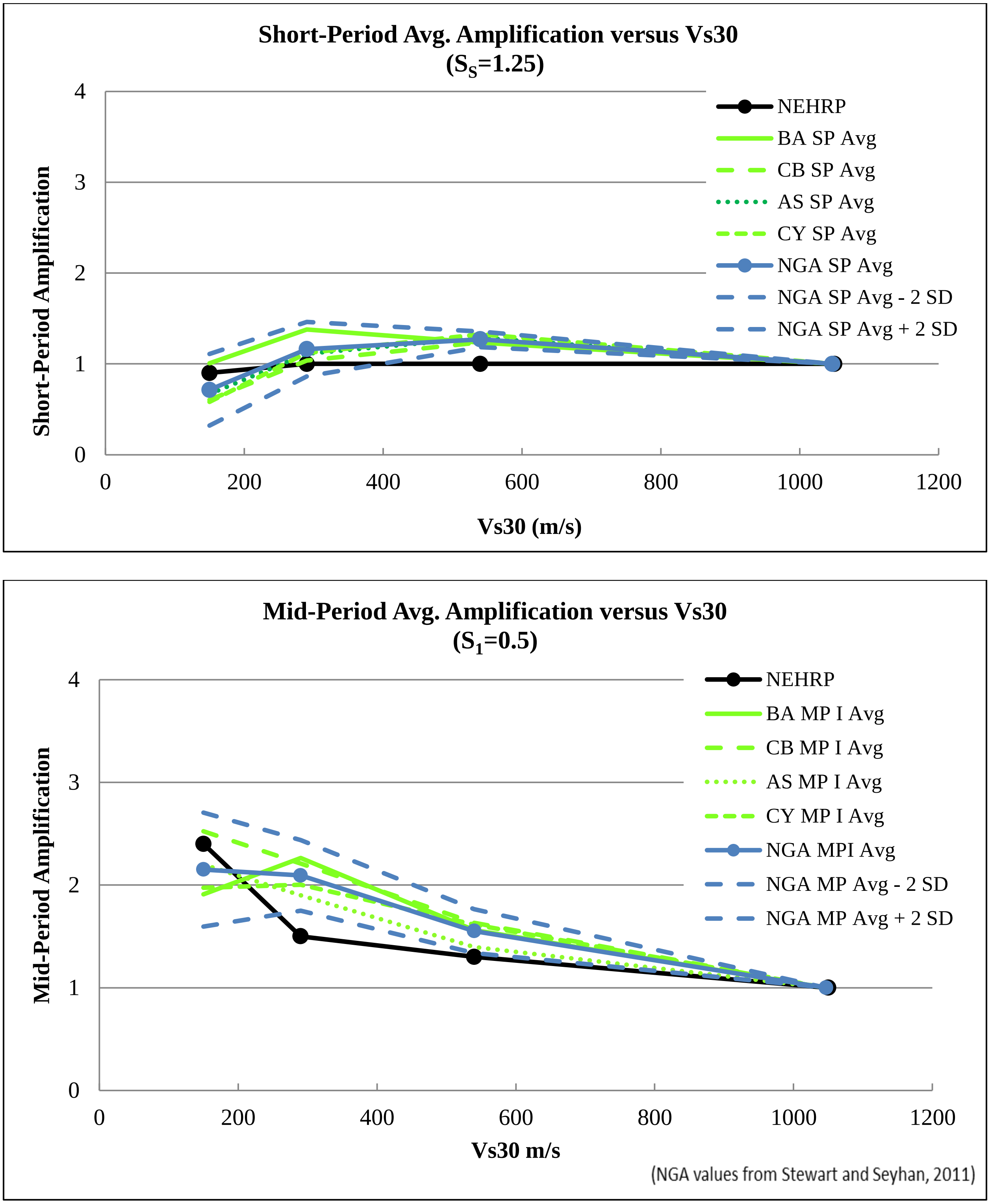
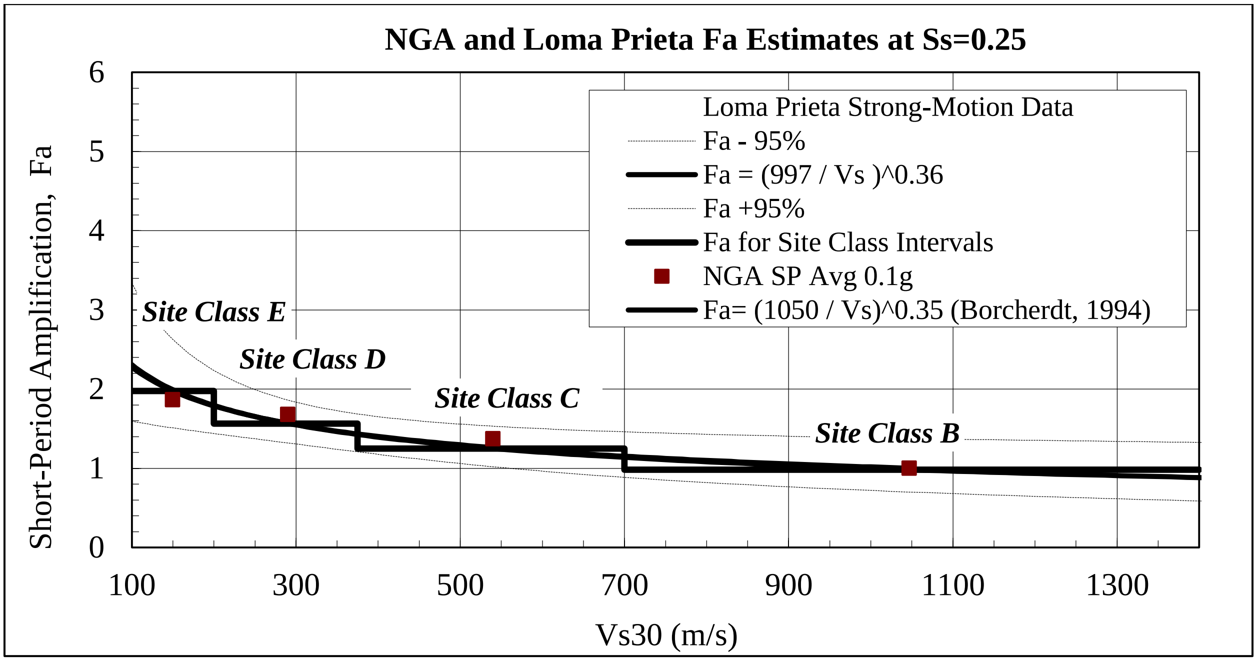


Figure 12. Short-period coefficients at S_S=1.25 (Fig. 12a) and mid-period coefficients at S_1=0.5 (Fig. 12b) as a function of $\overline{v}_S$ for each NGA developer (green lines), mean and 95% NGA values (blue lines), and NEHRP site coefficients (black line). The plots show that the NEHRP F_a and F_v coefficients are within 95% NGA uncertainty limits for all $\overline{v}_S$ values except for F_a for site class C and Fv value for site class D at indicated ground-motion levels.



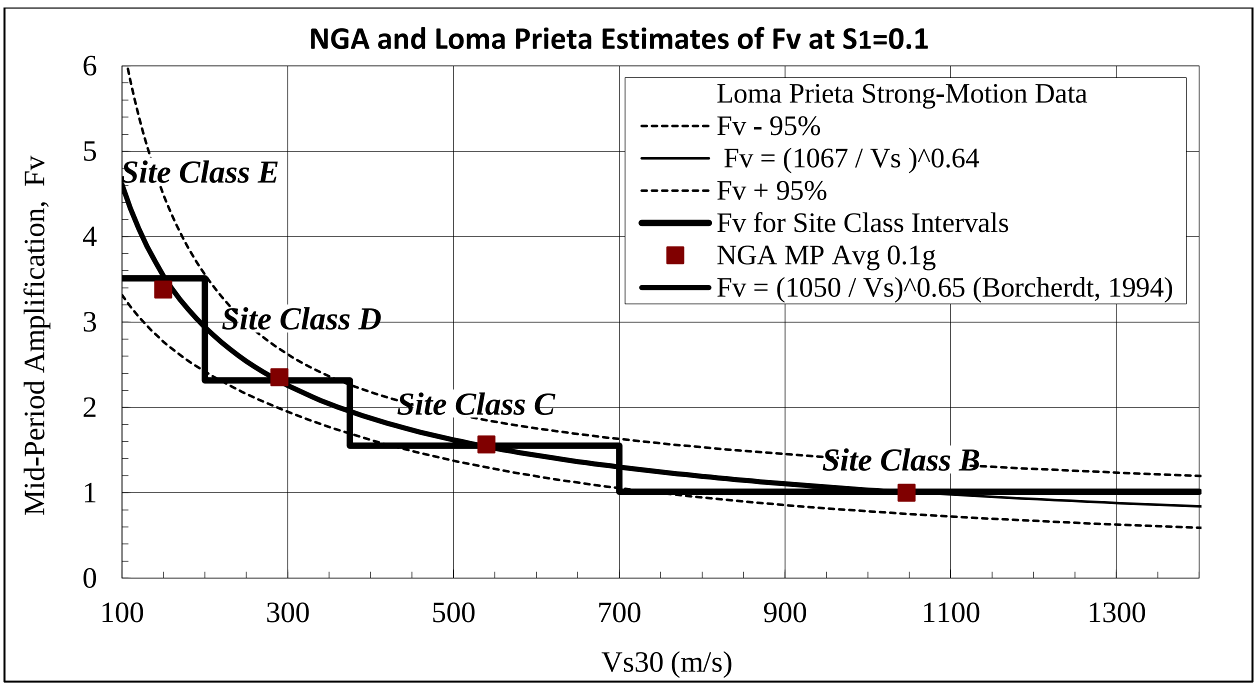


Figure 13. Short-period coefficients at S_S=0.25 (Fig. 13) and mid-period coefficients at S_1=0.1 (Fig. 13) from Loma Prieta strong motion data (black site-class step function and continuous curves: Seed, 1992; Seed et al., 1994; Borcherdt, 1992, 1994; and Dobry et al., 1992, 1994; and Joyner et al., 1992, 1994) and the NGA coefficients proposed herein (brown dots). The figures show that the empirical NGA coefficients are in very good agreement with the empirical coefficients inferred from observed Loma Prieta strong-motion data, especially for F_v. The plots confirm that the proposed NGA coefficients (see Tables 1, 2, and 3) are in good agreement with Loma Prieta coefficients inferred with respect to a $\overline{v}_S = 795\, m/s$ and in turn consistent with the use of the site coefficients referenced to the mid-point of site class B.

Figure 13 shows that the average spectral amplification values inferred from the NGA data base (Ancheta, 2012) agree extremely well with the coefficients derived from the strong-motion recordings of the Loma Prieta earthquake, and in turn the adopted NEHRP coefficients at 0.1g with the exception of F_a which was increased from 2.0 to 2.5 to account for observed response of Mexico City clays. The plots confirm that the proposed NGA coefficients (see Tables 1, 2, and 3) are in good agreement with the Loma Prieta coefficients inferred using various independent analyses techniques. The agreement confirms that average spectral amplifications inferred from strong-motion recordings at low strain levels are consistent with those derived from GMPEs and the NGA data base. The agreement confirms that the Loma Prieta coefficients inferred with respect to an average ground condition of $\bar{v}_S \approx 795\, m/s$ with corresponding regression analysis of recorded data implying unity amplification near 1050 m/s is consistent with NGA coefficients proposed herein and consistent with MCE_R maps inferred at $\bar{v}_S = 760\, m/s$.

REFERENCE SITE CONDITION DISCUSSION

Further insight into the appropriate $\bar{v}_S$ to be used as a reference velocity for the simplified procedure with site classes can be gained by considering the results of the application of a linear regression model to derive continuous curves to relate the logarithm of short- and mid-period empirical amplification coefficients to the logarithm of $\bar{v}_S$. Application of this model to the Loma Prieta coefficients led to a set of functions that allow the site coefficients computed with respect to $\bar{v}_{S\,ref} \approx 795\, m/s$ to be expressed as a continuous function of $\bar{v}_S$ by the following functions

$$F_a = (\bar{v}_{S\,norm}/\bar{v}_S)^{m_a} \tag{1a}$$

and

$$F_v = (\bar{v}_{S\,norm}/\bar{v}_S)^{m_v} \quad , \tag{1b}$$

where the empirical regression fits to the Loma Prieta coefficients imply that $\bar{v}_{S\,norm} \approx 1050\, m/s$ (Borcherdt, 1994). Application of this model to coefficients computed for the Northridge strong motion recordings yields a similar result, namely linear regression models fit to the logarithm of spectral ratios computed with respect to an average $\bar{v}_S$ for the rock sites of $\bar{v}_{S\,ref} = 795\, m/s$ indicate in all cases that $\bar{v}_{S\,norm} \neq \bar{v}_{S\,ref}$ and $\bar{v}_{S\,norm} > \bar{v}_{S\,ref}$ (Borcherdt, 2002). Hence, if continuous curves specified by the functions in 1a and 1b are to be used to predict amplifications with respect to $\bar{v}_{S\,ref} \approx 760\, m/s$, then the normalization velocity for the functions implied by the empirical fits is $\bar{v}_{S\,norm} \approx 1050\, m/s$. This model specified by 1a and 1b with $\bar{v}_{S\,norm} \approx 1050\, m/s$ implies that the normalization velocity in the model, namely $\bar{v}_{S\,norm} = 1050\, m/s$, is at the mid-point of the $\bar{v}_S$ interval for site class B. The fact that $\bar{v}_{S\,norm} \approx 1050\, m/s$ in the above model is not equal to the $\bar{v}_S$ for the average rock conditions to which the coefficients were computed, namely $\bar{v}_{S\,ref} = 795\, m/s$, has led to considerable confusion in the literature.

Nevertheless, within the known approximations implied by average site coefficients applied to a range of site conditions in each site class interval, the above considerations show that the NEHRP site coefficients computed with respect to an average $\bar{v}_{S\,ref} = 795\,m/s$ for rock sites, which is near $760\,m/s$, the site coefficients predicted by the empirical curves 1a and 1b with $\bar{v}_{S\,norm} = 1050\,m/s$, and the reference site condition of $\bar{v}_{S\,ref} = 760\,m/s$ for the MCE_R design maps are all consistent with each yielding an amplification coefficient of unity for $\bar{v}_{S\,ref} \approx 760\,m/s$.

Figure 14 shows the NGA mid-period site coefficients at S_1=0.1 as proposed herein (Tables 1b and 2b, red step function) and mid-period coefficients inferred by Stewart and Seyhan (Table 6.2, 2012, purple step function) superimposed on mid-period site coefficients at S_1=0.1 (Fig . 13b) as inferred from Loma Prieta strong motion data (black curves). The plots show that the mid-period coefficients proposed in Tables 1b and 2b are in close agreement with those measured from the Loma Prieta strong-motion recordings. The coefficients depicted by the purple curves significantly under predict the measured coefficients, especially for site class E. Application of the purple coefficients using the simplified procedures as currently adopted in ASCE/SEI 7-10 implies a significant uniform reduction in maximum considered earthquake design motions as predicted on MCE_R maps.

INFERENCE OF NGA SITE COEFFICIENTS AT INTERMEDIATE VALUES OF $\bar{v}_S$

A model such as that represented by equations 1a and 1b could be used to predict NGA coefficients for the various site classes. The NGA coefficients as inferred for the short- and mid-period bands at the mid-points of the $\bar{v}_S$ intervals (Figs. 8-12 show that a simple model as described by 1a and 1b does not predict all of the NGA coefficients as inferred directly from the GMPEs for various levels of input motion equally well. Until such a model is developed, the proposals herein recommend that if continuous curves based on the NGA data base are to be used to infer the coefficients at intermediate values of $\bar{v}_S$, then those values should be inferred using linear interpolation of the coefficients as specified at the mid-point of each site class interval. This approach has the advantages that coefficients predicted for values of $\bar{v}_S$ near the mid-point of each site class will agree exactly with those adopted for the site class as predicted directly using the NGA GMPEs. Examination of Figures 13 and 14 implies that linear interpolation provides a simple, but reasonably good approximation for intermediate values of $\bar{v}_S$. It also has the advantage that no additional inconsistencies are introduced between adopted site coefficients and those implied directly from the NGA GMPEs.

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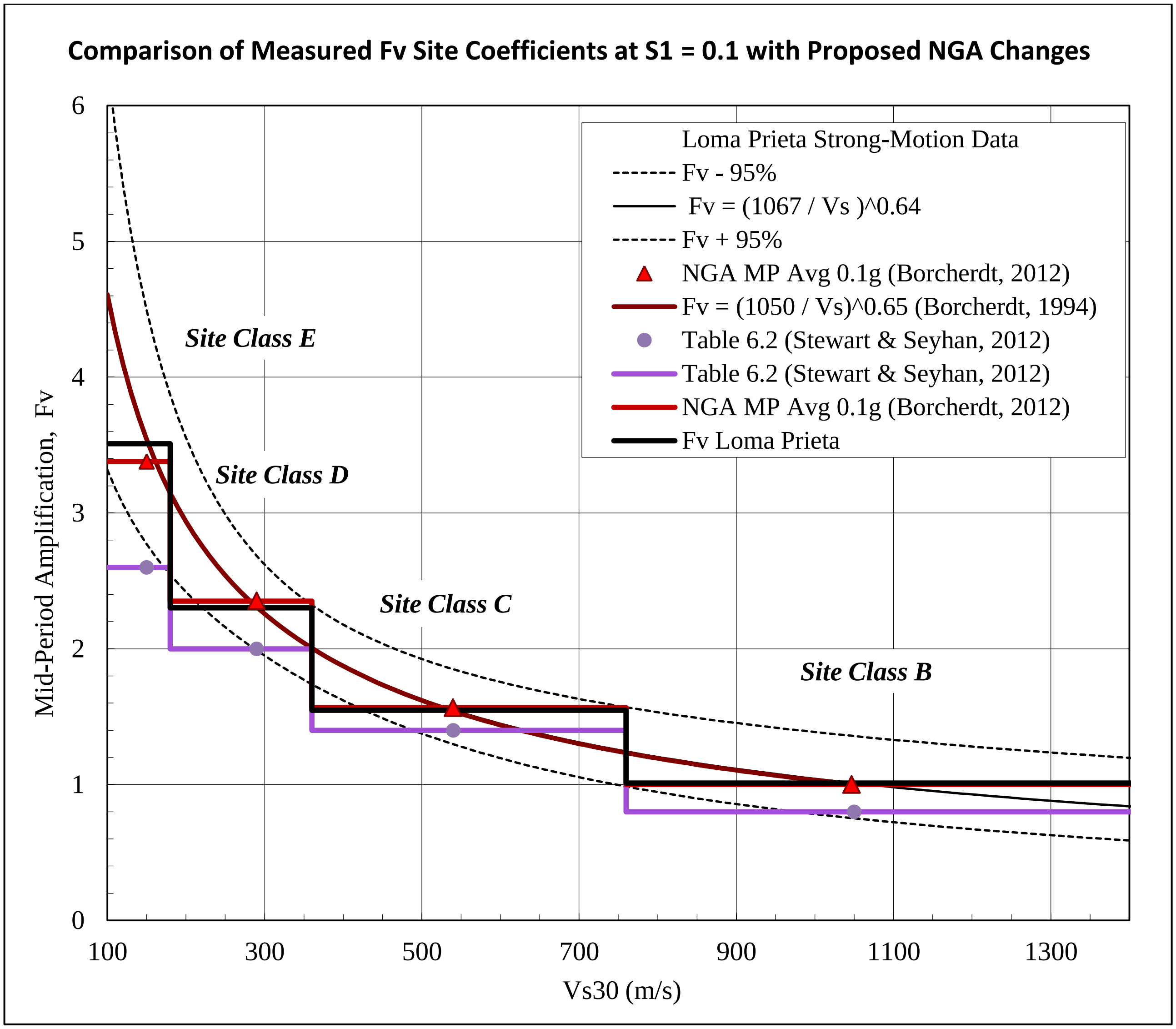

Figure 14. NGA mid-period site coefficients at S_1=0.1 as proposed herein (Tables 1, 2, and 3; red step function) and mid-period coefficients inferred by Stewart and Seyhan (Table 6.2, 2012, purple step function) superimposed on mid-period site coefficients at S_1=0.1 (Fig. 13) as inferred from Loma Prieta strong motion data (black curves). The plots show that the mid-period coefficients proposed in Tables 1, 2, and 3 are in close agreement with those measured from the Loma Prieta strong-motion recordings. The coefficients depicted by the purple curves significantly under predict the measured coefficients. Application of the purple coefficients using the simplified procedures as currently adopted in ASCE/SEI 7-10 implies a significant uniform reduction in MCE_R design motions, dependent on the model chosen by Stewart and Seyhan (2012) to predict the site coefficients.

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