PACIFIC EARTHQUAKE ENGINEERING
RESEARCH CENTER

Expert Panel Recommendations for Ergodic Site Amplification in Central and Eastern North America

Principal Investigator and Panel Chair:

Jonathan P. Stewart
University of California, Los Angeles

Graduate Students:

Grace A. Parker
University of California, Los Angeles

Joseph A. Harmon
University of Illinois at Urbana-Champaign

Authoring Panel Members:

Gail M. Atkinson
Western University

David M. Boore
U.S. Geological Survey

Robert B. Darragh and Walter J. Silva
Pacific Engineering and Analysis

Youssef M.A. Hashash
University of Illinois at Urbana-Champaign

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University of Illinois at Urbana Champaign

Authoring Panel Members:

Gail M. Atkinson
Western University, London, Ontario (Canada)

David M. Boore (retired)
U.S. Geological Survey, Menlo Park, CA

Robert B. Darragh and Walter J. Silva
Pacific Engineering and Analysis, El Cerrito, California

Youssef M.A. Hashash
University of Illinois at Urbana-Champaign

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An error was caught in Eq. 2.4 on page 17. This equation has been updated along with the explanatory text on page 17. Figures 3.3-3.14 on pages 22-33 have been updated to reflect this equation change, as well as the coefficients in the electronic supplement.

The axis labels on Figures 2.3 and 4.4 have been updated to clarify that the plots are in arithmetic rather than natural log units.

EXECUTIVE SUMMARY

The U.S. Geological Survey (USGS) national seismic hazard maps have historically been produced for a reference site condition of V_{S30} = 760 m/sec (where V_{S30} is time averaged shear wave velocity in the upper 30 m of the site). The resulting ground motions are modified for five site classes (A-E) using site amplification factors for peak acceleration and ranges of short- and long-oscillator periods. As a result of Project 17 recommendations, this practice is being revised: (1) maps will be produced for a range of site conditions (as represented by V_{S30}) instead of a single reference condition; and (2) the use of site factors for period ranges is being replaced with period-specific factors over the period range of interest (approximately 0.1 to 10 sec).

Since the development of the current framework for site amplification factors in 1992, the technical basis for the site factors used in conjunction with the USGS hazard maps has remained essentially unchanged, with only one modification (in 2014). The approach has been to constrain site amplification for low-to-moderate levels of ground shaking using inference from observed ground motions (approximately linear site response), and to use ground response simulations (recently combined with observations) to constrain nonlinear site response. Both the linear and nonlinear site response has been based on data and geologic conditions in the western U.S. (an active tectonic region).

This project and a large amount of previous and contemporaneous related research (e.g., NGA-East Geotechnical Working Group for site response) has sought to provide an improved basis for the evaluation of ergodic site amplification in central and eastern North America (CENA). The term ‘ergodic’ in this context refers to regionally-appropriate, but not site-specific, site amplification models (i.e., models are appropriate for CENA generally, but would be expected to have bias for any particular site). The specific scope of this project was to review and synthesize relevant research results so as to provide recommendations to the USGS for the modeling of ergodic site amplification in CENA for application in the next version of USGS maps.

The panel assembled for this project recommends a model provided as three terms that are additive in natural logarithmic units. Two describe linear site amplification. One of these describes V_{S30}-scaling relative to a 760 m/sec reference, is largely empirical, and has several distinct attributes relative to models for active tectonic regions. The second linear term adjusts site amplification from the 760 m/sec reference to the CENA reference condition (used with NGA-East ground motion models) of V_S =3000 m/sec; this second term is simulation-based. The panel is also recommending a nonlinear model, which is described in a companion report [Hashash et al. 2017a]. All median model components are accompanied by models for epistemic uncertainty.

The models provided in this report are recommended for application by the USGS and other entities. The models are considered applicable for V_{S30} = 200–2000 m/sec site conditions and oscillator periods of 0.08–5 sec. Finally, it should be understood that as ergodic models, they lack attributes that may be important for specific sites, such as resonances at site periods. Site-specific analyses are recommended to capture such effects for significant projects and for any site condition with V_{S30} < 200 m/sec. We recommend that future site response models for hazard applications consider a two-parameter formulation that includes a measure of site period in addition to site stiffness.

ACKNOWLEDGMENTS

This project was sponsored by U.S. Geological Survey (USGS) contract G16AP00005. This support is gratefully acknowledged. We thank Mark Petersen of the USGS, Yousef Bozorgnia of UC Berkeley and UCLA, and panel member Christine Goulet (who elected to not author the report) for consulting with the authoring panel members over the course of the work and providing valuable input. Behzad Hassani of Western University (Canada) and Okan Ilhan of University of Illinois are thanked for supporting the project by providing digital files related to their research work.

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1 INTRODUCTION

1.1 PROJECT MOTIVATION AND INTENDED USE

The Next Generation Attenuation East (NGA-East) Project is a multi-disciplinary research project coordinated by the Pacific Earthquake Engineering Research Center (PEER) that produced ground motion models (GMMs) for central and eastern North America (CENA) [PEER 2015a, b, and Goulet et al., 2017]. The majority of these models provide ground motion intensity measure predictions as a function of earthquake source and wave propagation path for sites with a hard-rock reference velocity condition of shear-wave velocity V_s = 3000 m/sec and diminution parameter κ_0=0.006 sec [Hashash et al. 2014]. Some of those models also provide ground motions for the National Earthquake Hazards Reduction Program (NEHRP) B/C boundary condition of V_{S30} = 760 m/sec, where V_{S30} is the time-averaged shear-wave velocity in the upper 30 m of the site. The Geotechnical Working Group (GWG) of NGA-East produced a set of linear and nonlinear site amplification models that are currently being finalized (details presented subsequently in this report).

The NGA-East GMMs began with a series of candidate models [PEER 2015a], listed in Table 1.1. A subset of these models were selected as seed models and then adjusted to correct for various distance scaling issues [PEER 2015b]. The models from the PEER [2015b] report are being used as seed models for the generation of a range of GMMs intended to capture, in aggregate, epistemic uncertainties in ground motions from source and path effects following a Sammon's map approach (e.g., Scherbaum et al. [2010]). This process remains in progress (C. Goulet, *personal communication*, February 2017), with the resulting models not yet available. Nonetheless, we understand the reference site condition for these GMMs will remain as V_s = 3000 m/sec and κ_0=0.006 sec.

The United States Geological Survey (USGS) National Seismic Hazard Maps (NSHMs) present ground-motion intensity measures with specified probabilities of exceedence over a 50-year time period [Petersen et al. 2015]. The maps are in the process of being updated to account for new methods, models and data that have become available since the release of the 2014 maps [Petersen et al. 2015]. These updates are slated to be submitted for publication in mid-2018 and early-2020, in order to facilitate potential incorporation into the next edition of the NEHRP Recommended Seismic Provisions for New Building and Other Structures. These updates will utilize the NGA-East GMMs to compute ground motion measures for the central and eastern U.S. A special consideration for the next update is that maps will be produced for a variety of site conditions (represented by a range of V_{S30}) and periods, as a result of interim draft recommendations from Project 17 [M. Petersen, *pers. communication*, July 2016]. This is a departure from past practice in which the maps were produced for the NEHRP B/C boundary site condition (V_{S30}=760 m/sec) and the ground motion measures of peak acceleration and 5% damped pseudo-spectral acceleration at oscillator periods of 0.2 and 1.0 sec.

The purpose of this project was to form an expert panel to review alternate site amplification models and to provide recommendations to the USGS (and other interested parties) regarding the estimation for CENA of median site effects and their epistemic uncertainties. The recommendations are rooted in an inherent assumption that such models need to be based on V_{S30} as the sole predictive variable for site response, for compatibility with the NEHRP site categories A-E used in current practice (which are defined for ranges of V_{S30}). The consideration of models using alternative independent variables such as depth or dominant site period was beyond the scope of this project. The panel had two in-person meetings (July and November 2016) and many teleconferences. The resulting recommended model has three components: V_{S30}-scaling and its uncertainty, ground motion scaling from 3000 m/sec to 760 m/sec and its uncertainty, and the nonlinear component of site amplification and its uncertainty. The nonlinear component of the model and its uncertainty are given in a companion report by Hashash et al. [2017a]; other model components are given here. While the panel recommendations at the time of this writing are mature, they are not necessarily final, as a result of potential future changes in some of the underlying models.

Table 1.1 **Table summarizing the attributes of NGA-East median candidate GMMs [PEER 2015a]. AB06, AB11 = Atkinson and Boore [2006, 2011]; BT15=Boore and Thompson [2015]; SS14 = Seyhan and Stewart [2014]; GRA=ground response analysis. All point source simulations utilize parameters calibrated against NGA-East data.**

PEER [2015a] Chapter	Author	Approach	Distance type	Distance range (km)	M range	Site term & parameter	Site correction: V_{S30} to 760[3]	Site correction: 760 to 3000
2	DM Boore	Point source simulations	R_{ps}	0–1200	4–8	No	N/A	Boore [2015]
3	RB Darragh, NA Abrahamson, WJ Silva, N Gregor	Point source simulations	R_{JB}	0–1000	4.5–8.5	No	1D GRA transfer functions for NEHRP Cats; goes from V_{S30} to 4.68 km/sec	
4	E Yenier and GM Atkinson	Point source simulations	R_{ps}	0–600	3–8	Yes (V_{S30})	SS14	AB06 BC crustal amp [Atkinson 2012]
5	S Pezeshk, A Zandieh, KW Campbell, B Tavakoli	Hybrid empirical	R_{RUP}	0–1000	3–8	No	SS14 (for validation only)	BT15
6	AD Frankel	Finite fault simulations	R_{RUP}	2–1000	4.5–8	No	N/A	Frankel et al. [1996]
7	A Shahjouei and S Pezeshk	Hybrid empirical	R_{JB}	2–1000	5–8	No	SS14 (used for validation only)	AB06 and BT2015;
8	N Al Noman and CH Cramer	Empirical with intensity data	R_{RUP}	<10–2000	2.5–7.7	Yes (V_{S30})	Set by regression, parameter d_1	NA
9	V Graizer	Empirical	R_{RUP}	0–1000	4–8.2	Yes (V_{S30})	GRA-based: Eq. 9.6	GRA-based: similar to AB06, AB11
10	B Hassani and GM Atkinson	Referenced empirical	R_{JB}	0–400	3–8	Yes (V_{S30})	SS14	AB06 BC crustal amp [Atkinson 2012]
11	J Hollenback, N Kuehn, CA Goulet, NA Abrahamson	Empirical with finite fault simulations	R_{RUP}	0–1200	4–8.2	Yes (V_{S30})	Set by regression, parameter c_8	Boore [2015]

1.2 LITERATURE REVIEW

1.2.1 Empirical Site Amplification Studies

Seismic site amplification has traditionally been analyzed in one of two ways: empirically, or through the use of simulations [Stewart et al. 2001]. Empirical methods can generally be classified as reference and non-reference site approaches. The reference site approach takes amplification as the ratio between ground motions from nearby soil and rock sites, assuming that they have the same source and path effects. Classical work utilizing this approach with California data was presented by Borcherdt and Gibbs [1976], Rodgers et al. [1984], Idriss [1990], Boatwright et al. [1991], Borcherdt and Glassmoyer [1994], Borcherdt [1994], Bonilla et al. [1997], Hartzell et al. [1997], and Borcherdt [2002]. Significantly, site amplification evaluated with reference site approaches [Borcherdt and Glassmoyer 1994] comprised the principle basis for NEHRP site factors from 1992 until a 2015 update [BSSC 2015]. There are limited applications of the reference site approach in CENA. Khaheshi Banab et al. [2012] showed that for a soft soil site in eastern Canada, weak motions were amplified near the site period by more than a factor of 10 with respect to a nearby hard-rock reference site.

Non-reference site approaches use a median GMM to calculate reference (typically rock) motions in a manner that accounts for event-to-event variability, and site amplification is evaluated as the difference between motions on various site conditions and the reference motions [Field and Jacob 1995]. This approach has been extensively used in active tectonic regions (e.g., Stewart et al. [2003], Sandıkkaya et al. [2013], and Seyhan and Stewart [2014]). However, until recently, there has been a lack of such studies in stable continental regions like CENA. Atkinson et al. [2015] used a ground-motion regression to determine a GMM for southern Ontario in which site amplifications were determined for each soil site with respect to motions on hard-rock sites. Hassani and Atkinson [2016a] derived the frequency of peaks in H/V spectral ratios using CENA data, and used those peak frequencies as predictive parameters for analysis of site effects. They find that the data-derived peak frequencies are more effective than V_{S30} at predicting site effects in the CENA data. Results from Hassani and Atkinson [2016a] are compared to the proposed model in Chapter 3.

While the process of developing GMMs from ground motion data implicitly uses a non-reference site approach, the GMMs for stable continental regions generally either neglect site amplification or assume it to be constrained by a model from active tectonic regions. An exception is the model for southern Ontario of Atkinson et al. [2015[, referenced above; that study was focused on a limited number of periods, for use primarily in ShakeMap applications. Recently, a GMM model for Oklahoma earthquakes [Yenier et al. 2017] empirically determined site terms relative to the regional average reference condition of NEHRP C. However, the utility of empirical site terms in the context of V_{S30}-based amplification models has been limited in CENA due to a lack of V_{S30} information at seismographic sites (against which such site terms might be correlated). The majority of past seismic site amplification work in CENA has focused on simulation-based approaches, as described next.

1.2.2 Simulation-Based Site Amplification

As a result of limited ground motion observations and a lack of information on near-surface velocity structure at seismographic sites in CENA, empirical site amplification studies have been scarce and previous work has largely investigated site amplification with numerical approaches based on simulations of wave propagation through shallow sediments. In this section, we begin with a description of this approach as applied to active tectonic regions (ATRs). These results are reviewed here because they establish precedent for the use of simulation-based results to constrain portions of GMMs and to guide the development of site amplification terms provided in building codes. We then describe prior simulation work for CENA, which has not previously been applied in this manner.

In ATRs, for several decades there has been ample data with which to constrain site amplification models at small-to-moderate levels of ground motion, and hence the application of simulations has been limited to the problem of ground response at large strains. One such application was for the major update to building code site factors in 1992 [BSSC 1992], which was based on an empirical model (reference-site approach) at modest ground motion amplitudes (about 0.1*g* peak acceleration) [Borcherdt 1994] and was based on simulations for stronger shaking [Dobry et al. 2000]. These simulations were for 1D ground response using equivalent-linear and nonlinear codes of the time. In the NGA-West1 project [Power et al. 2008], equivalent-linear simulations performed using a random vibration theory (RVT) approach [Silva and Lee 1987] were used to develop a nonlinear site amplification model [Walling et al. 2008] that was adopted in several of the GMMs provided by that project [Abrahamson and Silva 2008; Campbell and Bozorgnia 2008]. Likewise, in the NGA-West2 project [Bozorgnia et al. 2014], RVT-type equivalent linear simulation results were formulated into a model presented by Kamai et al. [2014], which was adopted in some GMMs (e.g., Abrahamson et al. [2014]). Moreover, those simulation results helped, along with empirical data, to inform a site amplification model [Seyhan and Stewart 2014] used in the 2015 update of the NEHRP site factors [BSSC 2015].

For CENA, we highlight three studies (or collections of studies). The first was by Hwang et al. [1997] and was targeted at the CENA region generally. They sought to establish site coefficients akin to those for the NEHRP Provisions for CENA. Their ground response simulations were equivalent-linear in SHAKE91 [Idriss and Sun 1992], using simulated input motions generated using the method described in Hwang and Huo [1994]. They considered five representative profiles for each NEHRP site class (A, B, C, D and E; profiles shown in Lin et al. [1996] and modulus reduction and damping curves taken as the mean of available models at the time (Appendix A of Hwang and Huo [1994]). Their results for site classes A and B (rock sites) match those in the 1992 NEHRP Provisions. Site factors for Classes C-E are generally higher. Figure 1.1(a) shows their recommended site amplification for Classes C-E for a rock peak acceleration level of 0.3*g*, and Figure 1.1(b) shows the variation of Class D amplification with shaking amplitude. This model is compared to results from the present study in Chapter 3.

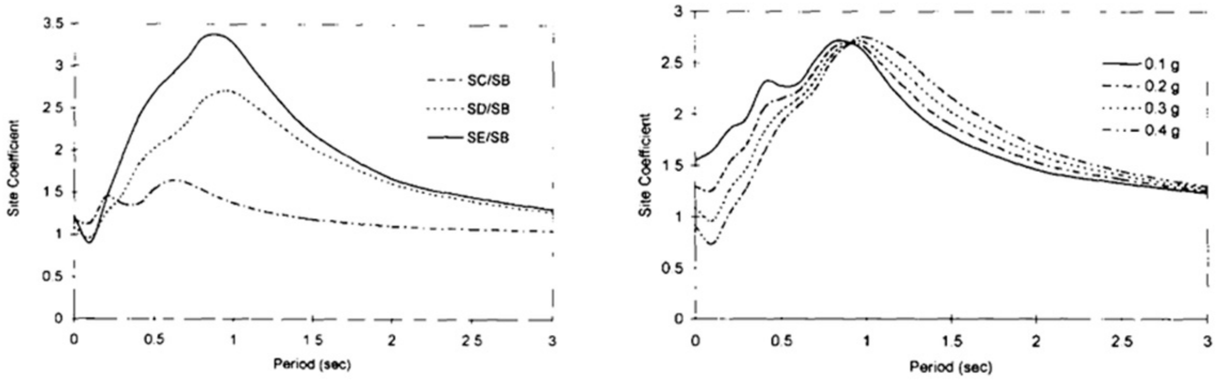

Figure 1.1(a) Computed CENA site amplification by Hwang et al. [1997] for NEHRP classes C, D, and E relative to a site class B condition for rock peak acceleration 0.3*g*; (b) Dependence of computed amplification for class D on rock peak acceleration.

We next briefly summarize prior ground response analysis work directed towards evaluation of site effects for the Mississippi embayment region of CENA [Hashash and Park 2001; Romero and Rix 2001; Park and Hashash 2005a; Park and Hashash 2005b; and Hashash et al. 2008]. The literature for this region is substantial and has arguably been supplanted by more recent work by Hashash et al. [2017a]; hence, we do not provide a thorough literature review here. We simply note that some of the major considerations in this work have been the effects of overburden on modulus reduction and damping curves (e.g., Hashash and Park [2001] and Park and Hashash [2005a]); use of site profiles for the region that are separately developed for upland regions of Pleistocene age and lowland Holocene alluvial sediments, with alternate sediment thicknesses for each region used in the simulations [Hashash and Park 2001; Romero and Rix 2001; and Hashash et al. 2008]; and both equivalent linear [Romero and Rix 2001] and nonlinear methods (Hashash publications) have been applied. Figure 1.2 shows a representative outcome of these studies for upland and lowland areas for soil columns of different depths [Hashash et al. 2008].

The third CENA study described here is from Aboye et al. [2015], who developed site factors for the city of Charleston, South Carolina. They developed a series of reference V_S profiles assuming different Quaternary layer thicknesses and taking layer velocities from measurements in well-characterized Quaternary and Tertiary units in the Charleston area. After introducing V_S profile variability, they adopt 56 profiles, placed over a half-space with $V_S = 700$ m/sec. They use region-specific modulus reduction and damping models [Zhang et al. 2005; 2008], simulated input motions (stochastic point source approach), and both equivalent linear and nonlinear ground response simulation methods. Figure 1.3 shows representative results for amplification of 0.2-sec PSA. This model is compared to results from the present study in Chapter 3 (linear amplification).

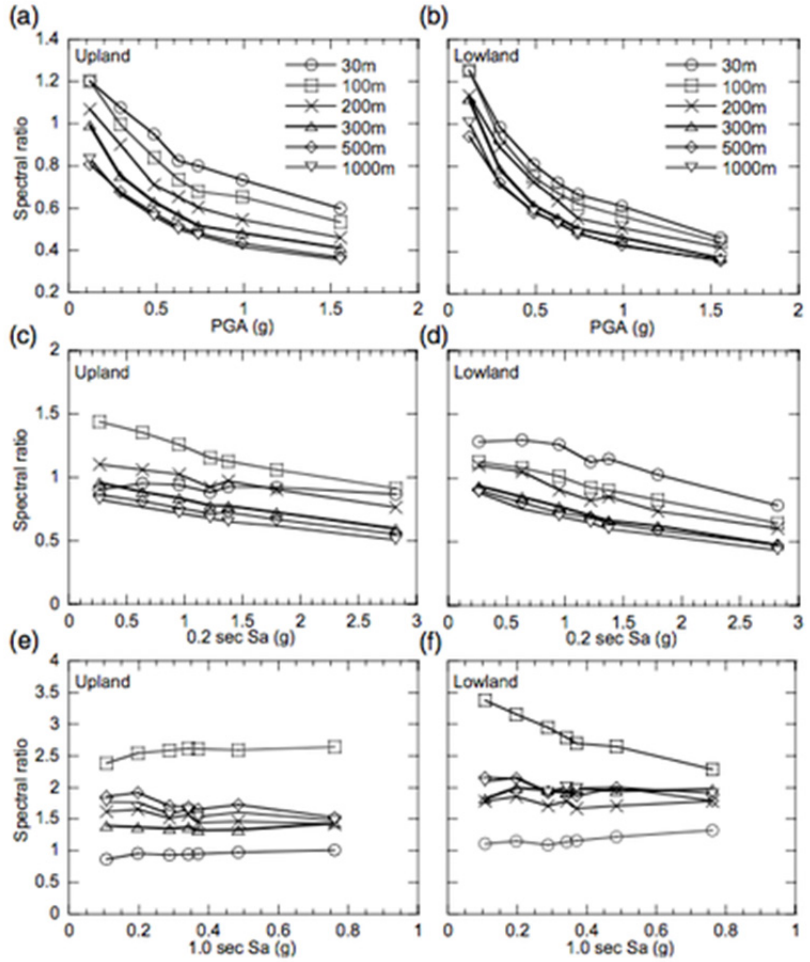

Figure 1.2 Computed Mississippi Embayment, depth-dependent site amplification for PGA (top), 0.2 sec PSA (middle), and 1.0 sec PSA (bottom) from Hashash et al. [2008]. Upland sites have mean V_{S30} = 314 m/sec and correspond to Pleistocene terrace deposits; Lowland sites have mean V_{S30} = 249 m/sec and correspond to Holocene alluvium.

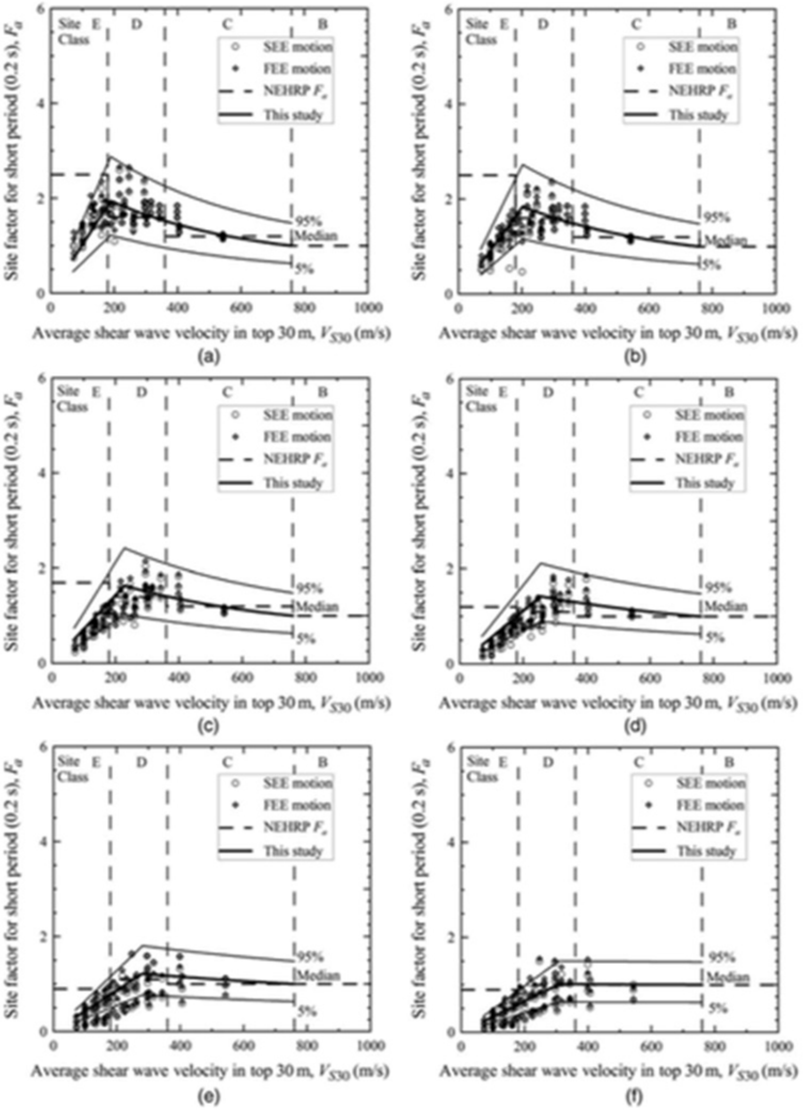

Figure 1.3 **Computed amplification of 0.2 sec PSA for Charleston, South Carolina by Aboye et al. [2015]. The input ground motion intensity for rock is 0.2 sec PSA = (a) 0.125*g*, (b) 0.25*g*, (c) 0.5*g*, (d) 0.75*g*, (e) 1.0*g*, and (f) 1.25*g*. The paper also presents results for PGA and 1.0 sec PSA.**

1.3 NGA-EAST GROUND-MOTION MODELS

Table 1.1 summarizes some of the principal attributes of ten NGA-East candidate GMMs [PEER 2015a]. Three of the models [Boore 2015; Darragh et al. 2015; and Yenier and Atkinson 2015] are based on the point-source simulation methodology. Parameters included in the simulations, especially the stress parameter and path attenuation terms, are set based on comparisons to NGA-

East data. Two of the models [Pezeshk et al. 2015, Shahjouei and Pezeshk 2015] use the hybrid empirical approach of Campbell [2003], in which GMMs for active tectonic regions (from NGA-West2; Bozorgnia et al. [2014]) are modified for CENA using ratios of simulated ground motions. One model uses a conceptually-similar referenced empirical approach in which an active tectonic region GMM is adjusted through residuals analysis using NGA-East data [Hassani and Atkinson 2015]. Three of the models are based on direct regression of NGA-East data to develop GMMs [Al Noman and Cramer 2015; Graizer 2015; and Hollenback et al. 2015], while a fourth [Yenier and Atkinson 2015] uses direct regression to calibrate the regionally-adjustable parameters of the generic point-source model. Due to the limited parameter space covered by the data, additional information used during model building included intensity data [Al Noman and Cramer 2015], or simulations [Graizer 2015; Hollenback et al. 2015]. Finally, one GMM consists of an inventory of finite-fault simulation results [Frankel 2015].

All of the GMMs in Table 1.1 provide ground motion estimates for the reference site condition in CENA defined by Hashash et al. [2014]. This reference condition consists of V_S = 3.0 km/sec and diminution parameter κ_0 = 0.006 sec. Five of the models contain no site term and provide ground motion estimates only for the reference condition. Five models contain a V_{S30}-based site term that is intended to capture the effects of V_{S30} on the linear site amplification. Some models used site corrections of various sorts during development, even if the models themselves do not contain a site term. As a result, there are a number of site amplification models, reflecting various approaches in their development, within the documentation for the ten NGA-East candidate GMMs.

As shown in Table 1.1, the alternative approaches for estimating site amplification that were used during NGA-East GMM development included:

1. Adopting models for active tectonic regions, specifically the Seyhan and Stewart [2014] model (SS14) developed for NGA-West2 (this is the site amplification model contained in the Boore et al. 2014 GMM). SS14 was used as the site term in NGA-East models by Yenier and Atkinson [2015] and by Hassani and Atkinson [2015], and to support model development by Pezeshk et al. [2015] and Shahjouei and Peszehk [2015].
2. Regression of data using a linear V_{S30}-scaling model [Al Noman and Cramer 2015; Hollenback et al. 2015].

3. Ground response analysis simulations, typically using viscous-elastic soil conditions [Darragh et al. 2015; Graizer 2015].

These approaches for analysis of site effects for soil and soft rock sites (V_{S30} < 760 m/sec) are combined with models for site amplification from 760 to 3000 m/sec, as described further in Chapters 2–4 of this report.

1.4 PANEL COMPOSITION

The panel composition is listed on the report cover. The panel was formed to have representation from the developers of alternate contemporary site amplification models. The specific considerations associated with each panelist are as follows:

G. M. Atkinson: Experience with NGA-East GMMs; advocate for Hassani and Atkinson [2016a] site amplification model; experience with ground motion, site amplification and hazard maps for Canada.

D. M. Boore: Experience with NGA-East GMMs, advocate for Boore and Campbell [2017] model for amplification from 3000 to 760 m/sec.

R. B. Darragh and W. J. Silva: Experience with NGA-East GMMs, advocate for Darragh et al. [2015] site amplification models.

C. A. Goulet: Experience with NGA-East GMMs; NGA-East overall project management.

Y. M. A. Hashash: Advocate for simulation-based site amplification models produced by NGA-East Geotechnical Working Group (GWG); experience with Mississippi Embayment site amplification.

J. P. Stewart: Advocate for semi-empirical models for V_{S30}-scaling from NGA-East Geotechnical Working Group (GWG); member of Project 17; experience on committees responsible for NEHRP Provisions.

2 RECOMMENDED MODEL

2.1 APPROACH

Site amplification relative to a V_S = 3000 m/sec reference condition is denoted F_S and is provided in natural log units. The recommended site amplification model, considering V_{S30} as the predictive site variable, has three additive components representing: (*i*) V_{S30}–scaling (relative to V_{S30}=760 m/sec), (*ii*) amplification at the V_{S30}=760 m/sec site condition relative to 3000 m/s, and (*iii*) nonlinear effects. The first two of these components are independent of the strength of the reference (rock) ground motions, and hence can be described as linear and are denoted F_{lin} in natural log units. The nonlinear component is denoted F_{nl} and is also in natural log units. The total amplification is the sum:

$$F_S = F_{lin} + F_{nl} \tag{2.1}$$

The two components of F_{lin} are summed as follows:

$$F_{lin} = F_V\left(V_{S30}, T\right) + F_{760}\left(T\right) \tag{2.2}$$

where F_V is the V_{S30}-scaling term and F_{760} represents amplification at the V_{S30} = 760 m/sec site condition relative to 3000 m/sec reference condition. Panel-recommended median models for F_V and F_{760} are given in the following sections along with their epistemic uncertainties. Justification for the selection of these models is given in Chapter 3 and 4. A panel-recommended model for nonlinear effects and their uncertainties is given in the companion report by Hashash et al. [2017a]. Note that Equation (2.2) is suitable for use with a GMM having a reference condition of V_S = 3000 m/sec. It can be extended to a reference condition of V_{S30}=760 m/sec by dropping the F_{760} term. The use of Equation (2.1) and F_{nl} for reference conditions of V_S = 3000 m/sec and 760 m/sec is discussed in Hashash et al. [2017a].

As explained further in Chapters 3 and 4 and Hashash et al. [2017a], the recommended model is largely controlled by empirical observations (inferences from interpretation of NGA-East ground motion data) for the F_V term and by simulations for the F_{760} term and the F_{nl} term. Before detailing the proposed model, we briefly explain why we adopted this approach.

First – *why did we adopt a hybrid approach in which simulations are solely used for the nonlinear model while empirical data in conjunction with simulations were considered for the linear model?* Our response is two-fold. First, as described in Section 1.2, there is precedent for such an approach in the development of site amplification models in active tectonic regions, and indeed in the original NEHRP factors [BSSC 1992]. Moreover, whereas the use of ground response simulations to predict absolute levels of site amplification have been shown to often be problematic when applied in a consistent manner across multiple sites (e.g., Baturay and Stewart, [2003]; Kwok and Stewart [2006]; and Thompson et al. [2012]), their application for prediction of nonlinear effects has proven to be effective (e.g., Kwok and Stewart [2006] and Seyhan and Stewart [2014]).

Second – *why do we split the linear amplification term into two components instead of using a single term referenced to V_S=3000 m/sec?* This approach is adopted because of some critical details related to the ground motion data analysis used to generate the F_V model. The empirical data are useful to constrain the changes in site amplification over the range of site conditions present in the dataset, which is approximately V_{S30} = 200 to 2000 m/sec. The term we adopt for changes in site amplification over this V_{S30} range is 'V_{S30}-scaling.' As explained further in Parker et al. [2017], the V_{S30}-scaling is analyzed using a non-reference site approach with GMMs having a native reference condition of V_S = 3000 m/sec. Because of a lack of empirical information on the conversion from 760 m/sec to 3000 m/sec, GMM developers adjusted the data using assumed models for F_V and F_{760}, which allowed coefficients in the models to be set (this is particularly important for the constant term in the GMMs). To the extent that those site models are biased, the GMMs also are biased. However, that bias does not pass through to the analysis of F_V because it is removed during the partitioning of residuals. As a result, the F_V term is considered to be relatively robustly data-constrained. We recognize the potential for bias that is introduced by summing F_V and F_{760} to establish the total linear amplification. However, consider the alternatives. Applying a non-reference site analysis in which amplification is inferred from total residuals (relative to a V_S = 3000 m/sec reference GMM) would cause the F_{760}

term to disappear from our model. However, such an approach does not avoid bias from F_{760} terms, due to their use in the derivation of host GMMs. Another similar alternative would be to derive site factors referenced to V_S = 3000 m/sec fully from simulations (such models are available, for example, from Darragh et al. [2015], Boore and Campbell [2017], and Hashash et al. [2017b]), but this approach has no data constraint and may produce bias. In short, the proposed approach allows V_{S30}-scaling to be relatively robustly data-constrained, and while the remaining shift to 3000 m/sec (F_{760}) is admittedly not constrained by empirical data, it is captured through a consensus median model with associated epistemic uncertainties.

2.2 V_{S30}-SCALING MODEL

The V_{S30}–scaling model is trilinear in log-log space, as given below:

$$F_V = \begin{cases} c\ln\left(\dfrac{V_1}{V_{\text{ref}}}\right) & V_{S30} \le V_1 \\ c\ln\left(\dfrac{V_{s30}}{V_{\text{ref}}}\right) & V_1 < V_{S30} \le V_2 \\ c\ln\left(\dfrac{V_2}{V_{\text{ref}}}\right) + \dfrac{c}{2}\ln\left(\dfrac{V_{s30}}{V_2}\right) & V_{S30} > V_2 \end{cases} \tag{2.3}$$

The model form is shown in Figure 2.1. Term c represents the slope in log-log space for the central portion between corner velocities V_1 and V_2. Term V_{ref} is taken as 760 m/sec; its physical meaning is the velocity at which $F_V = 0$. The model is flat (constant F_V) for $V_{S30} < V_1$. The model has a slope of $c/2$ for $V_{S30} > V_2$. Model coefficients c, V_1, and V_2 are oscillator period-dependent. The coefficients are plotted as a function of period in Figure 2.2 and are tabulated in the electronic supplement. The basis for the proposed V_{S30}-scaling model is described in Chapter 3.

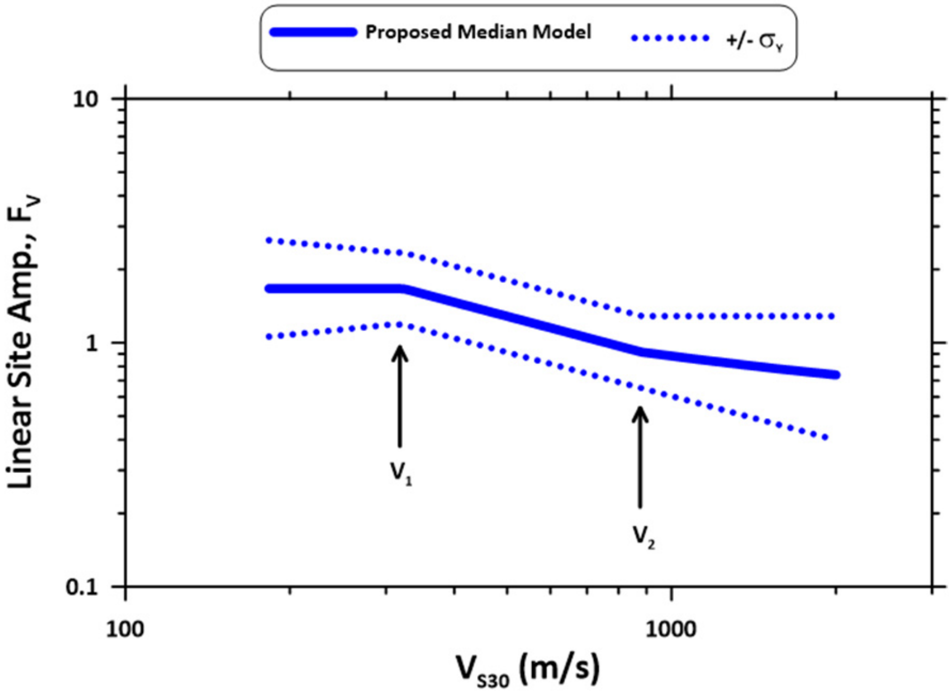

Figure 2.1 Form of recommended V_{S30}-scaling model and the associated uncertainty for 1.0-sec oscillator period [Equation (2.3), coefficients in electronic supplement].

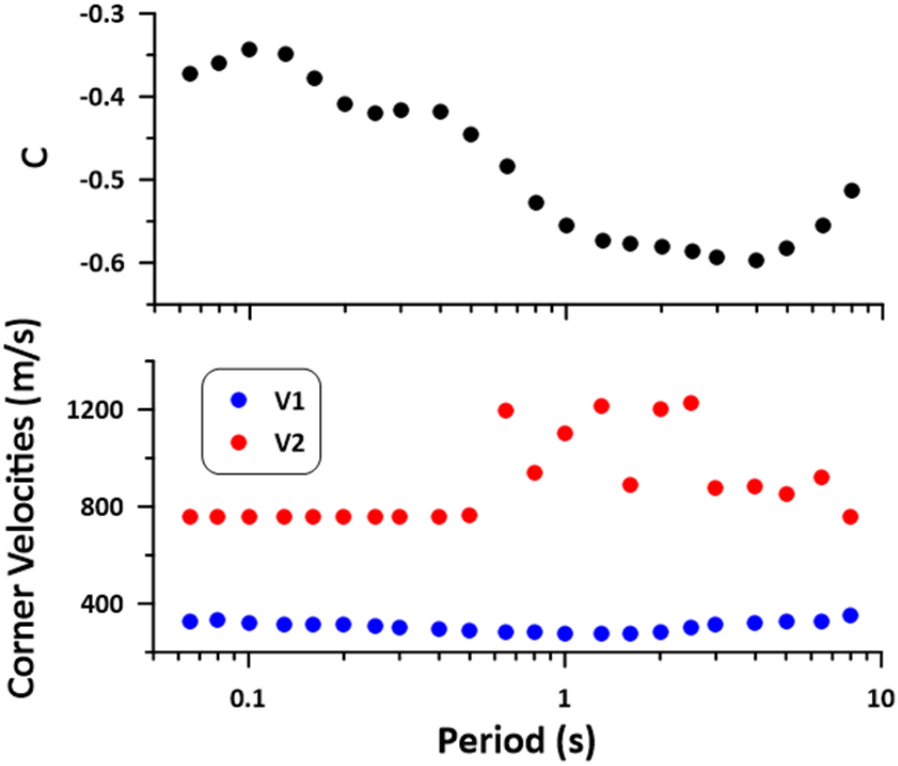

Figure 2.2 Period-dependence of coefficients in F_V model

The epistemic uncertainty associated with the model is given by a log-normal standard deviation σ_v that is constant over the middle portion of the V_{S30} range (between V_f and V_2) and increases at the low- and high-velocity limits of the model, as shown in Figure 2.1. The dispersion is described by:

$$\sigma_v = \begin{cases} \sigma_\ell - 2\left(\sigma_\ell - \sigma_{vc}\right)\dfrac{V_{S30} - V_\ell}{V_f - V_\ell} + \left(\sigma_\ell - \sigma_{vc}\right)\left(\dfrac{V_{S30} - V_\ell}{V_f - V_\ell}\right)^2 & V_{S30} < V_f \\ \sigma_{vc} & V_f \le V_{S30} \le V_2 \\ \sigma_{vc} + \left(\sigma_u - \sigma_{vc}\right)\left(\dfrac{V_{S30} - V_2}{V_u - V_2}\right)^2 & V_2 < V_{S30} \end{cases} \tag{2.4}$$

The coefficients for the uncertainty model are the uncertainty in the central portion of the velocity range (σ_{vc}), the increased uncertainty ($\sigma_\ell - \sigma_{vc}$) at the lower-limit velocity for the model (V_ℓ), and the increased uncertainty ($\sigma_u - \sigma_{vc}$) at the upper-limit velocity (V_u). Velocity V_f is specific to the uncertainty model and velocity V_2 is the same as for the median model. These and other coefficients are given in the electronic supplement.

2.3 F_{760}-AMPLIFICATION MODEL

The F_{760} model modifies ground motion intensity measures from a reference condition of V_S = 3000 m/sec to V_{S30} = 760 m/sec as a function of oscillator period. The model consists of a simple median and standard deviation (σ_{lnF760}) in natural log units, which are shown in Figure 2.3. The median and standard deviation are tabulated as a function of oscillator period in the electronic supplement. Justification for the proposed model is given in Chapter 4.

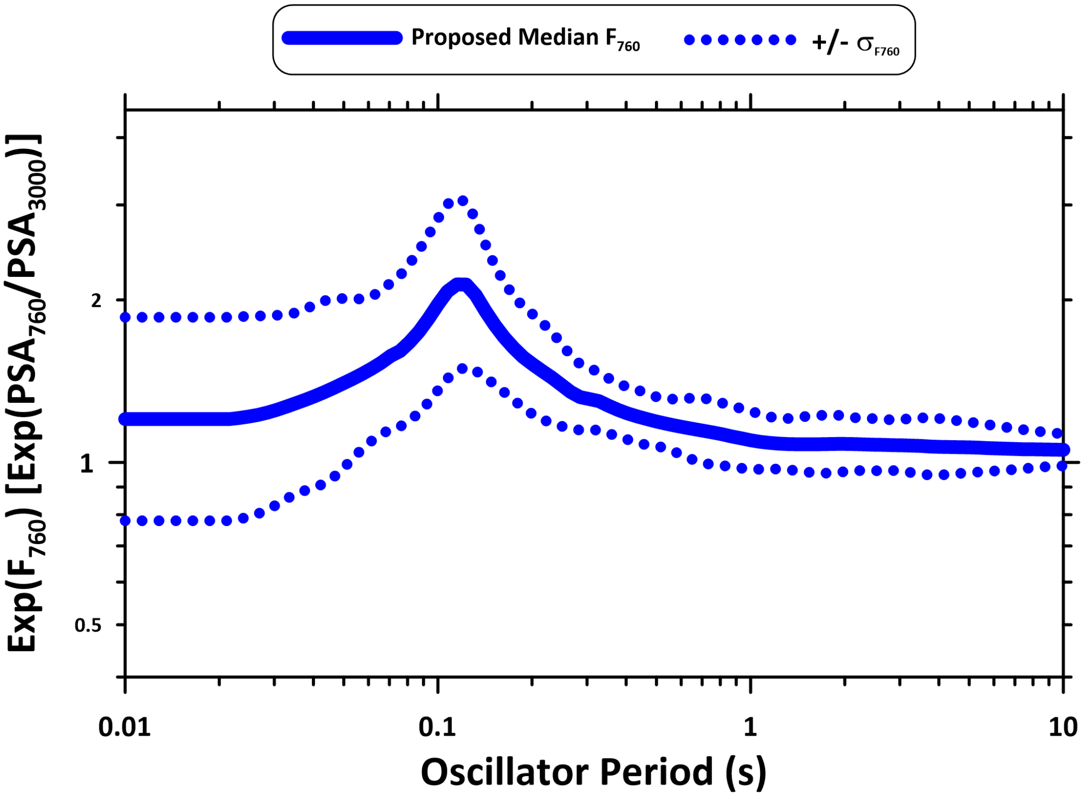

Figure 2.3 Reference condition site factor, F_{760}, and the associated uncertainty as a function of PSA oscillator period (values in electronic supplement).

3 V_{S30}-SCALING MODEL

3.1 MODELS CONSIDERED

The proposed model for V_{S30}-scaling (F_V) was selected upon consideration of results from prior research as described in Sections 1.2-1.3. In this section we describe how results for selected models were adapted for the model-to-model comparisons and explain why certain models were not selected for use in the comparison plots.

We consider two empirical models: (1) a model relating site amplification to peak frequency (f_{peak}) from horizontal to vertical spectral rations using NGA-East data for CENA [Hassani and Atkinson 2016a]; and (2) an empirical V_{S30}-scaling model developed by the NGA-East Geotechnical Working Group (referred to subsequently as GWG-E [Parker et al. 2017]). Additional empirical models that are not shown in the comparison plots are Hollenback et al. [2015], Al Noman and Cramer [2015], and Graizer [2015]. The site effects model for two Hollenback et al. [2015] GMMs was developed in Fourier amplitude space and only the final model values are available for PSA. The GMM developed by Al Noman and Cramer [2015] was not considered ready to be used as a seed model [Goulet, personal communication, 2017]. Finally, the Graizer [2015] GMM was selected as a seed for a limited frequency range only.

The Hassani and Atkinson [2016a] model conditions amplification on f_{peak} as shown in Figure 3.1. To apply this model, we convert f_{peak} to V_{S30} using the mean relationship between the two parameters as given by Hassani and Atkinson [2016b], shown in Figure 3.2. Values of f_{peak} corresponding to four values of V_{S30} (one in each NEHRP category A-D) were derived as follows: 270 m/sec – 2.33 Hz, 560 m/sec – 7.41 Hz, 1170 m/sec – 23.8 Hz, and 2032 m/sec – 57.3 Hz. Tabulated amplification values (provided by B Hassani, personal communication, 2016) were then used to estimate the site term for each approximate V_{S30}. Results are shown in Figures 3.3 to 3.14 along with those for other models. The Hassani and Atkinson results shown in these figures were shifted vertically so that the average between classes C and B passes through 1.0 at 760 m/sec. The GWG-E model is used as-is (no modification).

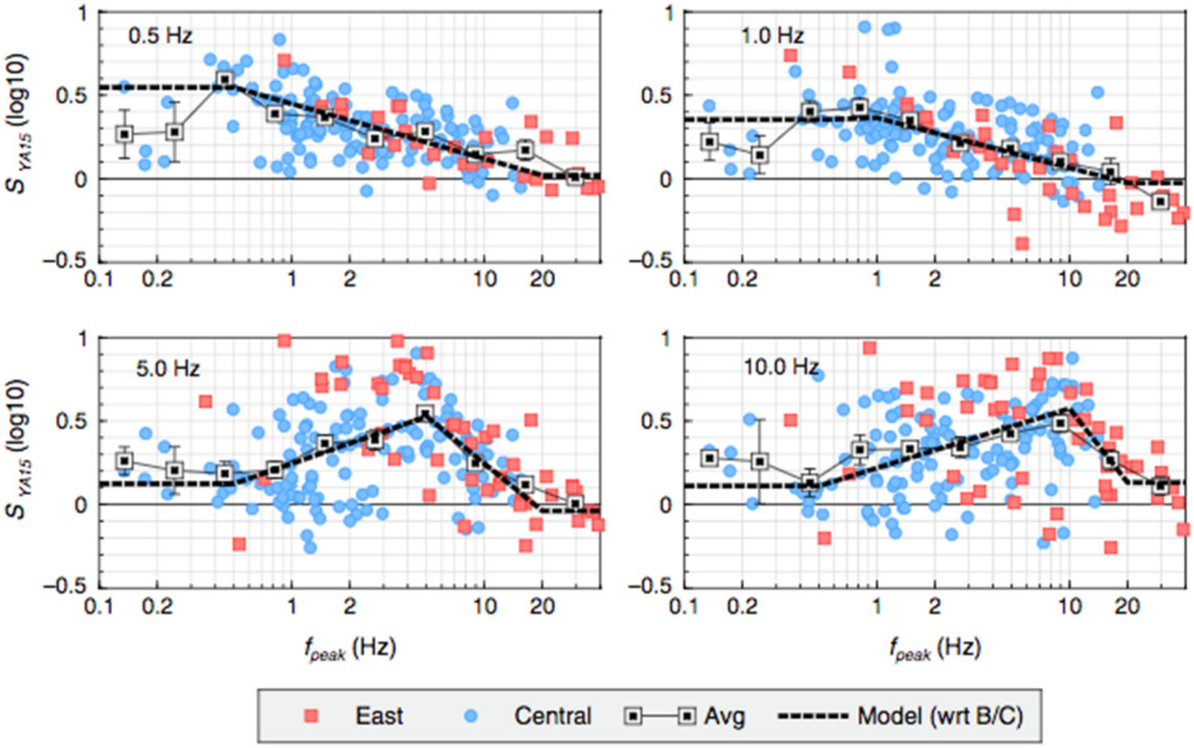

Figure 3.1 CENA amplification vs peak frequency from Hassani and Atkinson [2016a].

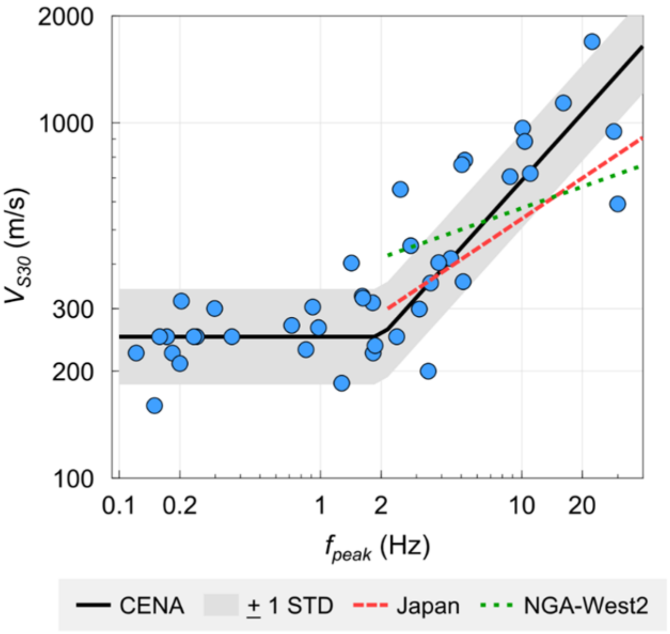

Figure 3.2 The f_{peak} to V_{S30} relationship from Hassani and Atkinson [2016b].

We considered four simulation-based models: (1) Darragh et al. [2015] [also referred to as Pacific Engineering and Analysis, (PEA)]; (2) a simulation-based V_{S30}-scaling model developed by the NGA-East Geotechnical Working Group (referred to subsequently as GWG-S; [Hashash et al. 2017b)]; (3) Hwang et al. [1997]; and (4) Aboye et al. [2015]. We have not presented in our summary plots prior simulation-based amplification results for the Mississippi Embayment by Hashash and Park [2001], Romero and Rix [2001], Park and Hashash [2005a], Park and Hashash [2005b], and Hashash et al. [2008]. We consider those earlier results to be superseded by Hashash et al. [2017b].

Models (1), (3), and (4) were introduced in Section 1.2. The Darragh et al. [2015] model uses a reference condition of V_S = 3000 m/sec. To apply this model, we adjusted digital amplification values (provided by Walt Silva, personal communication, 2016) to a reference condition of V_{S30} = 760 m/sec by dividing by F_{760} values given in their report (details in Chapter 4). Hwang et al. [1997] present tabulated amplification values for 0.2 and 1.0 sec PSA for NEHRP categories A-D, which we plot at category mid-velocities (V_{S30} = 1868, 1052, 498, and 243 m/sec). The Hwang et al. [1997] results were adjusted to an amplification of 1.0 at V_{S30} = 760 m/sec; original results were at 1.0 for class B. We applied the median model from Aboye et al. [2015] as shown in Figure 1.3 for 0.2 and 1.0 sec PSA. The as-presented model gives an amplification of unity at V_{S30} = 760 m/sec, and hence no adjustments were applied.

The GWG-S model was provided in a form that was already corrected to the 760 m/sec reference rock condition. Digital values of the model predictions were provided by Joseph Harmon (Personal communication, 2016).

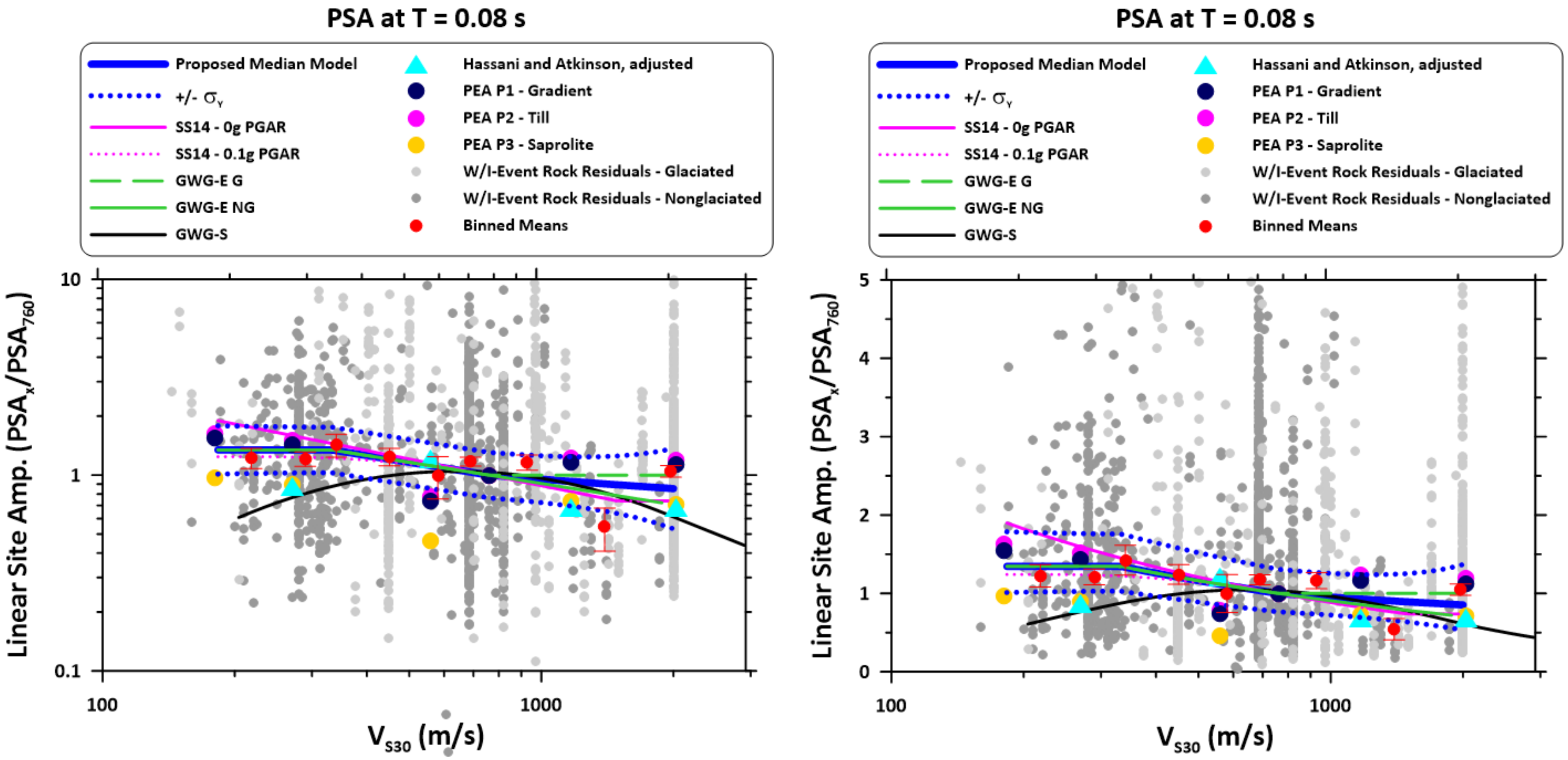

Figure 3.3 Scaling of site amplification with V_{S30} at PSA oscillator period 0.08 sec, for CENA region from alternate models, and for a reference model for active tectonic regions (ATRs) (log-log plot on the left, linear-log plot on the right). Proposed Median Model = Average of GWG-E models, sometimes adjusted at low V_{S30}. SS14 = Seyhan and Stewart [2014], semi-empirical model developed for active regions, for $PGA_r = 0$ (linear site amplification only) and for $PGA_r = 0.1g$ (as used for developing current NEHRP site factors). GWG-E G and GWG-E NG = Geotechnical Working Group empirically-based model for glaciated and nonglaciated regions, respectively. GWG-S = Geotechnical Working Group simulation based model. Hassani and Atkinson [2016a,b] adjusted = f_{peak}-based model for CENA adjusted to unity at 760 m/sec. PEA = Darragh et al. [2015] simulation-based model, adjusted to a reference condition of 760 m/sec using three simulation-based factors for representative V_S profiles (Profile 1 – Gradient, Profile 2 – Till, and Profile 3 – Piedmont Region Saprolite). W/I-Event Rock Residuals and their binned means represent the empirical data considered by GWG-E.

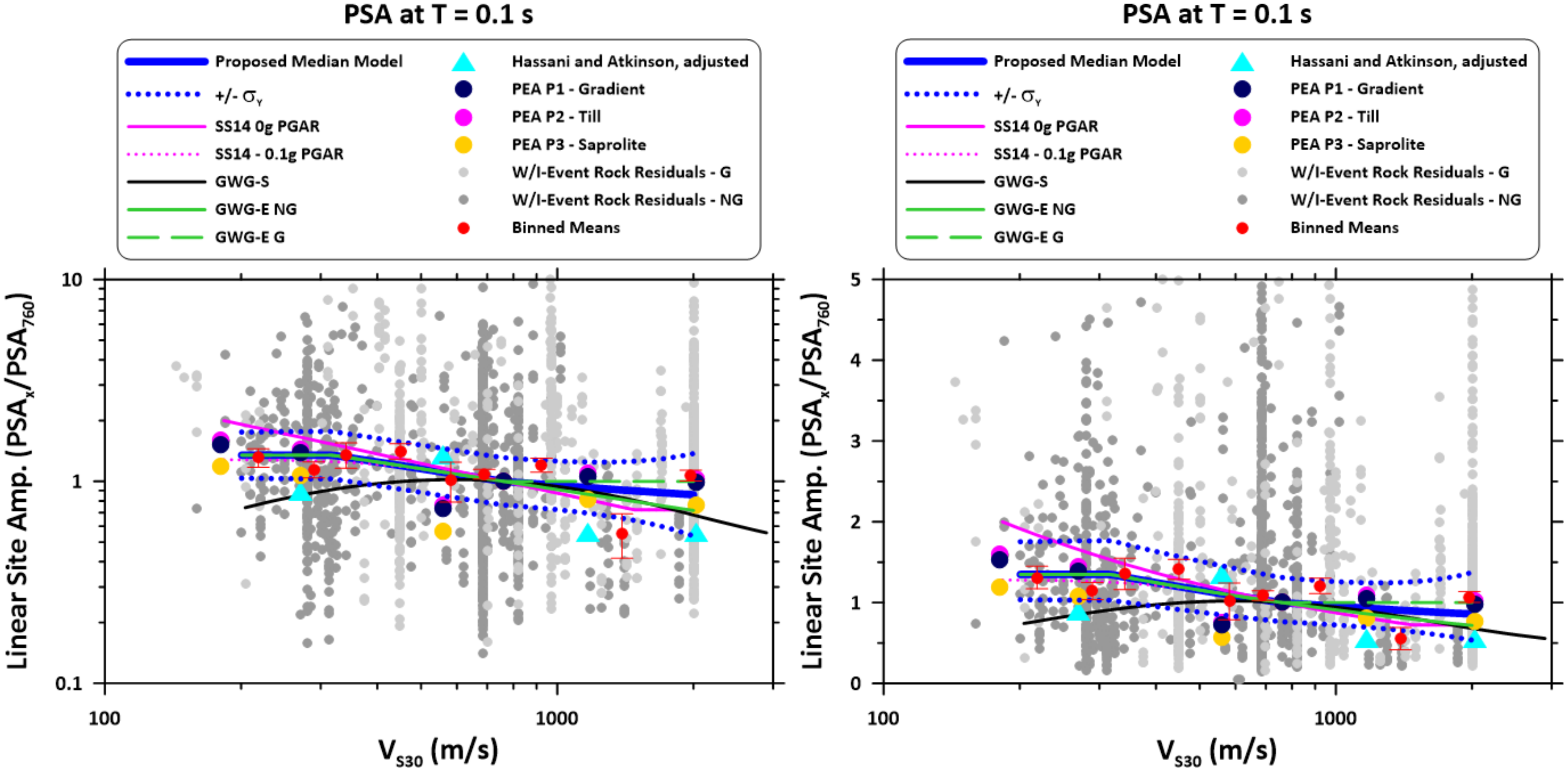

Figure 3.4 Scaling of site amplification with V_{S30} at PSA oscillator period 0.1 sec. See explanation of figure and symbols in Figure 3.3 caption.

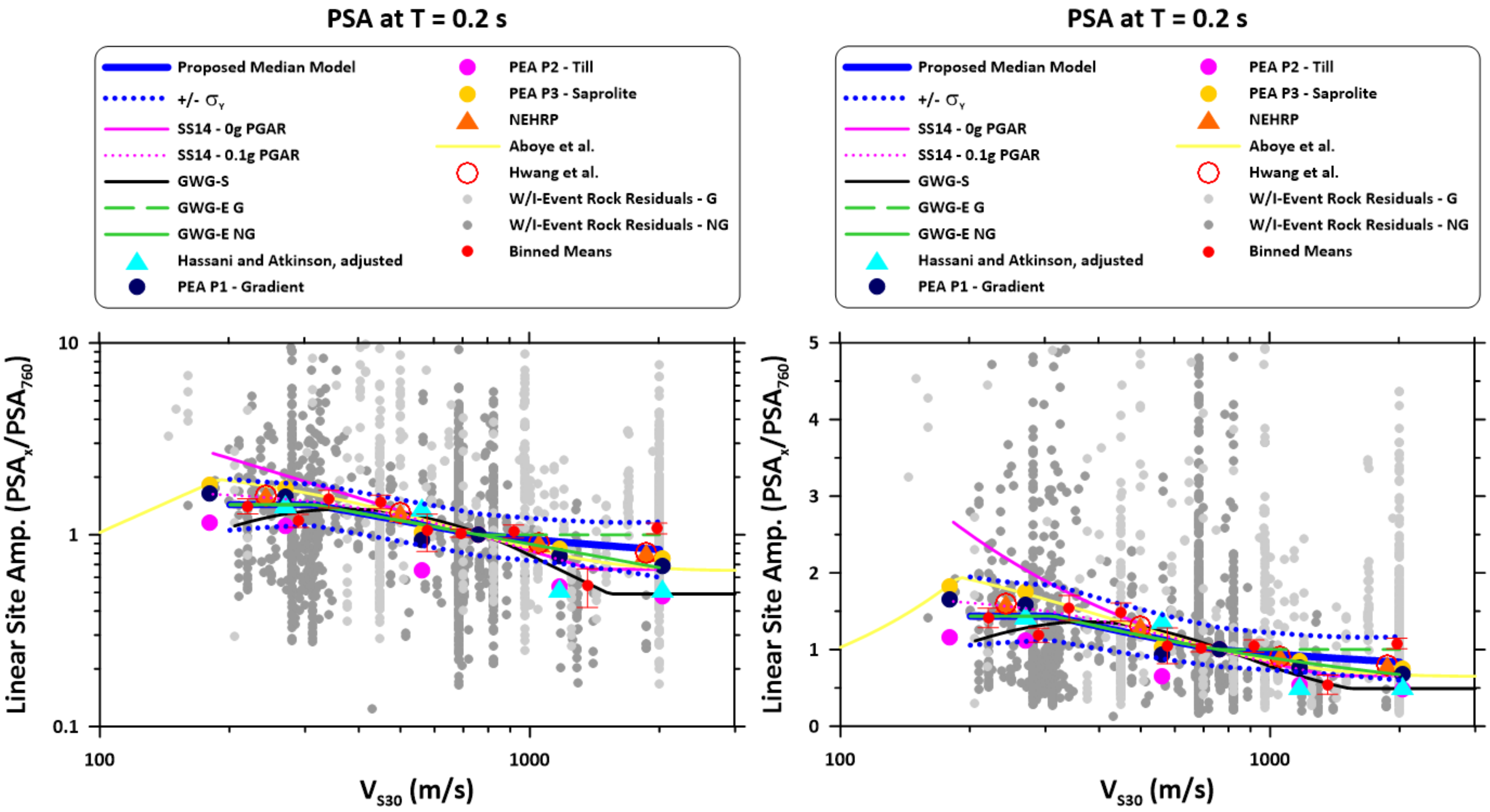

Figure 3.5 Scaling of site amplification with V_{S30} at PSA oscillator period 0.2 sec. See explanation of figure and symbols in Figure 3.3 caption. Additional symbols in this plot and not explained Figure 3.3 caption: NEHRP = factors from NEHRP provisions [BSSC 2015]; Aboye et al. = Aboye et al. [2015]; Hwang et al. = Hwang et al. [1997].

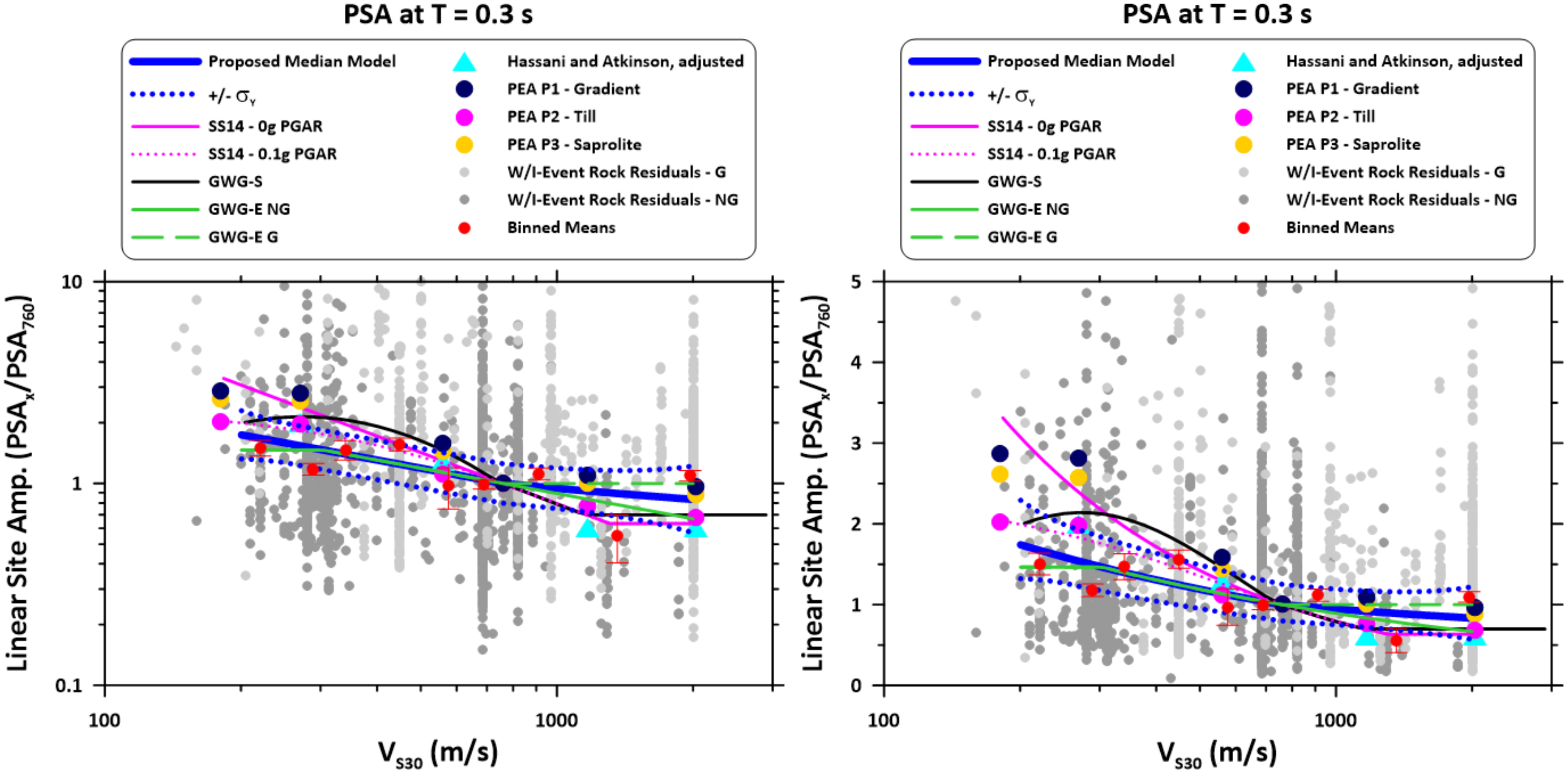

Figure 3.6 Scaling of site amplification with V_{S30} at PSA oscillator period 0.3 sec. See explanation of figure and symbols in Figure 3.3 caption.

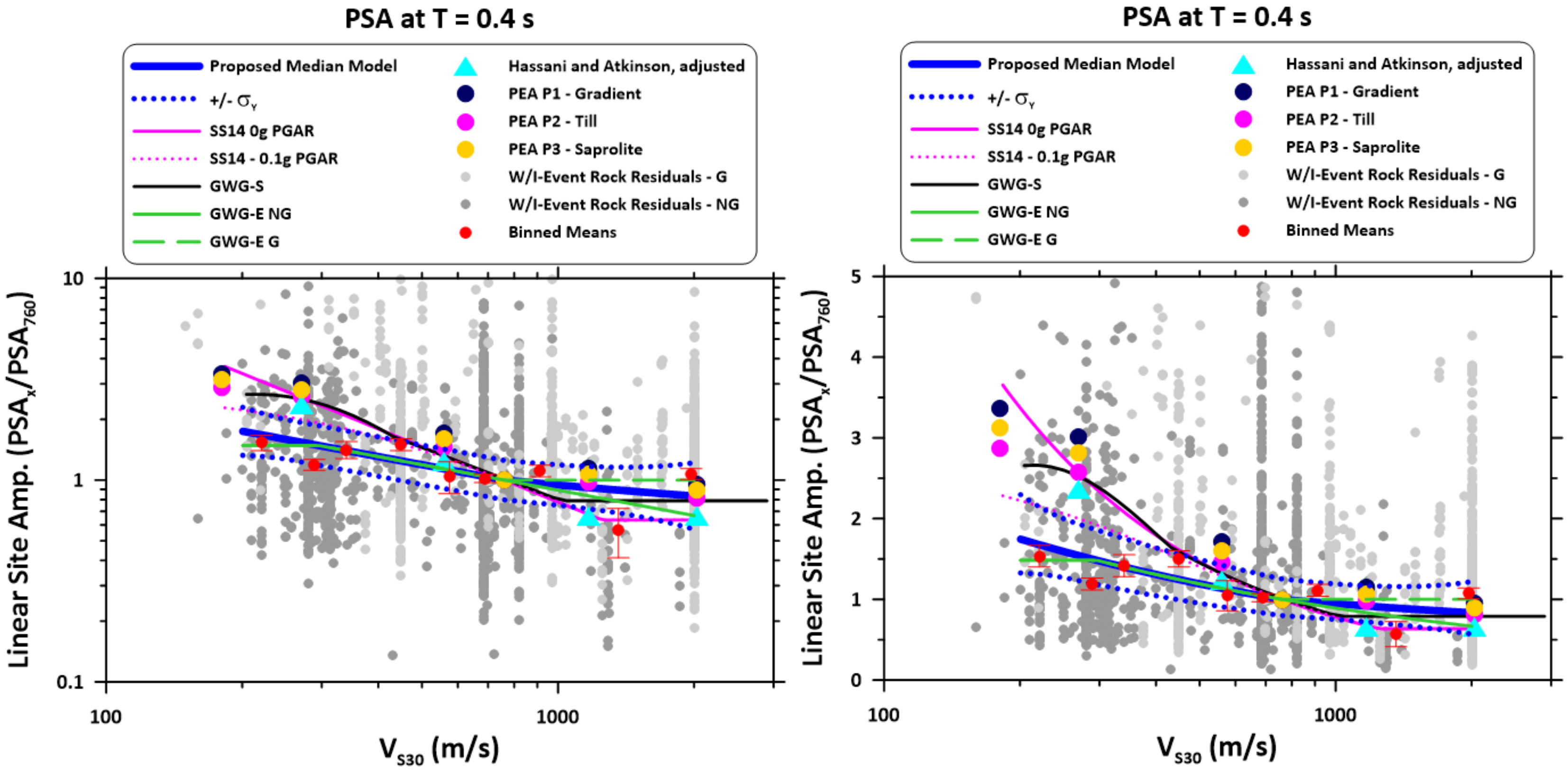

Figure 3.7 **Scaling of site amplification with V_{S30} at PSA oscillator period 0.4 sec. See explanation of figure and symbols in Figure 3.3 caption.**

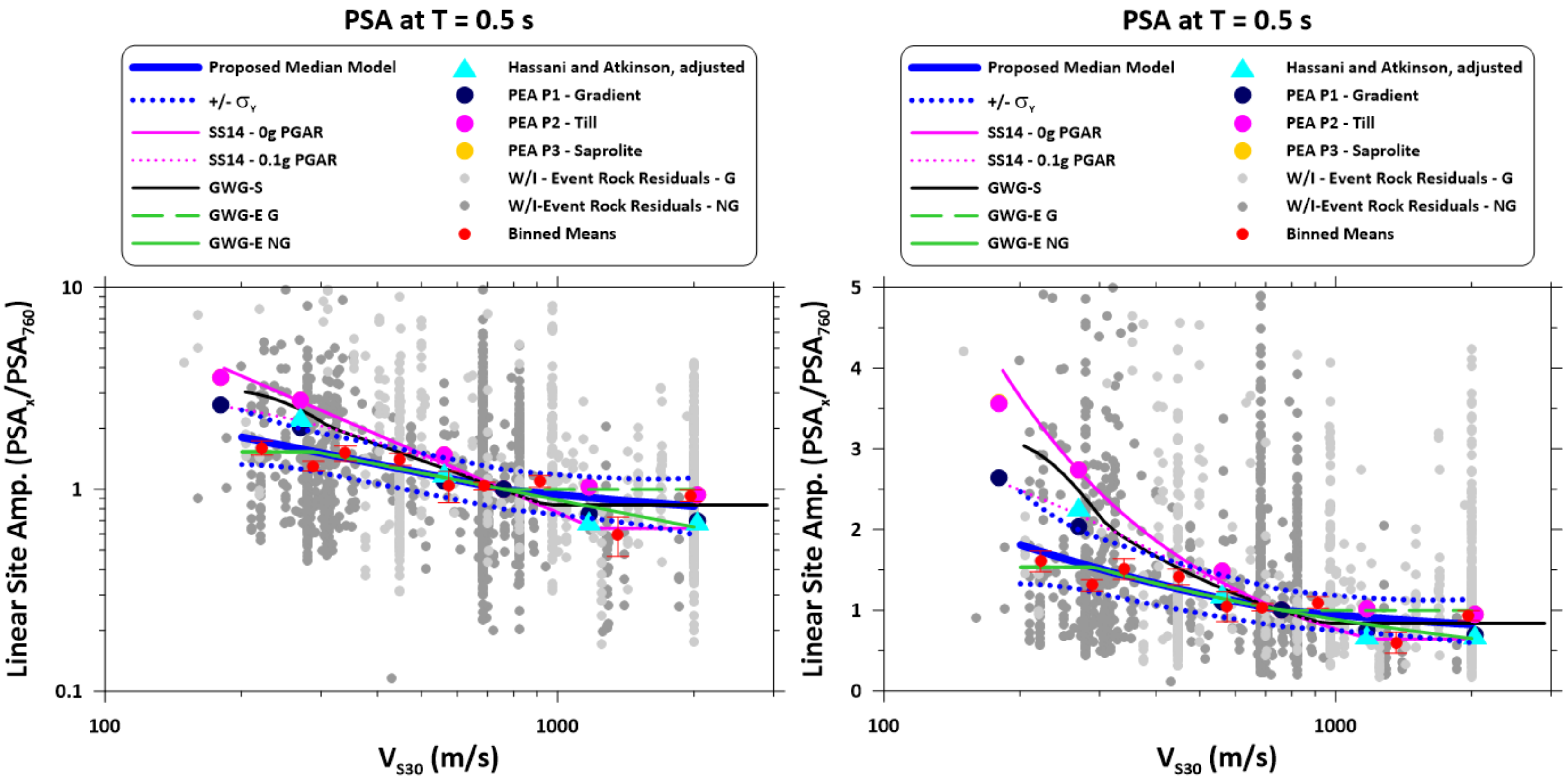

Figure 3.8 Scaling of site amplification with V_{S30} at PSA oscillator period 0.5 sec. See explanation of figure and symbols in Figure 3.3 caption.

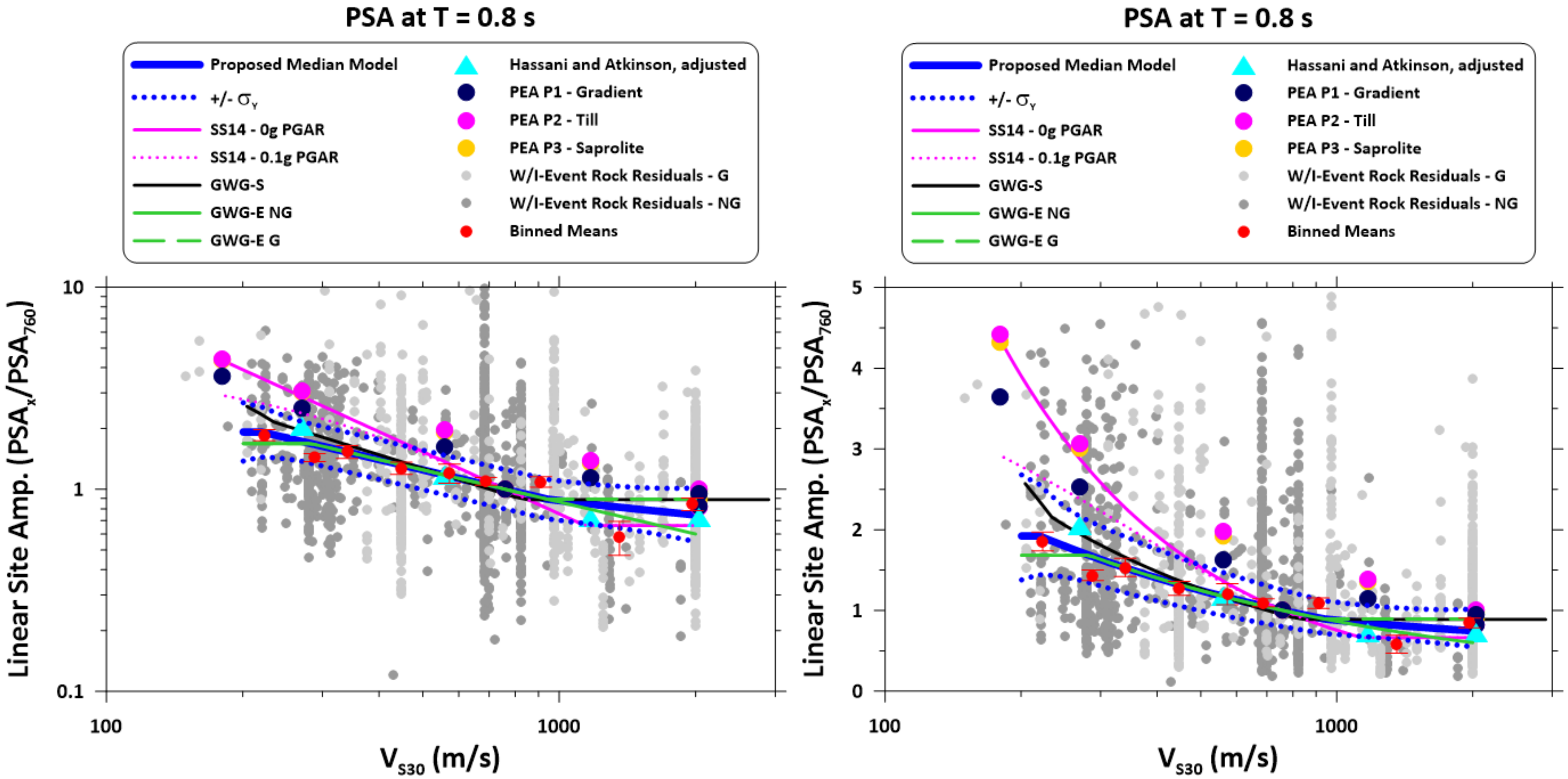

Figure 3.9 Scaling of site amplification with V_{S30} at PSA oscillator period 0.8 sec. See explanation of figure and symbols in Figure 3.3 caption.

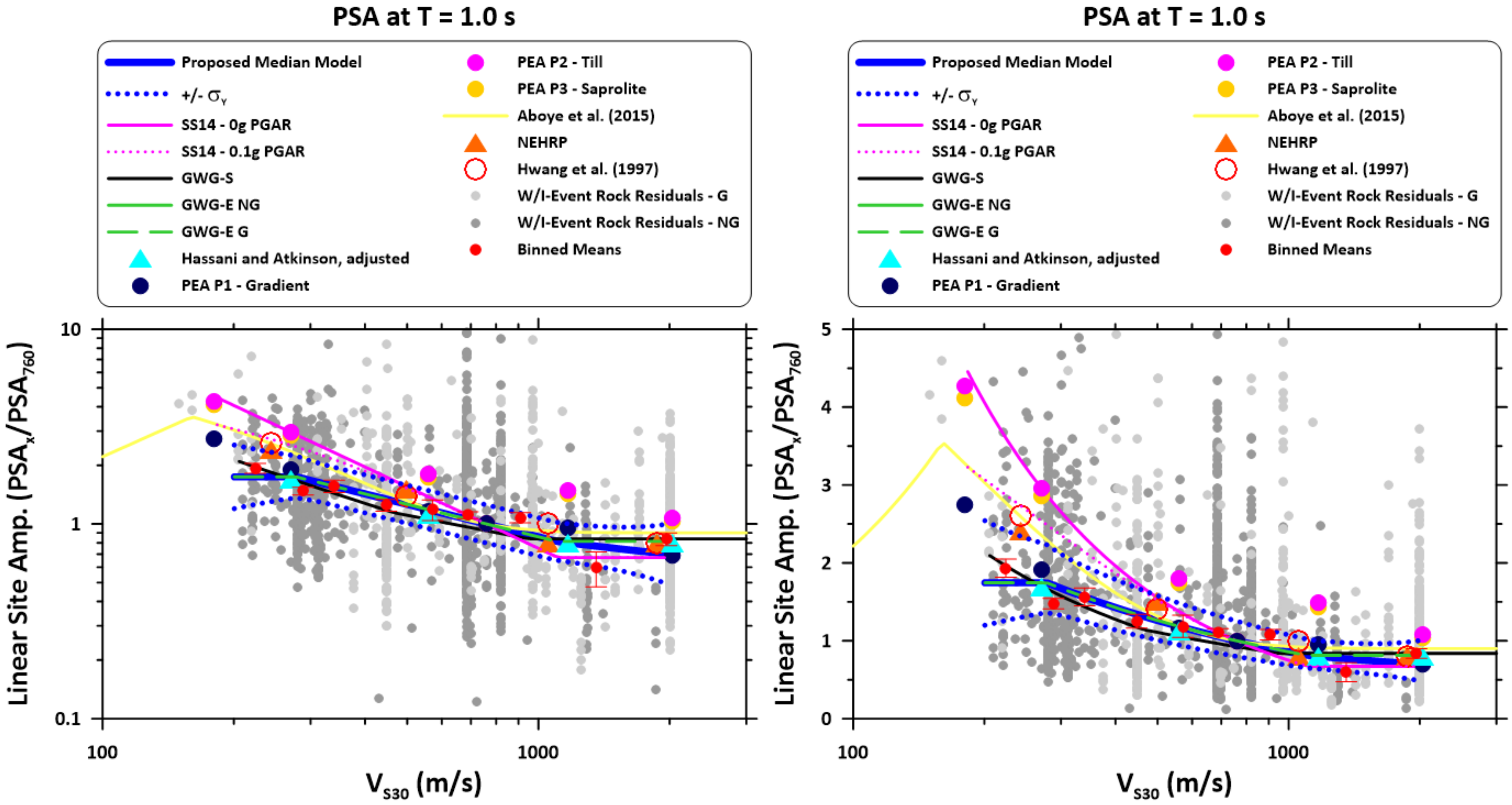

Figure 3.10 Scaling of site amplification with V_{S30} at PSA oscillator period 1.0 sec. See explanation of figure and symbols in Figure 3.3 caption.

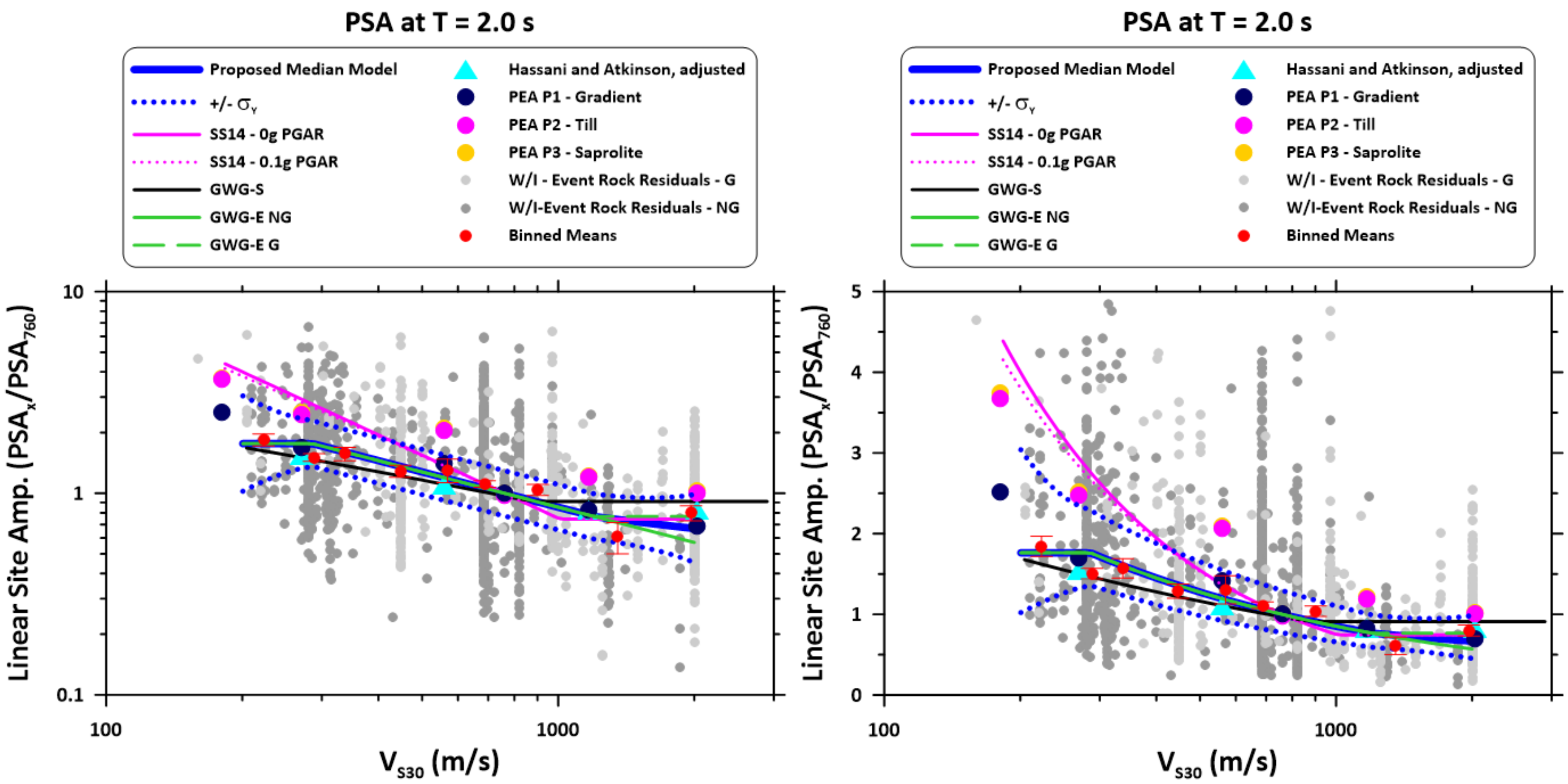

Figure 3.11 Scaling of site amplification with V_{S30} at PSA oscillator period 2.0 sec. See explanation of figure and symbols in Figure 3.3 caption.

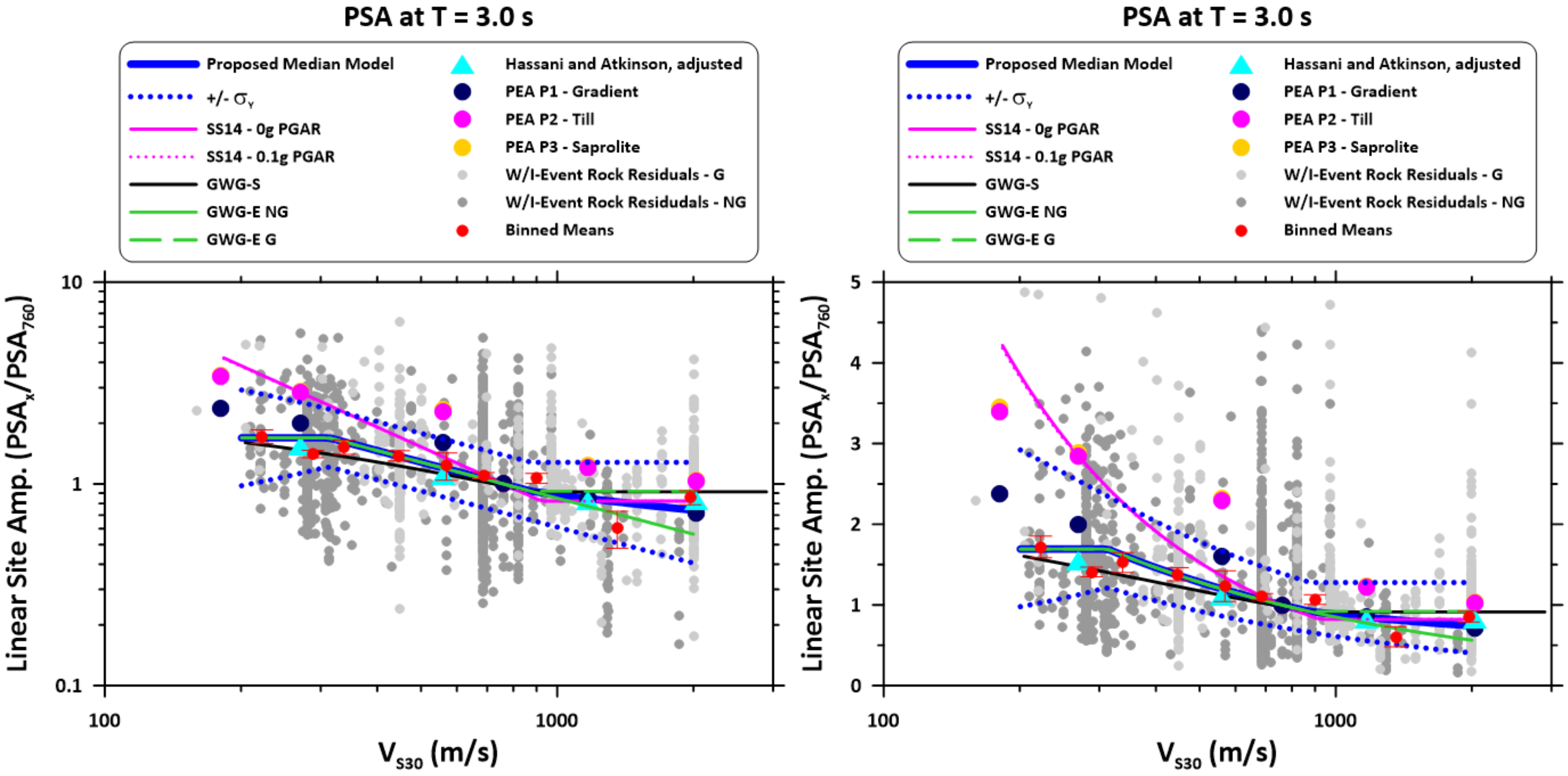

Figure 3.12 Scaling of site amplification with V_{S30} at PSA oscillator period 3.0 sec. See explanation of figure and symbols in Figure 3.3 caption.

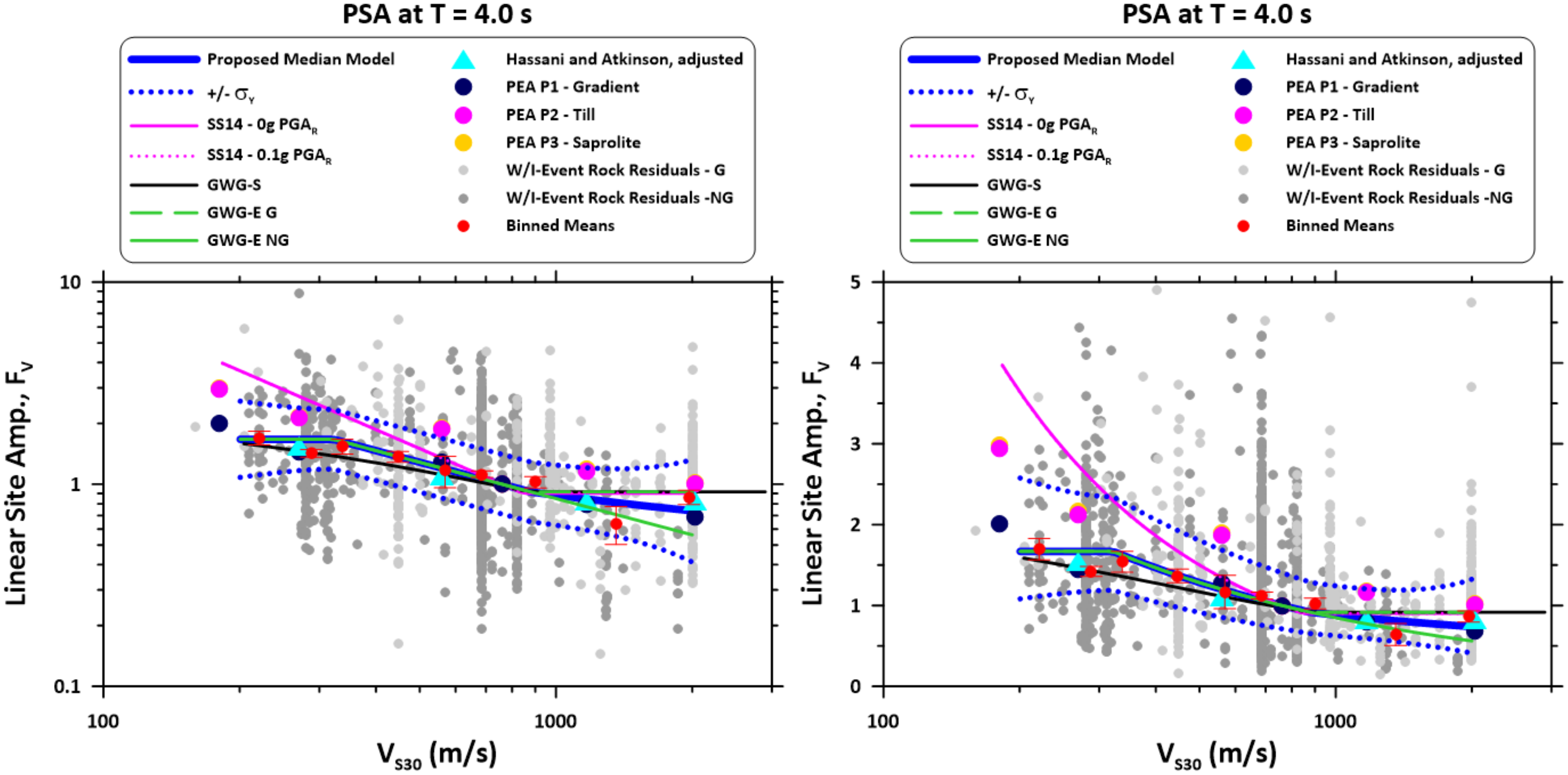

Figure 3.13 Scaling of site amplification with V_{S30} at PSA oscillator period 4.0 sec. See explanation of figure and symbols in Figure 3.3 caption.

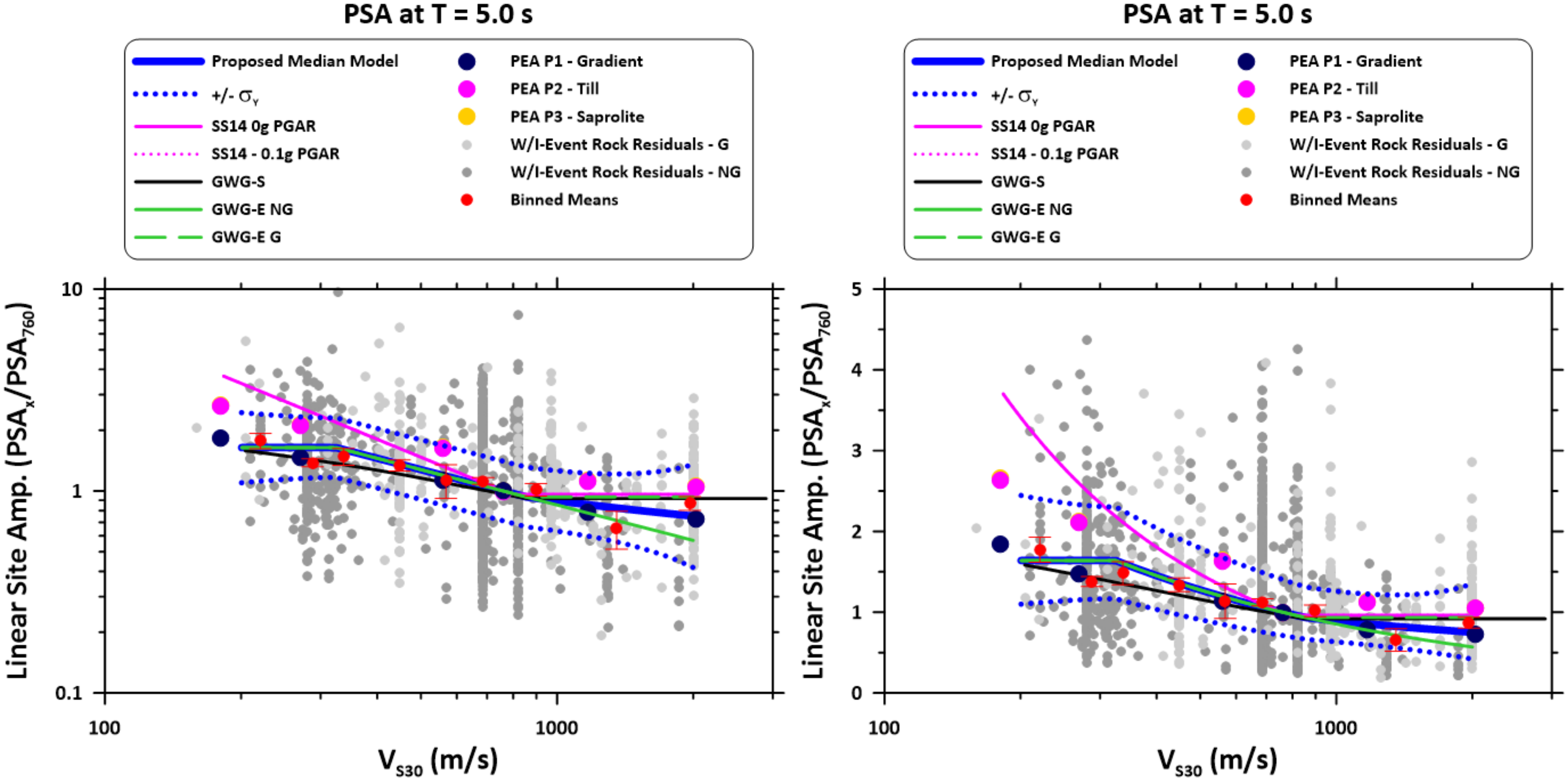

Figure 3.14 Scaling of site amplification with V_{S30} at PSA oscillator period 5.0 sec. See explanation of figure and symbols in Figure 3.3 caption.

3.2 MODEL COMPARISON AND RECOMMENDED MEDIAN

Figures 3.3–3.14 present the CENA models described in Section 3.1. Also shown for comparison is the Seyhan and Stewart [2014] model for active tectonic regions (all periods) and the site factors in the NEHRP provisions for periods of 0.2 and 1.0 sec.

One notable feature in the plots is that the GWG-S and Aboye et al. [2015] simulation-based models have downward curvature in the V_{S30}-scaling at short periods ($T \leq 0.3$ sec), which is not present in the Darragh et al. [2015] model. One explanation for the difference in simulation results is different small-strain soil damping formulations. The Darragh et al. [2015] model equivalent-linear simulations used strain-dependent 'Peninsular Range curves' [Silva et al. 1997), a more linear subset of the EPRI [1993] curves, in the upper 150 m (500 ft) with visco-elastic soil behavior below. At greater depth, the visco-elastic damping was limited so as to not allow the ground surface diminution parameter (κ_0) to exceed 0.04 sec. The linear viscous-elastic simulations in Hashash et al. [2017b] use small-strain damping ratio (D_{min}) from the Campbell [2009] Q-V_S Model 1 without constraint by the resulting surface κ_0. As a result, the GWG-S simulations can have higher levels of profile damping than those of Darragh et al. [2015]. The physics of wave propagation require increased damping to decrease ground motion, particularly at high frequencies. The panel elected to not incorporate the downward curvature feature in V_{S30}-scaling into the recommended median model, due to this feature not being evident in the GWG-E empirical data (also shown in the figures).

The Hassani and Atkinson [2016a] model exhibits peaked behavior in amplification-V_{S30} space at the V_{S30} value corresponding to the PSA oscillator period being plotted. For example, in Figure 3.4 (oscillator response for $T = 0.1$ sec, corresponding to $f_{\text{peak}} = 10$ Hz) the Hassani and Atkinson [2016a] model peaks at ~600 m/sec. The peaks occur at slower velocities as period increases. This behavior is a consequence of f_{peak} being the sole site-response variable in the Hassani and Atkinson [2016a] model; in the implementation of the model for this study, V_{S30} is used as a proxy-measure for f_{peak}, in which stiffer sites (higher V_{S30}) have higher peak frequencies. Other recent models not considered in the present study propose the use of both V_{S30} and f_{peak} for improved site-response modeling [Kwak et al. 2017; Hassani and Atkinson 2017].

The GWG-E model demonstrates relatively flat scaling at slow ($V_{S30} < V_1$) and fast ($V_{S30} > V_2$) velocities. Both trends are generally supported by the simulation-based models as well and have different physical explanations. At slow V_{S30} and short periods, the reduction of scaling is likely due to the effects of soil damping. For longer periods, the cause of the flat scaling at slow V_{S30}, especially as compared to western models (SS14), is unknown but may result from different average soil depths. While sediment depth information at seismograph sites is generally unknown, Parker et al. [2017] investigated bias in the GWG-E model for sites in particular basins, and found no systematic features that would justify adjustment to the model. At fast V_{S30}, the reduction of scaling is thought to be caused by the reduced predictive power of V_{S30} as a site parameter for stiff sites with relatively long wavelengths (compared to slower sites with shorter wavelengths). Overall the best agreement between GWG-E and simulation-based models are at $V_{S30} > \sim 400$ m/sec and $T > 0.2$ sec.

The model shown in Figures 3.3-3.14 for active tectonic regions [Seyhan and Stewart 2014] provides a poor match to the CENA results for most periods. Some particular areas of divergence are:

- The SS14 model does not show flattening of the V_{S30}-scaling at slow velocities
- For the central range of V_{S30} (approximately between V_1 and V_2), the SS14 V_{S30}-scaling is steeper than that for CENA models.

Because the NEHRP site factors follow the SS14 model, to the same extent that the CENA results reject SS14, then they also reject the current NEHRP factors (in CENA).

The panel based the median model largely on the GWG-E model. Referring to Equation (2.3), corner velocities V_1 and V_2, zero gradient for $V_{S30} < V_1$, and slope c for $V_1 < V_{S30} < V_2$ are taken from GWG-E. One exception is that GWG-E has different slopes for $V_{S30} > V_2$ for glaciated and non-glaciated sites; for the median model we take an average slope ($c/2$) in this range. The second exception is that at slow velocities and oscillator periods of 0.3–0.8 sec, we decrease V_1 from GWG-E values, which raises the amplification at slow velocities. This change was motivated by the GWG-E amplification being lower than other models for soft soils in this period range.

The resulting recommended model is described by Equation (2.3) with the coefficients in the electronic supplement. Limitations on application of the model are given in Chapter 5.

3.3 MODEL UNCERTAINTY

We evaluated the model uncertainty shown in Figures 3.3–3.14 using engineering judgment, rather than through a formal calculation of standard deviations between models. This approach was applied for three principal reasons: (1) the variations among models is uneven across periods, being relatively low for $T > 1$ sec and large at smaller period−in the judgment of the panel, these period-to-period features do not reflect true epistemic uncertainties in site amplification; (2) for many periods, the median model is not at the center of the range in log space (there are often more models above than below the median)−as a result, application of a formal standard deviation around the median model would not have encompassed the expected number of models; and (3) the panel judged that increases in the model uncertainty should be applied at upper and lower ends of the velocity range, where data are sparse −reliance on formal statistical methods would frequently not provide this. As a result of these considerations, the use of formal standard deviations to set the epistemic uncertainty was not considered to be appropriate.

Rather, a subset of the panel studied the results in Figures 3.3–3.14 and proposed a range that can be interpreted as ± one standard deviation (σ_v). This was reviewed by the full panel, and after some adjustments, the results in the figures were prepared. In developing the range, we sought to center the model on the median, to have the width of the range represent uncertainty in a smoothed manner across the velocity range (not fluctuating), and to increase the uncertainty at slow and fast velocities where data are relatively sparse. In Equation (2.4), term σ_{vc} represents the selected standard deviation in the central portion of the velocity range. The relations in Equation (2.4) for $V_{S30} < V_1$ and $V_{S30} > V_2$ are polynomials constrained to have dispersion of σ_{vc} and zero slope at V_1 and V_2.

4 F_{760} MODEL

4.1 MODELS CONSIDERED

The proposed model for adjusting ground motion intensity measures from the V_S = 3000 m/sec reference condition to V_{S30} = 760 m/sec (F_{760}) is based on a number of alternative simulation results, all of which are based on one-dimensional ground response analyses of various types. This section presents the simulation results considered by the panel, while Section 4.2 presents the recommended model and its uncertainty.

Most F_{760} models in the literature simulate ground response using the square-root-impedance method, also known as the quarter-wavelength method [Boore 2013]. Nonlinear effects are not considered, which is considered to be justifiable given the fast velocities and correspondingly small strains. This method of analysis does not consider resonance effects. The parameters controlling the analysis results are the V_S profile for the V_{S30} = 760 m/sec site condition and the level of soil damping (expressed through diminution parameter κ_0). An alternative is to consider resonance effects, which produce peaks in the site transfer function that are smoothed out when using the quarter-wavelength method. This alternative maintains the treatment of soil behavior as linear and also treats damping through the use of κ_0. A second alternative is wave propagation analysis using geotechnical ground response analysis, which captures resonance effects and nonlinear effects, as applicable.

The panel considered results from three investigations – Boore and Campbell [2017], Darragh et al. [2015], and GWG-S [Hashash et al. 2017b]. Boore and Campbell [2017] use both a square-root impedance approach and an approach that captures resonance. We consider the Boore and Campbell [2017] results to supersede results from previous related studies [Frankel et al., 1996; Beresnev and Atkinson, 1997; Boore and Joyner, 1997; Atkinson and Boore 2006; Boore, 2015; and Boore and Thompson, 2015]. Darragh et al. [2015] and Hashash et al. [2017b]

used wave propagation analysis procedures (RVT-based equivalent linear and linear viscous-elastic, respectively) that capture resonance and nonlinear effects. For material properties, Darragh et al. [2015] use 'Peninsular Range curves' given in Silva et al. [1997] in the upper 150 m, while Hashash et al. [2017b] take small-strain damping ratio (D_{min}) from the Campbell [2009] Q-V_S Model 1. The Darragh et al. [2015] results supersede prior results presented by Silva et al. [2003].

Figure 4.1 shows the shear-wave velocity profiles considered by Boore and Campbell [2017] and Figure 4.2 shows the profiles used by Darragh et al. [2015] and Hashash et al. [2017b]. The Boore and Campbell [2017] profiles are measurements from CENA sites in which V_{S30} is within 10% of 760 m/sec. Hashash et al. [2017b] used V_S profiles with V_{S30} between 700 and 800 m/sec. The three Darragh et al. [2015] profiles are intended to be representative of three different CENA geologic conditions: glacial till, Piedmont saprolite, and a weathered rock gradient, all with V_{S30} = 760 m/sec. They were constructed using suites of measured profiles reflecting these near surface geologies.

Aside from V_S profiles, the other site parameter that strongly influences F_{760} is the diminution parameter κ_0. This parameter scales Fourier amplitudes predicted by stochastic simulation procedures by $\exp(-\pi\kappa_0 f)$, where f is frequency in Hz and κ_0 (units of sec) reflects the effects of site damping (e.g., Anderson and Hough [1984]). Boore and Campbell [2017] present available literature on κ_0 for V_{S30} = 760 m/sec sites, which we summarize as follows:

1. Literature regarding κ_0 for 760 m/sec sites in CENA suggest that while measurements from sites having this velocity condition are unavailable, past practice has been to use κ_0 in the range of 0.01 to 0.025 sec.
2. The Pinon Flat site in CA is often used to estimate κ_0 for 760 m/sec sites in CENA because it has a V_S profile similar to those observed in CENA. Stochastic simulations of peak acceleration and velocity show the best fit to CENA ground-motion data for $\kappa_0 \sim 0.02$ sec.
3. A re-evaluation of Fourier amplitude spectra from Pinon Flat recordings (originally presented in Hough et al. [1988]) found $\kappa_0 \sim 0.01$–0.03 sec with an average of 0.015 sec.

Based on these findings, for the present application we use Boore and Campbell [2017] simulation results for κ_0 = 0.01, 0.02, and 0.03 sec. We note that Darragh et al. [2015] use κ_0 = 0.02 sec for 760 m/sec profiles, which is compatible with this range.

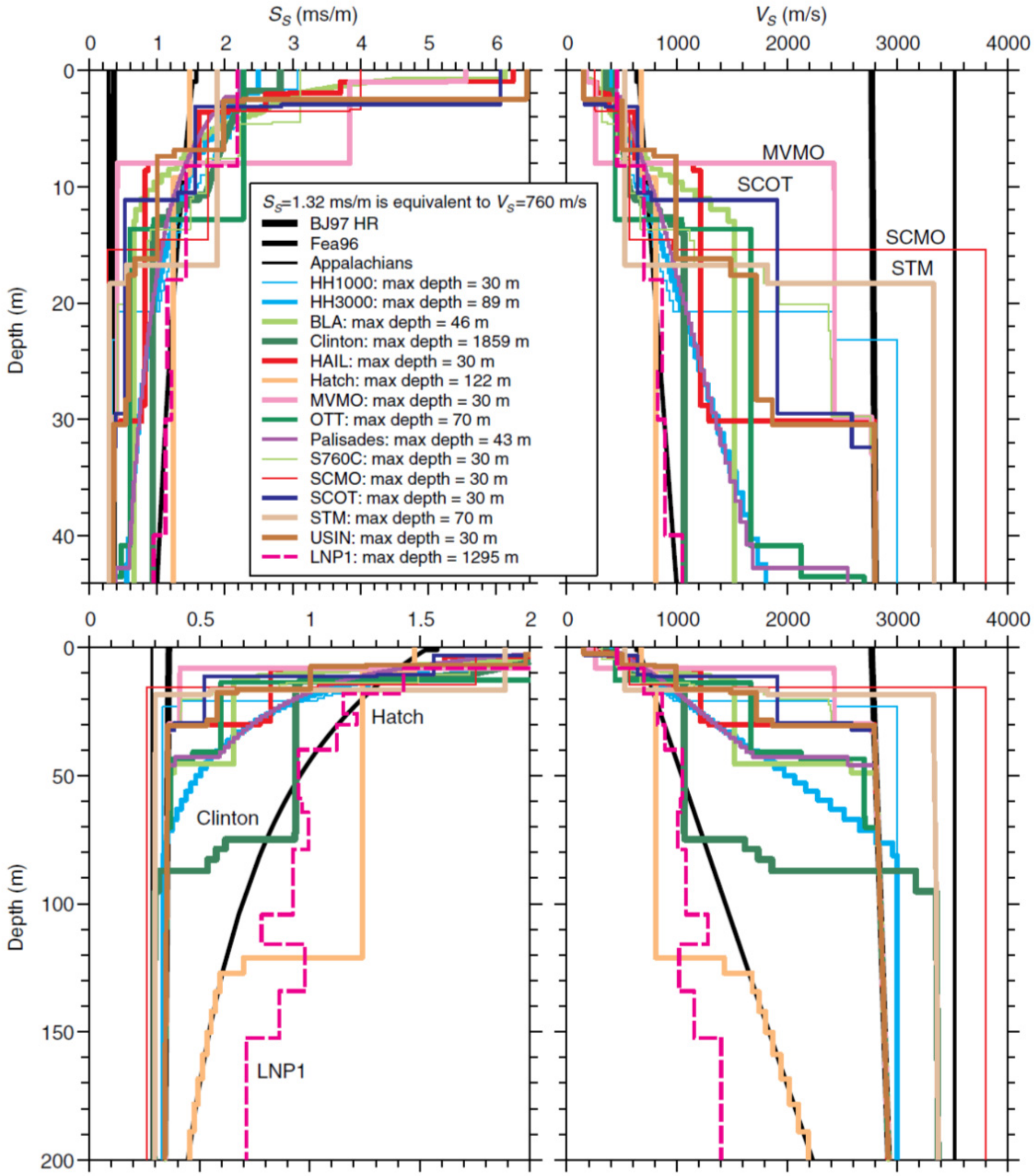

Figure 4.1 Shear-wave slowness and velocity vs depth for 15 V_S profiles in CENA with V_{S30} within 10% of 760 m/sec used in the development of the Boore and Campbell [2017] F_{760} model. Figure from Boore and Campbell [2017].

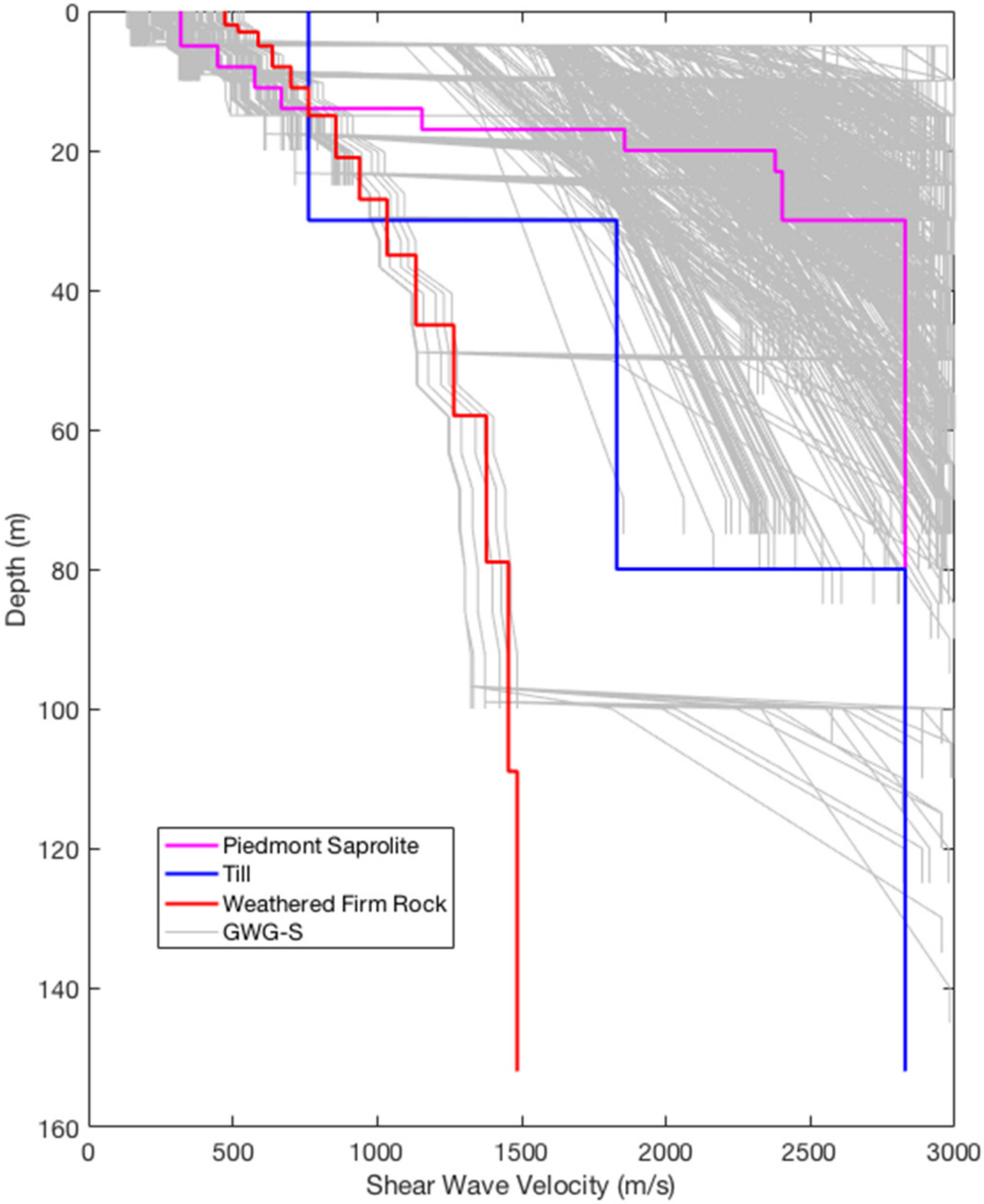

Figure 4.2 Shear-wave velocity vs depth profiles in CENA with V_{S30} between 700 and 800 m/sec (marked as GWG-S in legend [Hashash et al. 2017b]) or equivalent to 760 m/sec [Darragh et al. 2015].

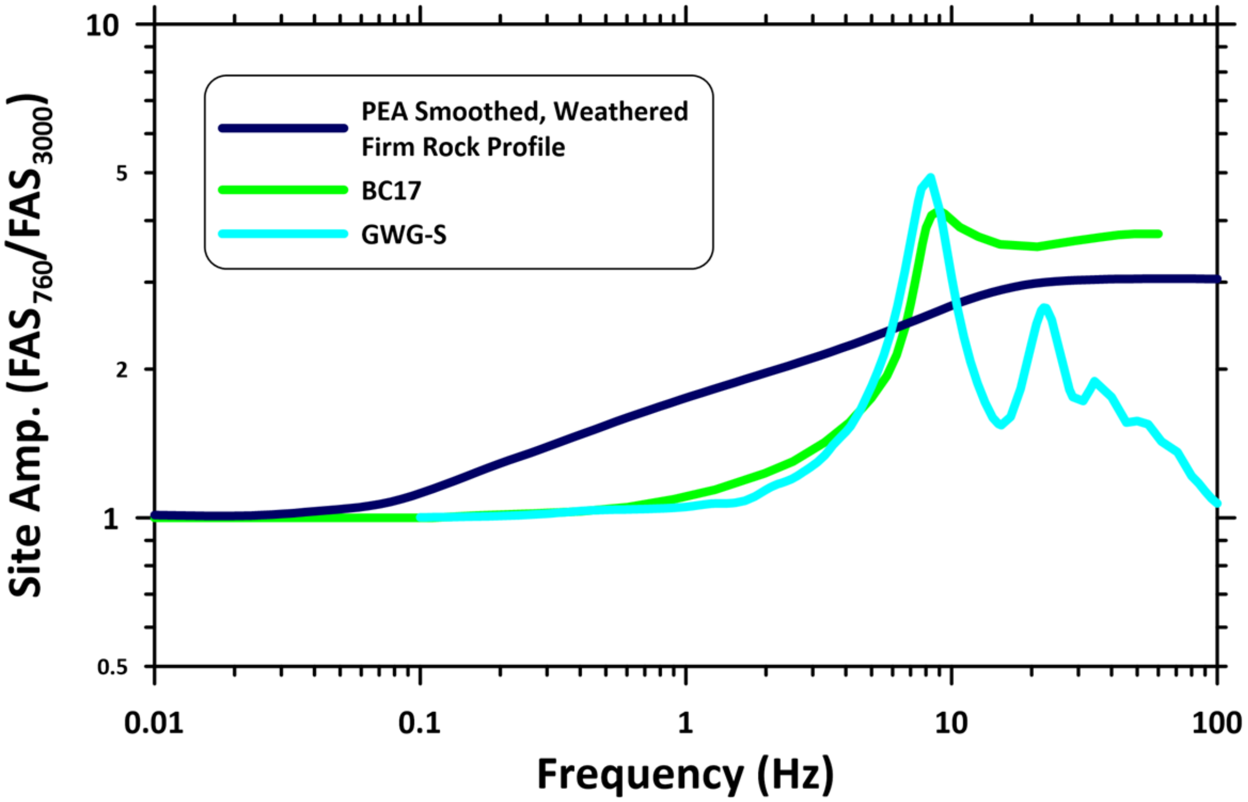

Figure 4.3 **Transfer functions describing the ratio of Fourier amplitude spectral ordinates (FAS) from V_S = 3000 to V_{S30} = 760 m/sec from the Boore and Campbell [2017] (labelled BC17), Darragh et al. [2015] (labelled PEA), and Hashash et al. [2017b] (labelled GWG-S) simulations. Note the resonance near about 8–10 Hz in two of the transfer functions.**

Transfer functions (ratio of Fourier amplitudes) for the V_S = 3000 to V_{S30} = 760 m/sec site condition from the three studies are shown in Figure 4.3. These transfer functions include the effects of κ_0 (or soil damping) for the Hashash et al. [2017b] simulations, but are unattenuated in the case of the Darragh et al. [2015] and Boore and Campbell [2017] results (no κ_0 effect applied). Note that the PEA transfer function in Figure 4.3 is for the weathered firm rock profile (Figure 4.2) with some smoothing applied to remove peaks.

For the development of 5% damped pseudo spectral acceleration (PSA) ratios, it is necessary to attach time series to the Fourier amplitude spectra, since these attributes affect oscillator response and hence PSA ratios. Boore and Campbell [2017] produce ratios for **M** = 2–8, rupture distances = 2–1200 km, and a range of κ_0. Of these factors, the most important for F_{760} was distance (higher F_{760} as distance decreases) and κ_0 (higher F_{760} as κ_0 decreases). Magnitude was relatively unimportant. For the results considered in the next section, we took results for **M**5 at 10 km and **M**8 at 500 km, both with κ_0 = 0.01, 0.02, and 0.03 sec (as noted previously). The Darragh et al. [2015] results shown in Figure 4.3 and used subsequently also apply for close distances, and κ_0 = 0.02 sec. The Hashash et al. [2017b] input motions cover a wide range of magnitudes and distances, but can generally be considered as having ample high-frequency energy as would be expected for ground motions reasonably near a seismic source for hard rock site conditions (V_S = 3000 m/sec). Hashash et al. [2017b] have F_{760} models for a variety of depths to the 3000 m/sec shear-wave horizon; the results presented here are depth independent and represent an average over the considered depth range.

4.2 RECOMMENDED MEDIAN AND STANDARD DEVIATION

Figure 4.4 shows the resulting 5% damped pseudo-spectral acceleration ratios from the three sets of simulations described in Section 4.1. Most of the results have a similar shape, with a peak near 0.1-0.2 sec, decay towards no amplification (unity) at long periods, and highly variable behavior at periods below the peak as a result of model-to-model variability and variability between κ_0 values.

We consider all of the results in Figure 4.4 to be credible representation of F_{760} behavior: no single set of results is preferred by the panel over the others. For this reason, the recommended model is the median of the models shown in the figure, and the epistemic uncertainty is represented by a natural log standard deviation (σ_{F760}) that is period-dependent. Both the median and the uncertainty are tabulated in the electronic supplement.

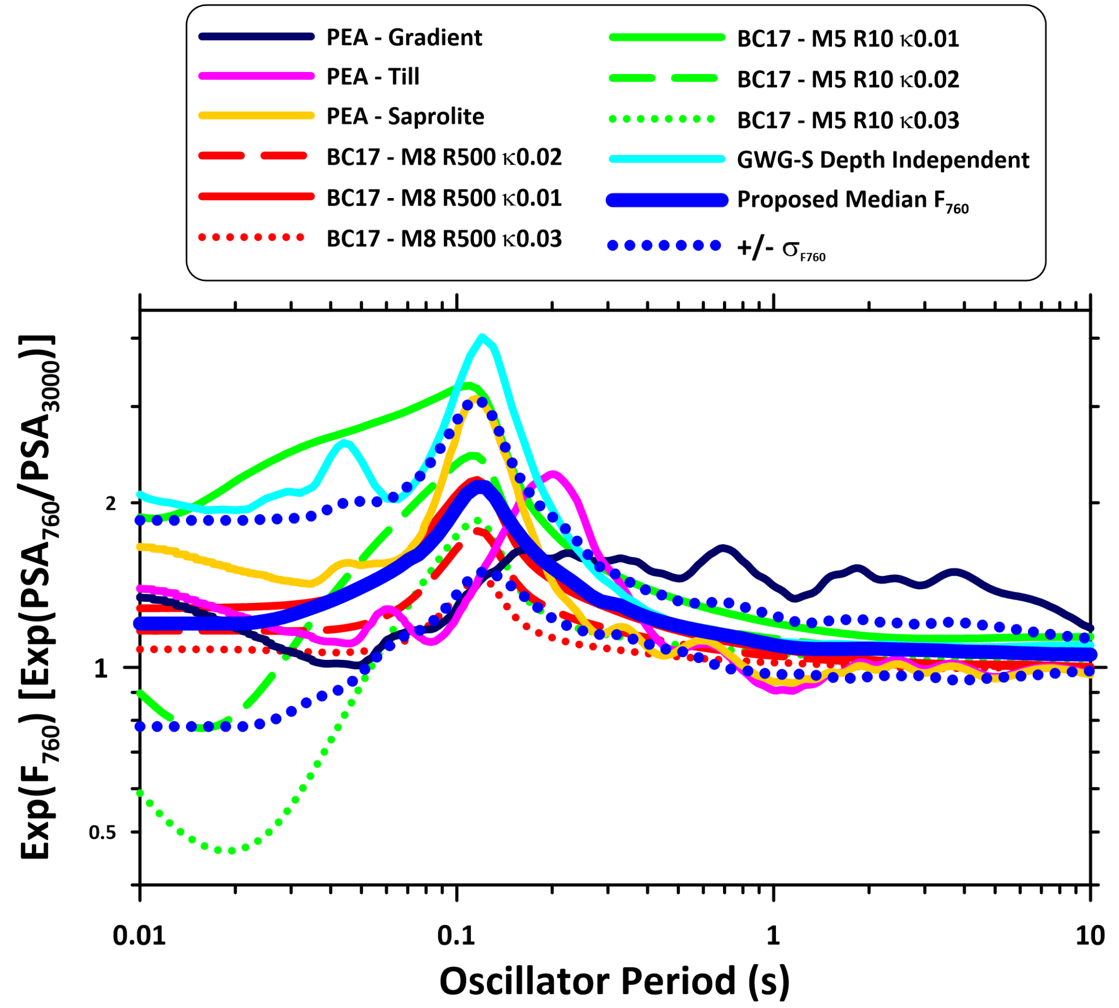

Figure 4.4 Reference site factor F_{760} for representing ratios of 5% damped pseudo spectral accelerations from Boore and Campbell [2017] (labelled BC17), Darragh et al. [2015] (labelled PEA), and Hashash et al. [2017b] (labeled GWG-S) simulations.

5 SUMMARY OF RECOMMENDATIONS AND MODEL LIMITATIONS

5.1 RECOMMENDED MODELS

We recommend that ergodic (non-site specific) V_{s30}-based site amplification in central and eastern North America be computed using Equations (2.1) to (2.3), with the coefficients given in the electronic supplement for the F_{lin} model and the equations and coefficients given in Hashash et al. [2017a] for the F_{nl} model. The model has three components in natural log units: F_V for V_{S30}-scaling referenced to V_{S30} = 760 m/sec, F_{760} for amplification of the 760 m/sec site condition relative to the CENA reference of V_S = 3000 m/sec, and F_{nl} for nonlinear effects. These models are based on a combination of ground-motion data analysis and ground response simulations, following the rationale given in Section 2.1. Justification for the specific forms of the F_V and F_{760} models are given in Chapters 3 and 4. We recommend that future CENA site amplification models consider incorporating site period in addition to site stiffness; such models were beyond the scope of this study.

5.2 LIMITATIONS

The models presented in this report are considered applicable for evaluation of ergodic site response effects for V_{S30} = 200 to 2000 m/sec and oscillator periods between 0.08 and 5.0 sec. The CENA data upon which the empirical models were developed are not suitable for evaluation of peak acceleration. We recommend site-specific analysis of site response effects for sites with $V_{S30} < 200$ m/sec.

Being ergodic, the models presented in this report do not provide site-specific estimates of site response effects, even if the V_{S30} value that is used is measured at the site of interest.

Additional site-specific attributes could be introduced to the site response estimate by measuring site frequency, soil depth, and other dynamic material properties. Resonance effects are known to be strong at many CENA sites (e.g., thin soil over hard rock), so consideration of these effects can have a substantial impact on site response estimates and are recommended. Such effects can be considered through the use of currently available empirical models (e.g., Hassani and Atkinson [2016a]), simulation-based models [Hashash et al. 2017b], or site-specific analysis.

Finally, we have a recommendation associated with the application of the site response models in this report with NGA-East GMMs. Ideally, the development of GMMs and site terms should occur in a coordinated manner. For example, when performing regression of data for GMM development, site amplification models are often used to correct ground motion intensity measures to a reference site condition. Source and path attributes are then evaluated from regression on the site-corrected data. The coordination referred to above would require that the site models used to correct the data are the same as those used for the forward application. However, that was not the case for CENA with the NGA-East GMMs currently available [PEER 2015a, b; Goulet et al. 2017] and the site amplification model provided here. As a result, it is possible that bias will be found when CENA data are compared to NGA-East GMMs combined with our site amplification models. Accordingly, we recommend future work to re-evaluate the GMMs using the available data and our site model, and that appropriate adjustments (likely to the constant term in the GMMs) be made to remove any bias that might be observed.

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