Nonlinear Site Amplification Factors for Sites Located within the Mississippi Embayment with Consideration for Deep Soil Deposit

Mojtaba Malekmohammadi,[a) M.EERI] and Shahram Pezeshk[b) M.EERI]

In this study, site amplification factors for the deep soil deposits of the Mississippi embayment are computed using a nonlinear site response analysis program to develop a model for the nonlinear soil response for possible use by ground motion developers, and to address the site-amplification estimation. The effects of geology, depth of sediment, and the average shear-wave velocity at the upper 30 m ranging from 180 to 800 m/s, as well as the peak ground acceleration at the bedrock on the nonlinear ground motion amplification for the upper Mississippi embayment are investigated. The site response computations cover various site conditions, depth of sediment from 70 to 750 m, and peak acceleration of the input rock motions from 0.01 to 0.90g. The amplification (or de-amplification) at various frequencies implied by the depth of sediment is greater than that implied just by site classification of the top 30 meters of soil.

INTRODUCTION

The determination of seismic forces applied to typical structures in most seismic design codes are based on a 5% damped design response spectrum. The design spectrum for a given site is typically obtained from a uniform hazard spectrum at the rock level and is modified by site factors to consider soil effects. In the National Earthquake Hazards Reduction Program (NEHRP) *Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, Part 1: Provisions* and *Part 2: Commentary,* ground motion site amplification factors are formulized on the basis of the site category which is related to the average shear-wave velocity at the upper 30*m* of soil (V_{s30}). The ordinate of response spectrum at the

[a)] Mueser Rutledge Consulting Engineers, 14 Penn Plaza, 225 West 34th Street, New York, NY 10122

[b)] Department of Civil Engineering, The University of Memphis, Memphis, TN 38152

ground surface is obtained by multiplying the rock response spectrum by a set of soil amplification factors, which are dependent on the V_{s30} of the site.

There are different approaches to estimate site amplification factors. One approach is to use empirical data, and one approach is to use theoretical analyses. Power *et al.* (2004) divided the empirical studies into two broad classes: (1) research studies that included both the 1989 Loma Prieta and the 1994 Northridge earthquake data and explicitly included nonlinearity of site response (Borcherdt 2002a&b; Choi and Stewart 2005; Rodriguez-Marek *et al.* 1999; Stewart *et al.* 2003); and (2) research studies that did not include Northridge earthquake data and did not explicitly include the nonlinearity of site response (Dorbry *et al.* 1999; Crouse and McGuire 1996; Joyner and Boore 2000; Borcherdt 2002a&b). Some studies obtain amplification factors as average ratios of Fourier spectra over certain period ranges (Borcherdt 2002a&b) where as some other studies obtain amplification factors as ratios of 5%-damped response spectra at discrete periods (Choi and Stewart 2005). It should be noted that a number of recent studies questioned the validity of the NEHRP site coefficients for other regions, especially regions with thick deposit of soil such as the Mississippi embayment (e.g., Park *et al.* 2004; Park and Hashash 2005; Cramer 2006), which is the main focus of this study.

The overall goal of this study is to address the site-amplification estimation considering deep soil deposits as well as the development of a new nonlinear site amplification model for the upper Mississippi embayment. Ground motion prediction developers in their approach can use the proposed new nonlinear site amplification model as they see fit.

GROUND MOTION DATABASE

In this study, we use the computer program SMSIM (available online at http://www.daveboore.com/software_online.html), which is based on the stochastic point source model, to compute the input ground motions at the surface of the reference bedrock (V_s = 3,000 *m/s*) for the Mississippi embayment using the seismological parameters of the region. Because of its simplicity and success, the point source stochastic method is now widely used to predict ground motions in locations where the number of ground motion recordings is scarce and no empirical ground motion relations are available. The stochastic point source model has been validated in various studies (e.g., Hanks and McGuire 1981;

Boore *et al.* 1997; McGuire *et al.* 1984; Toro and McGuire 1987; Silva *et al.* 1997) and provides accurate estimates of the acceleration time history and response acceleration.

The ground motion database used in this study consists of input motions simulated using the computer program SMSIM with the moment magnitudes ranging from 4 to 8 and eleven epicentral distances ranging from 10 to 1000 *km*. Silva *et al.* (1999) and Walling *et al.* (2008) performed similar analyses using the synthetic ground motion in evaluating site responses for the western United States. Walling *et al.* (2008) used a fixed moment magnitude of 6.5 and different epicentral distances to simulate a range of ground motion intensities at the bedrock. In this study, we select magnitudes and distances in a way so that the generated ground motions have evenly distributed *PGAs* from small to large.

The simulated ground motions have peak ground acceleration (*PGA*) values varying from 0.01*g* to 0.9*g*. The input parameters for the SMSIM computer program are adopted from Atkinson and Boore (2006). We used a stress drop of 140, *Kappa* value of 0.005 seconds, and the quality factor of $Q=max\ (1000, 893f^{0.32})$ to simulate ground motions for the Mississippi embayment. The *kappa* referred to is the profile damping contributed by both scattering due to wave propagation as well as intrinsic hysteretic damping (EPRI 2013). The seismological parameters used in this study are summarized in Table 1. It is important to note that many of the parameters listed in Table 1 are correlated and one cannot randomize various parameters independently.

Table 1. Seismological parameters used in this study.

Parameter	**Value**
Magnitude	4, 5, 6, 7, and 8
Distance	10, 25, 50, 75, 100, 150, 200, 300, 500, 750, and 1000 *km*
Shear-wave velocity of	3.0 *km*/sec

basement rock (β)	
Bedrock density	2.8 g/cm^3
Rupture propagation speed	0.8 β
Stress parameter	140 *bars*
Kappa	0.005
Geometric Spreading R^b, b =	-1.3 (0-70 *km*) +0.2 (70-140 *km*) -0.5 (>140 *km*)
Distance dependence of duration	0.0 (0-10 *km*) +0.16 (10-70 *km*) -0.03 (70-130 *km*) +0.04 (>140 *km*)
Quality factor	Q=max(1000,893$f^{0.32}$)

STUDY AREA

This study is focused on the upper Mississippi embayment, which has high level of seismicity in the Central and Eastern United States. The Mississippi embayment, which extends from southern Illinois to the Mexican gulf, is a wedge-shape geologic structure along the Mississippi river with thicknesses of soil deposits varying from a few meters at the edges to approximately 1,000 *m* around the Memphis metropolitan area (see Figure 1). The shallow slope of bedrock below the Mississippi embayment reduces basin effects and makes the one-dimensional site response analysis appropriate for the study region. One-dimensional analysis is based on the assumption that the response of the soil deposit is caused by the SH waves propagating vertically from the bedrock. This assumption is true when all layers are horizontal. Figure 1 shows the thickness of soil layers and the border of the Mississippi embayment.

GEOLOGY OF THE REGION

Romero and Rix (2001) divided the Mississippi embayment into two geologic structures: Pleistocene-age deposits which is called Uplands and Holocene deposits which is called Lowlands. The Pleistocene-age deposits (Uplands) are found in the interfluve, terrace regions and are characterized by a layer of loess near the surface. Loess deposits are clayey to sandy silt in Tennessee with a maximum thickness of 30 *m* along the bluffs of the

Mississippi River and thinning eastward (Romero and Rix, 2001). Pleistocene-age deposits were subdivided based on the relative elevation and geographic location. In contrast to Lowlands, Uplands deposits are more variable in shear-wave velocity and layer thickness. Lowlands deposits are mainly found along the Mississippi River and deposits in the floodplains of Wolf River, Big Creek, and Loosahatchie. Both of Uplands and Lowlands have low shear-wave velocities compared to the bedrock of the region, but the generic soil profiles proposed for Lowlands (Romero and Rix 2001, Park and Hashash 2005) have relatively lower shear-wave velocity up to the depth of 70*m*. Below 70*m* depth Uplands and Lowlands have the same shear-wave velocity.

SITE RESPONSE ANALYSIS

Among the available programs for site response analysis, the most widely used is perhaps the SHAKE91 computer program (Idriss and Sun 1992; Cramer 2006; Hartzel *et al.* 2004; Wen and Wu 1999). The program employs the equivalent linear method to compute the response of horizontally layered soil deposits underlain by horizontal bedrock. The computer program SHAKE91 and the other linear equivalent methods in general have the disadvantage of underestimating ground motions at short periods for thick deposits (Romero and Rix 2001). Furthermore, Field (2000) suggests that the equivalent linear method is not generally suitable for the strongly nonlinear response of the soil.

The basic approach used in this study is to perform one-dimensional site-response analyses using the computer program NOAH (NOnlinear Anelastic Hysteretic). NOAH is a finite difference procedure formulated by Bonilla *et al.* (1998) and Bonilla (2000) written in FORTRAN which compute the one-dimensional nonlinear wave propagation in saturated deep-soil deposits. Equations implemented in the NOAH program were developed by Towhata and Ishihara (1985) that compute nonlinear effects of soil layers such as anelasticity, hysteretic behavior, and generation of pore water pressure. Stress-strain space of soil materials subjected to cyclic loads is among the main dynamic properties of soil, which is presented in the form of the hyperbolic model in the NOAH program. The basis of the formulation implemented in the NOAH program is the assumption of the correlation between pore water pressure and shear strength presented by Towhata and Ishihara (1985). There are numerical constraints on how to discretize the problem in the time and space domain so that the solution converges to the analytical answer. Another companion computer code, which is called PRENOAH, is used to discretize the variables associated with time and space in a way to ensure stability in NOAH. NOAH's input and output format is modified to run in a batch format for a set of input ground motions and soil layers.

Assimaki and Li (2012) compared three different site response models and proposed a method to estimate the error associated with each model when nonlinear soil effects are not accounted for. They assumed that the nonlinear site response analysis result is a true estimation of the site response, and used it as a benchmark to evaluate errors associated with the linear visco-elastic and the equivalent linear model.

To better illustrate the effects of the site response model on the prediction of surface ground motion, we calculated the site response of a sample site with two layers of soil deposits and total thickness of 70 *m* on the top of the bedrock. Table 2 summarizes shear-wave velocity, density, and dynamic properties such as shear modulus degradation and damping of each layer used in the example. Figure 2 shows the site response calculated for two different ground motions (top) calculated by three site response computer programs (bottom): NOAH, SHAKE91, and Assimaki and Li (2012). Details on the input and procedure of SHAKE91, NOAH, and the nonlinear model can be found in Idriss and Sun (1992), Bonilla (2000), and Assimaki and Li (2012), respectively. As reflected in Figure 2, the mismatch between site responses calculated by SHAKE91 and the nonlinear soil response analysis increases (especially at periods less than 2 sec) with the increase in the intensity of the ground motion. SHAKE91, which is an equivalent linear method, has lower values of spectral acceleration at short periods in comparison with the other two nonlinear methods. For high intensity ground motions, both Assimaki and Li (2012) and NOAH models are reasonably close.

It is important to note that the site effect can be divided into the response of soil column, basin effects, and topographic effects. The basin effect and topographic effects are considered to be small in the Mississippi embayment and are not addressed in this study.

Table 2. Properties of the sample site used in the comparison of site response models.

	V_s (*m/s*)	Density (*kg/m*^{3})	Thickness (*m*)	G/G_{max}	Damping
Layer 1	213	1900	30	EPRI	EPRI
Layer 2	883	1900	40	EPRI	EPRI
Bedrock	3,000	2200	NA	EPRI	EPRI

DYNAMIC SOIL PROPERTIES: $G / G_{\max}$ AND DAMPING

Shear modulus degradation (G/G_{max}) and hysteretic damping ratio vs. shear strain are the key properties in the calculation of the site response at a site. In deep soil deposits, such as the Mississippi embayment, the overburden pressure plays an important role on dynamic soil properties. Generally soils display stiffer characteristics with increase in the depth. EPRI (1993) proposed a set of depth dependent generic $G/G_{\max}$ and damping ratio vs. shear strain curves for the Central United States. These curves are plotted in Figure 3. EPRI (1993) shear modulus and damping curves have been used in the estimation of the site response in numerous studies (e.g., Park and Hashash 2005; Romero and Rix 2001; Toro and Silva, 2001). In the absence of a better general estimate of G/G_{max} and hysteretic damping ratio for the study region, we used G/G_{max} and damping vs. shear strain of EPRI (1993). Park and Hashash (2005) argued that it is not possible to assign variability parameters for the randomization process due to the lack of laboratory data. Therefore, we did not randomize dynamic soil properties in performing the site response analysis.

SHEAR-WAVE VELOCITY

The shear-wave velocity of shallow soil plays a significant role on ground motion characteristics measured at the surface. In the absence of generic soil profiles, we selected 24 calibration sites compiled by Stewart and coworkers as the base profile for the upper 30*m* shear-wave (Assimaki and Li 2012).

To have amplification factors reflecting the general properties of the study area, we used the Romero and Rix (2001) generic soil profile for the depths below 30 *m* to the bedrock. Romero and Rix (2001) compared several shear-wave velocity profiles in the region and compiled generic shear-wave velocity profiles for Uplands and Lowlands geologic structure. We used four different bedrock depths of 70, 140, 400, and 750*m* to calculate the site response. These four depths are a good representation of the various depths that can be encountered in the Mississippi embayment. For each depth, we conducted a series of site response analyses using soil profiles simulated from both Uplands and Lowlands generic soil profiles to investigate the effects of geology as well as the effects of soil depth on the ground motion amplification. In this study, we used V_s = 3,000 *m/s* as the shear-wave velocity of the reference rock, following the recommendation of the Geotechnical Working Group of the Next Generation Attenuation (NGA)-East. Silva *et al.* (1999) and Kwok and Stewart (2008) developed ground motion amplification relationships using a bedrock shear-wave velocity of 1,000 *m/s* which is consistent to shear-wave velocity of their study area. Figure 4 illustrates the shear-wave soil profile for Uplands and Lowlands.

VARIABILITY IN SHEAR-WAVE PROFILE

Using the EPRI (1993) soil profile database, Toro (1993) developed a probabilistic characterization of soil shear-wave velocity profile and used the resulting probabilistic model to simulate shear-wave profiles. His probabilistic model consists of two separate components, one for the thickness of each layer called the layering model that captures the variability in the thickness of soil layers; and one for the shear-wave velocity associated with each layer called the velocity model to account for the variability in the shear-wave velocity of each layer. Based on the data from EPRI (1993) a non-homogenous Poisson model is used with a depth-dependent rate to account for the fact that soil thickness of layers increase with depth.

In this study, the variability in soil thickness and the shear-wave velocity of the region is taken into account through the model developed by Toro (1993), which generates a desired number of soil profiles around the base soil profile with a desired probability distribution. This model statistically captures the soil layer shear-wave velocity and thickness uncertainties and their correlation with depth.

The coefficient of variance (COV) of 0.15 is used for both thickness and shear-wave velocities to generate soil profiles. For each site, we used two base shear-wave profiles: one for Uplands and one for Lowlands, and each of them are independently used to simulate 60 soil profiles.

Using the model described above, soil profiles with V_{s30} ranging from 160 to 800 *m/s* are simulated for the region. Figure 5 shows Uplands (top) and Lowlands (bottom) soil profiles used in analysis of 140*m* soil deposit as an example. Generic Uplands and Lowlands profiles are truncated below 140*m* and a half space with V_s = 3,000 *m/s* is used.

METHODOLOGY

The amplification of ground motion is defined as the ratio of any intensity measure of the motion measured at the soil surface to the associated value at the bedrock. In this research, the ground motion amplification for each period is defined as the ratio of spectral acceleration of the motion at the soil surface to the spectral acceleration of the motion at the generic bedrock with a shear-wave velocity of $V_s = 3{,}000$ *m/s*:

$$Amp(T) = \frac{SA_{Soil}(T)}{SA_{Rock}(T)} \tag{1}$$

where $SA_{soil}(T)$ and $SA_{Rock}(T)$ are the values of acceleration response spectrum of the motion at the soil surface and at the bedrock for the spectral period *T*, respectively. Each input ground motion in the database is propagated through different site depths using a one-dimensional nonlinear analysis and ground motion amplification is calculated at *PGA* and spectral periods of 0.2, 1.0 and 5.0 seconds. Sites are considered to have soil deposit of depths of 70, 140, 400, and 750*m* above the reference bedrock. A total of 5,760 soil profiles are considered in this study, which corresponds to 24 different calibration sites, 4 different bedrock depths and 60 sets of probabilistically generated soil profiles for both Lowlands and Uplands soil profiles developed by Romero and Rix (2001).

Considering all different soil deposit thicknesses, shear-wave profiles, ground motion *PGA*s, and geologic structures, more than 120,000 nonlinear site response analyses are conducted in this research. Each site response analysis on a PC with dual processor of 3.16 GHz takes an average of 10 minutes. For this study we used the high performance computing facility at the University of Memphis to conduct site response analyses. The generated data are used to fit a parametric model to predict the soil response for sites located within the Mississippi embayment.

PARAMETERIZATION OF THE ANALYTICAL RESULTS

The purpose of this section is to develop a model to estimate the amplification factors. The approach taken here is similar to the approach by Walling *et al.* (2008). Boore *et al.* (1997) determined that the linear range, the site amplification can be modeled as a function of shear-wave velocity in terms of V_{s30} and a reference shear-wave velocity (V_{ref}):

$$\ln(Amp) = a \ln\left(\frac{V_{30}}{V_{ref}}\right) \tag{2}$$

where the parameter *a* is determined through a regression analysis. Later, Abrahamson and Silva (1997) developed a new model to account for nonlinear site response. Their nonlinear site response amplification model was expressed as:

$$\ln(Amp) = a + b\ln\left(PGA + c\right) \tag{3}$$

where PGA is the peak ground acceleration on a generic rock. Parameters a, b, and c are determined from a regression analysis. Choi and Stewart (2005) expanded Abrahamson and Silva (1997) model to develop a nonlinear site amplification model as a function of V_{s30} and PGA:

$$\ln(Amp) = a\ln\left(\frac{V_{30}}{V_{ref}}\right) + b\ln\left(\frac{PGA}{0.1}\right) \tag{4}$$

Unlike the model proposed by Boore *et al.* (1997) and Abrahamson and Silva (1997), equation (4) considers the effects of both PGA and V_{s30} on the soil response.

As part of the NGA project, Walling *et al.* (2008) proposed the following model for the site amplification of ground motions:

For $Vs_{30} < V_{Lin}$

$$\ln(Amp) = a\ln\left(\frac{Vs_{30}}{V_{Lin}}\right) - b\ln\left(PGA_{rock} + c_1\right) + b\ln\left[PGA_{rock} + c_1\left(\frac{Vs_{30}}{V_{Lin}}\right)^n\right] + d \tag{5a}$$

and for $Vs_{30} \geq V_{Lin}$

$$\ln(Amp) = \left(a + bn\right)\ln\left(\frac{Vs_{30}}{V_{Lin}}\right) + d \tag{5b}$$

where PGA_{rock} is the value of estimated peak ground acceleration at the bedrock, V_{Lin} is the shear-wave velocity above which the site response is linear, and V_{s30} is the top 30 m shear-wave velocity of the site. The parameters b and V_{Lin} are the period dependent parameters and a, c_1, d, and n are computed through regression analyses. Walling *et al.* (2008) set up their model in a way to capture the nonlinearity of the ground motion amplification associated with large values of PGA or small values of V_{s30}.

For the Mississippi embayment, we propose the following model:

$$\ln(Amp) = f_{base} + f_{depth} + f_{geology} + \eta \tag{6}$$

where f_{base}, f_{depth}, and $f_{geology}$ are the functional forms for base, depth, and geology model, respectively, and η is the residual. The proposed model for estimating the site response in the Mississippi embayment is formulated to capture site effects not only due to the soil nonlinearity and effects of ground motion but also the unique characteristic of the study area such as varying soil thickness and two geologic structures. The proposed functional models for f_{base}, f_{depth}, and $f_{geology}$ are described next.

BASE FUNCTIONAL MODEL

The base functional form that we used in this study is similar to the model used by Walling *et al.* (2008):

$$f_{base} = a_1 \ln\left(\frac{Vs_{30}}{a_2}\right) - a_3 \ln\left(PGA_{rock} + a_4\right) + a_3 \ln\left[PGA_{rock} + a_4\left(\frac{Vs_{30}}{a_2}\right)^{a_5}\right] \qquad (7)$$

where a_1 through a_5 are the regression coefficients. Equation (7) is based on the assumption that in the linear range, the functional form should reduce to the form developed by Boore *et al.* (1997). In other words, as *PGA* becomes smaller or as V_{s30} gets larger, the amplification of the ground motion becomes proportional to the V_{s30}. The proposed functional form for the base model also results in the prediction of amplification that is dependent on the V_{s30} at a given *PGA* level.

DEPTH FUNCTIONAL MODEL

One of the main features of the Mississippi embayment is the variation of thickness of soil deposit on the bedrock throughout the embayment (see Figure 1). Using the soil depth model, f_{depth}, in addition to the base model, enables our model to distinguish between sites with different soil thicknesses above the bedrock and to better predict the site amplification due to deep soil deposits:

$$f_{depth} = a_6 \ln\left[\frac{Z_{3000} + a_7}{\exp\left[a_8 - \ln\left(\frac{Vs_{30}}{a_9}\right)\right]}\right] + \left[a_{10}\ln(PGA_{rock}) + a_{12}Vs_{30}\right]\left|\ln(Z_{3000}) - a_{11}\right| \qquad (8)$$

where Z_{3000} is the depth to the layer with V_s = 3,000 *m/s* which is assumed to be the shear-wave velocity of the bedrock for the Central United States.

GEOLOGY FUNCTIONAL MODEL

The geology of the Mississippi embayment can be divided into Quaternary (Lowlands) and Tertiary (Uplands). The Lowlands geologic structure in comparison with Uplands tends to show more nonlinear behavior, especially at lower values of V_{s30} and large values of *PGA*. To be able to get a more accurate site amplification factor, we divided the Mississippi embayment into two different geological structures and introduced the following functional form for $f_{geology}$:

$$f_{geology} = \begin{cases} \dfrac{a_{14} \times \ln\left(PGA_{rock} + a_{13}\right)}{\ln(Z_{3000})} & \text{For Uplands} \\ 0 & \text{For Lowlands} \end{cases} \quad (9)$$

Coefficients a_1 through a_{14} are estimated using the least square method at four spectral periods of *PGA*, 0.2, 1.0, and 5.0 seconds, respectively (see Table 3). For each spectral period, the regression coefficients of the model are calculated independent of other periods with the associated analytical data determined from nonlinear analyses at that period.

The sufficiency of the proposed model is investigated by plotting residuals (η in equation 6) against V_{s30}, depth to bedrock, and *PGA* for spectral period of 0.2 and 5.0 seconds in Figure 6. From Figure 6, one can observe that there is no discernable trend in model residuals vs. different input parameters (trend line of the data are indicated on each plot). Similar results for residuals are obtained for the regression analysis at *PGA* and 1.0 second. The proposed model seems to provide predicted median amplification factors for each category with reasonable consistency.

COMPARISON TO OTHER STUDIES

Results of this study are compared with Choi and Stewart (2005), Walling *et al.* (2008), and the NEHRP coefficients, and results are presented in Figures 7 through 10. Choi and Stewart (2005) defined amplification as the residuals between the spectral acceleration from recordings and what is predicted by ground motion prediction equations. Abrahamson and Silva (1997), Sadigh *et al.* (1997), and Campbell and Bozorgnia (2003) models were used as the reference, and site factors are developed for each model. Choi and Stewart (2005) site factors were evaluated using coefficients developed for the Abrahamson and Silva (1997) attenuation model.

Figure 7 (top) illustrates the amplification versus the bedrock *PGA* for Uplands and Lowlands geologic structure for the bedrock depth of 140m. Since Lowlands geologic structure has lower generic shear-wave velocity, sites located within the Lowlands geology have higher amplification factors than sites located within the Uplands geology. The analytical data shown as dots in Figure 7 are for shear-wave velocities ranging from 420 to 480 *m/s* and the developed model is plotted using 450 *m/s* as the input for the shear-wave velocity. Figure 7 (bottom) illustrates the effect of sediment depth on the site amplification for the Lowlands geologic structure. It can be observed that as the depth of the sediment increases from 70 to 750*m*, the site amplification decreases. This effect becomes more pronounced as the *PGA* of the ground motion at the bedrock increases.

The difference between the model developed in this study and models developed by Choi and Stewart (2005) and Walling *et al.* (2008) can be related to the differences in seismological differences and site properties identified in the Mississippi embayment. Similar types of information are shown in Figures 8 through 10. It is important to know that for high spectral periods (low spectral frequencies), such as 5 seconds (0.2 Hz), as the sediment thickness increases, the site amplification increases. This is in the reverse order as for low spectral periods (high spectral frequencies). Furthermore, as it can be observed from Figure 10, the site amplification seems to remain almost constant; there is small decrease with the increase in peak ground acceleration at the reference rock for all sediment depths. Another trend observed in Figures 7 through 10 is the reduction of effect of the geology in ground motion amplification with increase in spectral period. At longer spectral periods, the geology of sediment plays a small role in the ground motion amplification. Furthermore, since the only difference in the Uplands and Lowlands shear-wave velocity is on the top 70*m*, the effect of geology decreases when the depth of the bedrock increases.

CONCLUSIONS

In this research we developed a parametric site response model for the Mississippi embayment as a function of *PGA* on the reference bedrock, V_{s30}, depth of soil columns, and geology using the nonlinear site response analyses. Using seismological parameters of the study area, we simulated a series of input ground motions. The input ground motions are then propagated through different soil profiles. Soil profiles are varied using the Toro (1993) model in a way to capture the uncertainty associated with shear-wave velocity and thickness. Four different bedrock depths are also used in evaluating site response analyses. Considering all the input cases, more than 120,000 nonlinear runs are conducted.

The results of the analytical analyses are used to fit a model to predict the ground motion site amplification in the region. The proposed model consists of three different components, to take into account the unique features of the study area such as variable bedrock depth and having two dominant geological structures.

The proposed model is used to compare the site response of the Mississippi embayment with other models developed for other study areas. Results from this study show that the site amplification within the Mississippi embayment is relatively higher in comparison with the proposed values of NEHRP, Choi and Stewart (2005), and Walling *et al.* (2008), which are derived with data from the west coast. Geology also has a considerable role in the site response of the study area when the bedrock depth is relatively shallow. The effect of geology decreases as the depth of the bedrock increases.

For short periods at low values of *PGA*, estimated values of the ground motion amplification for the Mississippi embayment tends to be higher relative to values proposed by NEHRP, Choi and Stewart (2005), and about the same as Walling *et al.* (2008) prediction. For ground motions with high *PGAs*, the proposed model predicts smaller site amplifications than NEHRP and Walling *et al.* (2008), and Choi and Stewart (2005).

For long periods, the Mississippi embayment shows no significant nonlinearity in the ground motion amplification, which is consistent with findings of other studies (Choi and Stewart 2005, Walling *et al.* 2008, and NEHRP); but the predicted value of ground motion amplification is substantially higher in comparison with values of NEHRP, Choi and Stewart (2005), and Walling *et al.* (2008).

Finally, it is important to note that this study is limited to depths of 70, 140, 400, and 750 meters and frequencies of PGA, 0.2, 1.0, and 5.0 seconds. Additional studies need to be performed to develop a complete and exhaustive evaluation of the nonlinear site amplification factors using various nonlinear site-response analysis programs, various depths, and various frequencies.

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Figure 1. Map of the top of the Paleozoic strata of the Mississippi embayment after Van Arsdale and TenBrink (2000).

Figure 2. Comparison of the computer program NOAH, SHAKE91, and Assimaki and Li (2012). Site response is calculated for high (PGA=0.82g; Left) and low (PGA=0.07g; Righ) levels of shaking and for a 70 m two layered soil deposit.

Figure 3. Depth dependent dynamic soil properties, damping ratio curves (top) and shear modulus degradation (bottom), proposed by EPRI (1993) used in the site response analyses.

Figure 4. Uplands and Lowlands shear-wave velocity soil profile developed by Romero and Rix (2001): (a) 0-1000 m depth (left); and 0-100 m depth (right).

Figure 5. 60 Shear-wave velocity profiles simulated for Uplands (top) and Lowlands (bottom) using the Toro (1993) model.

Figure 6. Residuals for spectral periods of 0.2 and 5.0 seconds. Trend lines are presented by dark black lines.

Figure 7. Analytical data for Uplands, Lowlands, and associated parametric estimates of ground motion amplification (top) and analytical data for depths 70, 140, 400, 750m, and associated parametric estimates of ground motion amplification (bottom) for spectral period 0.0 (or PGA).

Figure 8. Analytical data for Uplands, Lowlands, and associated parametric estimates of ground motion amplification (top) and analytical data for depths 70, 140, 400, 750m, and associated parametric estimates of ground motion amplification (bottom) for spectral period 0.2 second.

Figure 9. Analytical data for Uplands, Lowlands, and associated parametric estimates of ground motion amplification (top) and analytical data for depths 70, 140, 400, 750m, and associated parametric estimates of ground motion amplification (bottom) for spectral period 1.0 second.

Figure 10. Analytical data for Uplands, Lowlands, and associated parametric estimates of ground motion amplification (top) and analytical data for depths 70, 140, 400, 750m, and associated parametric estimates of ground motion amplification (bottom) for spectral period 5.0 second.

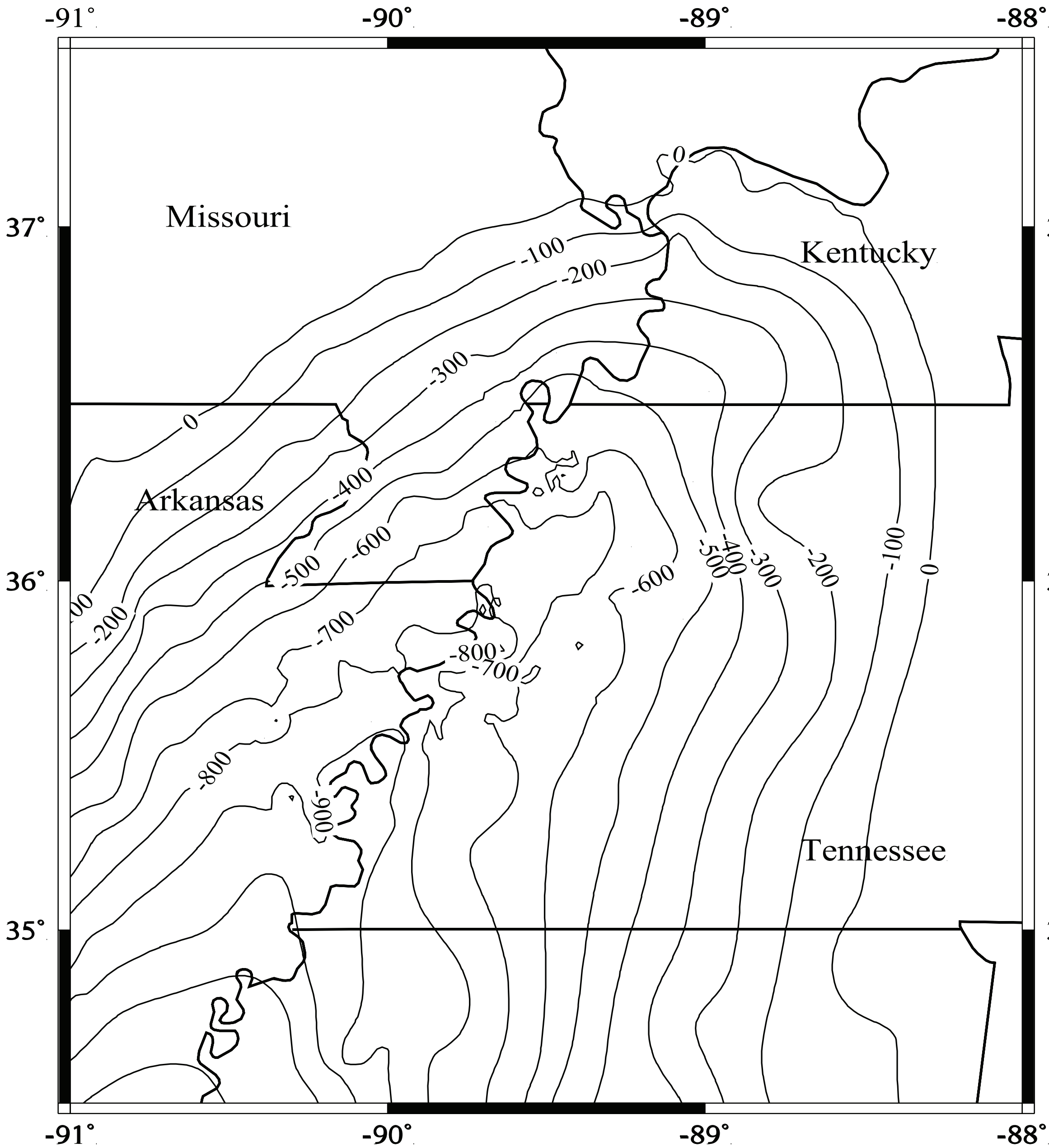

-91°
-90°
-89°
-88°
37°
36°
35°
Missouri
Kentucky
Arkansas
Tennessee
0
-100
-200
-300
-400
-500
-600
-700
-800
-900

Figure 1.

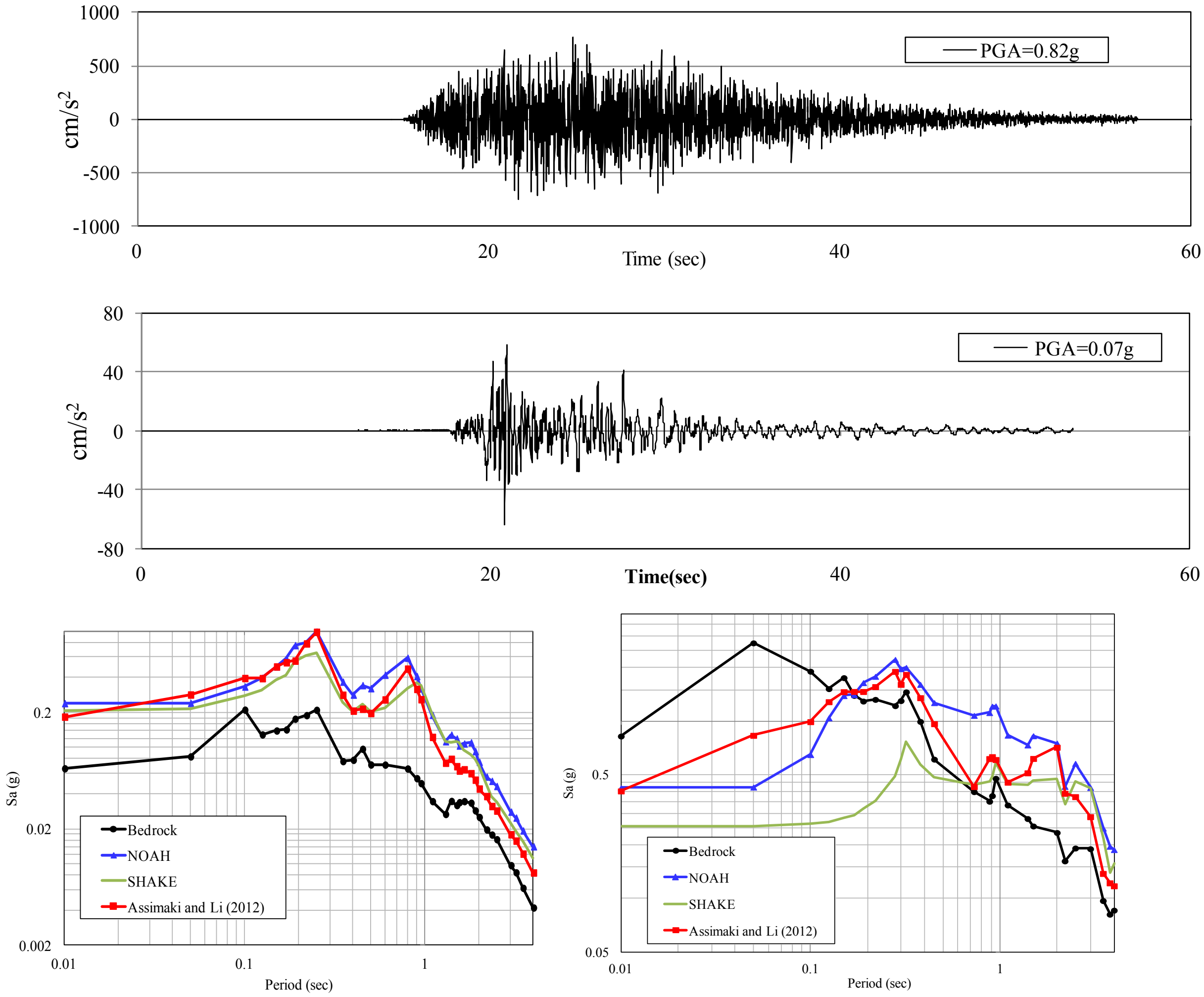
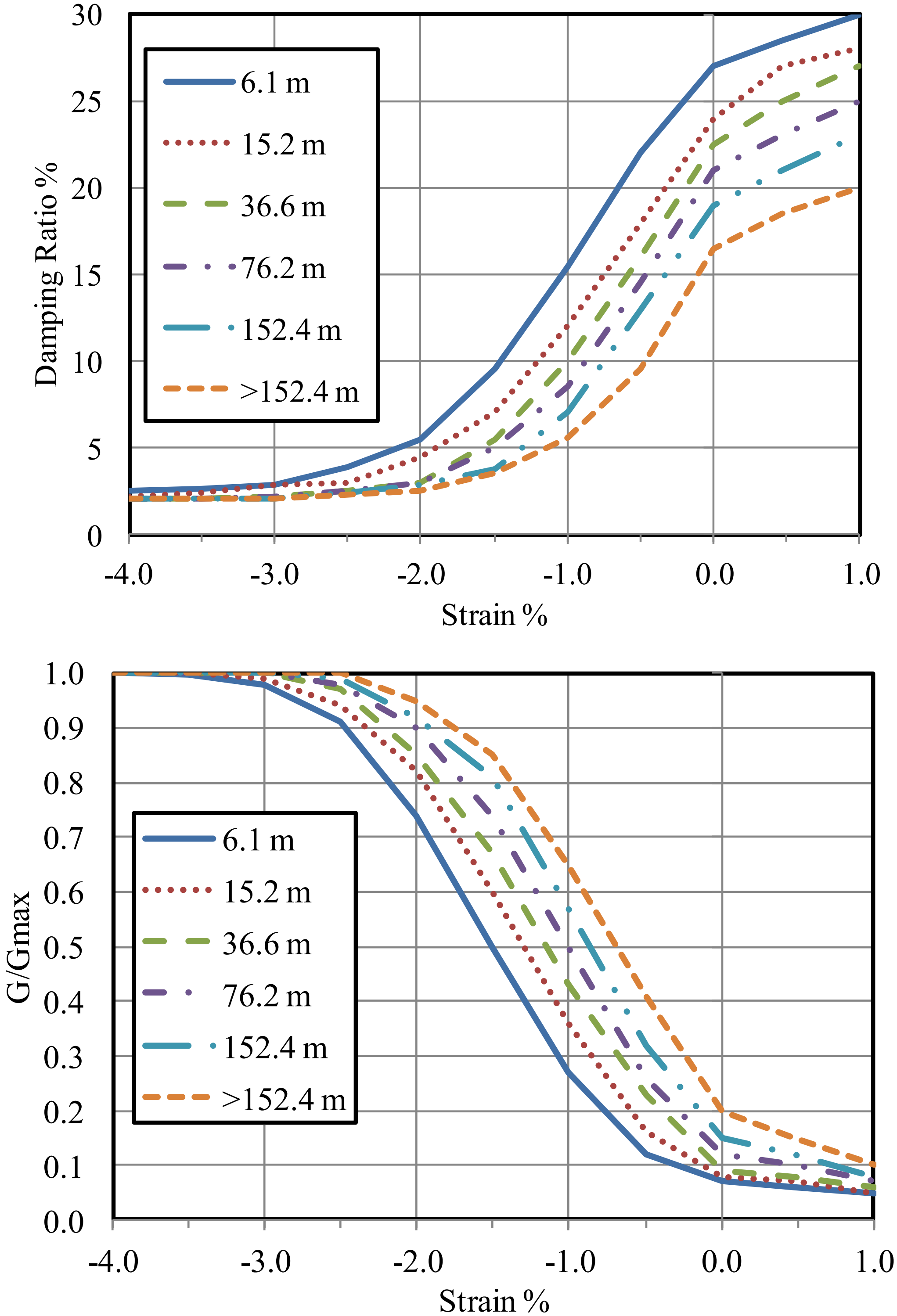

1000
500
0
-500
-1000
cm/s2
PGA=0.82g
0
20
Time (sec)
40
60
80
40
0
-40
-80
cm/s2
PGA=0.07g
0
20
Time(sec)
40
60
0.2
0.02
0.002
Sa (g)
Bedrock
NOAH
SHAKE
Assimaki and Li (2012)
0.01
0.1
1
Period (sec)
0.5
0.05
Sa (g)
Bedrock
NOAH
SHAKE
Assimaki and Li (2012)
0.01
0.1
1
Period (sec)

Figure 2.



30
25
20
15
10
5
0
Damping Ratio %
6.1 m
15.2 m
36.6 m
76.2 m
152.4 m
>152.4 m
-4.0
-3.0
-2.0
-1.0
0.0
1.0
Strain %
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
G/Gmax
6.1 m
15.2 m
36.6 m
76.2 m
152.4 m
>152.4 m
-4.0
-3.0
-2.0
-1.0
0.0
1.0
Strain %

Figure 3.

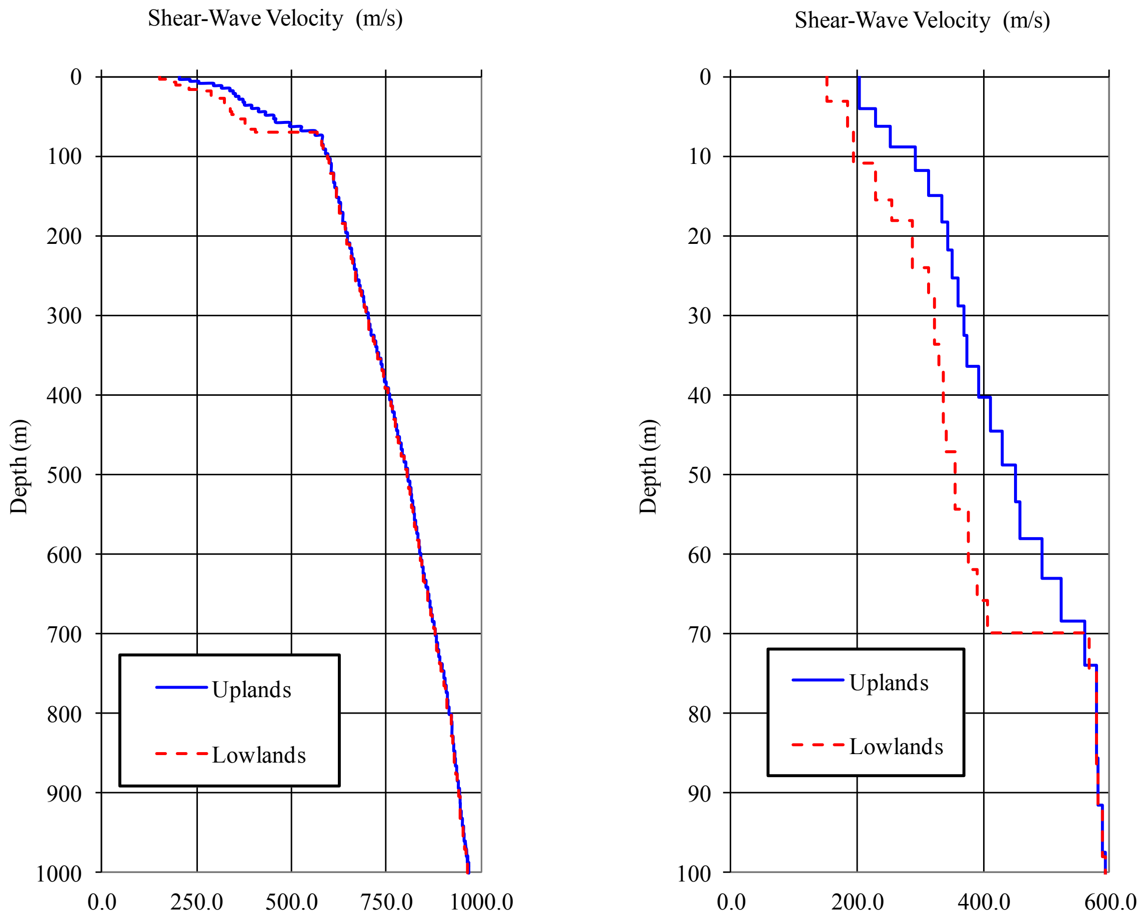
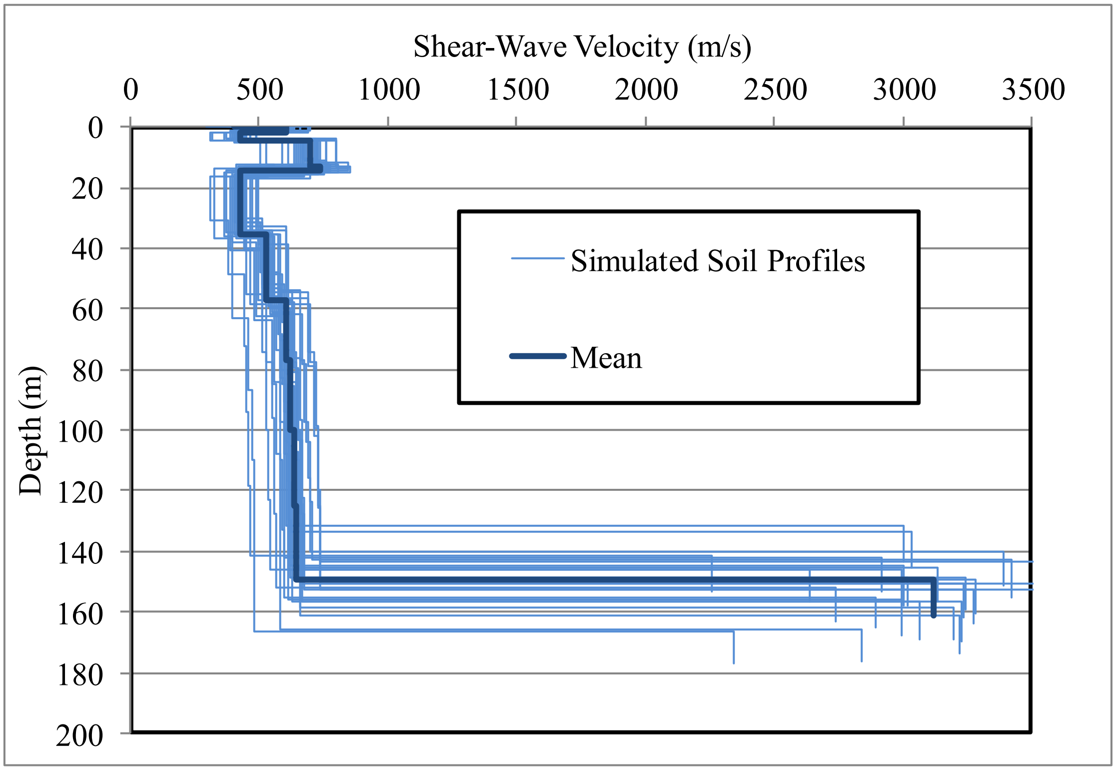

Shear-Wave Velocity (m/s)
Depth (m)
0
100
200
300
400
500
600
700
800
900
1000
0.0
250.0
500.0
750.0
1000.0
Uplands
Lowlands
Shear-Wave Velocity (m/s)
Depth (m)
0
10
20
30
40
50
60
70
80
90
100
0.0
200.0
400.0
600.0
Uplands
Lowlands

Figure 4.


Shear-Wave Velocity (m/s)
0
500
1000
1500
2000
2500
3000
3500
0
20
40
60
80
100
120
140
160
180
200
Depth (m)
Simulated Soil Profiles
Mean

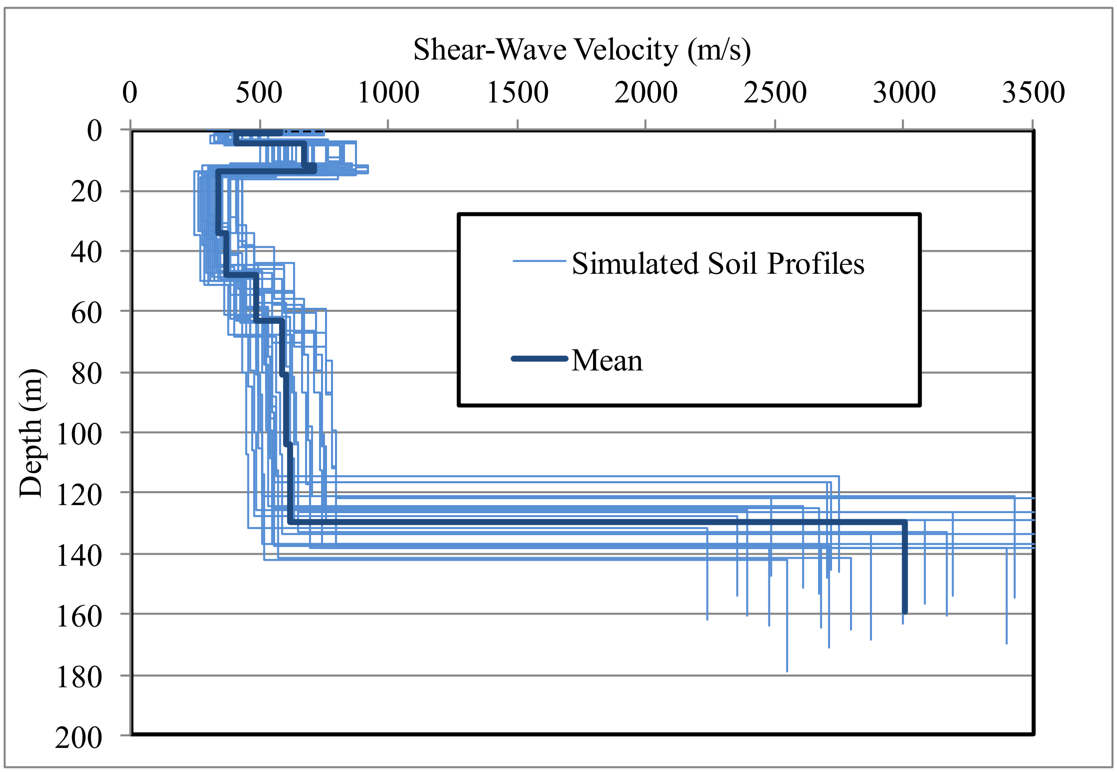
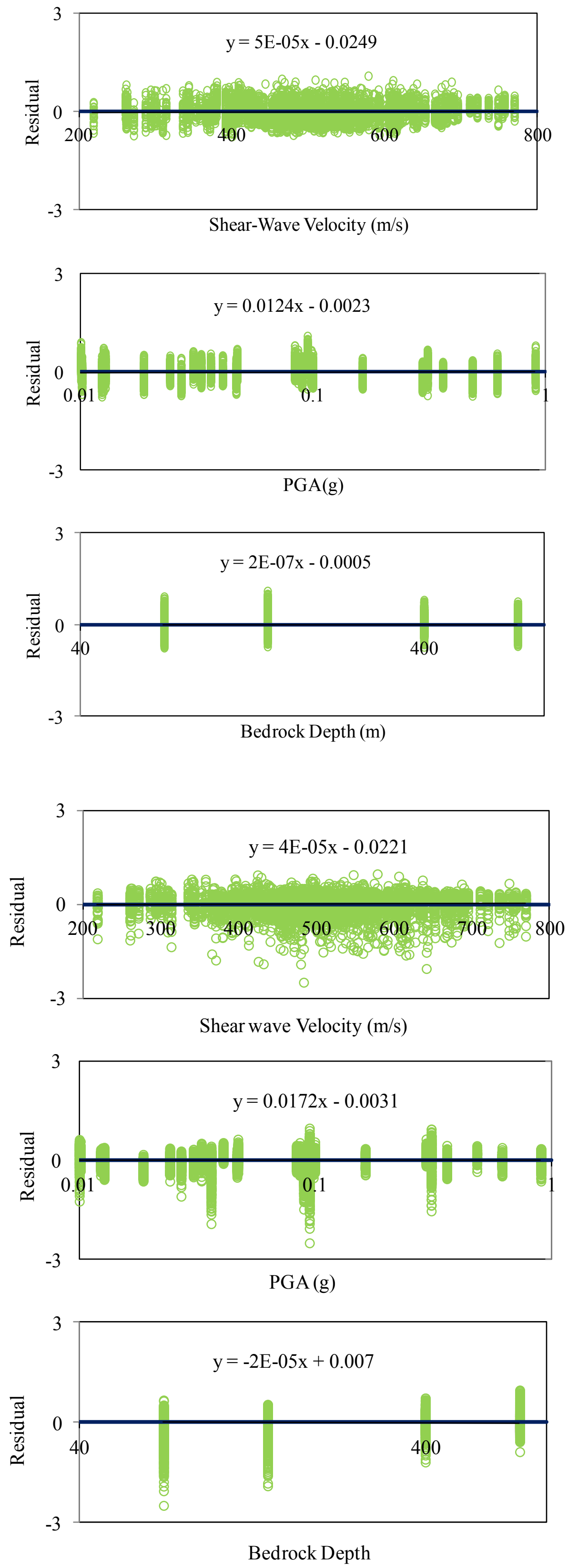
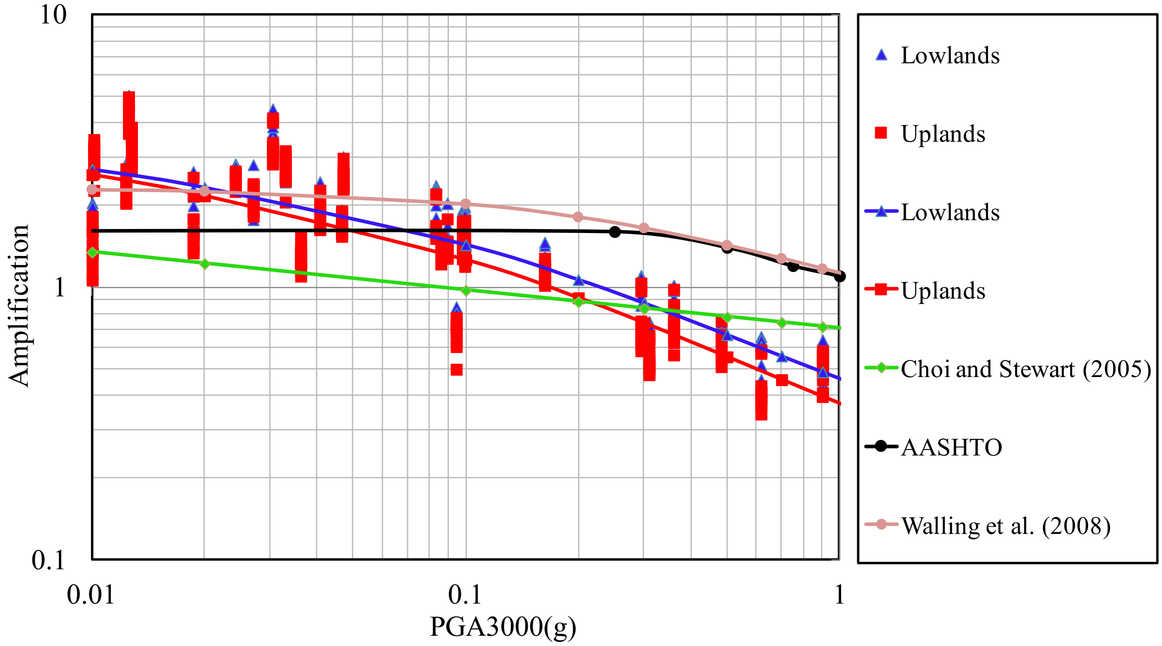

Shear-Wave Velocity (m/s)
0
500
1000
1500
2000
2500
3000
3500
0
20
40
60
80
100
120
140
160
180
200
Depth (m)
Simulated Soil Profiles
Mean

Figure 5.



y = 5E-05x - 0.0249
Residual
Shear-Wave Velocity (m/s)
y = 0.0124x - 0.0023
Residual
PGA(g)
y = 2E-07x - 0.0005
Residual
Bedrock Depth (m)
y = 4E-05x - 0.0221
Residual
Shear wave Velocity (m/s)
y = 0.0172x - 0.0031
Residual
PGA (g)
y = -2E-05x + 0.007
Residual
Bedrock Depth

Figure 6.


10
1
0.1
0.01
0.1
1
Amplification
PGA3000(g)
Lowlands
Uplands
Lowlands
Uplands
Choi and Stewart (2005)
AASHTO
Walling et al. (2008)

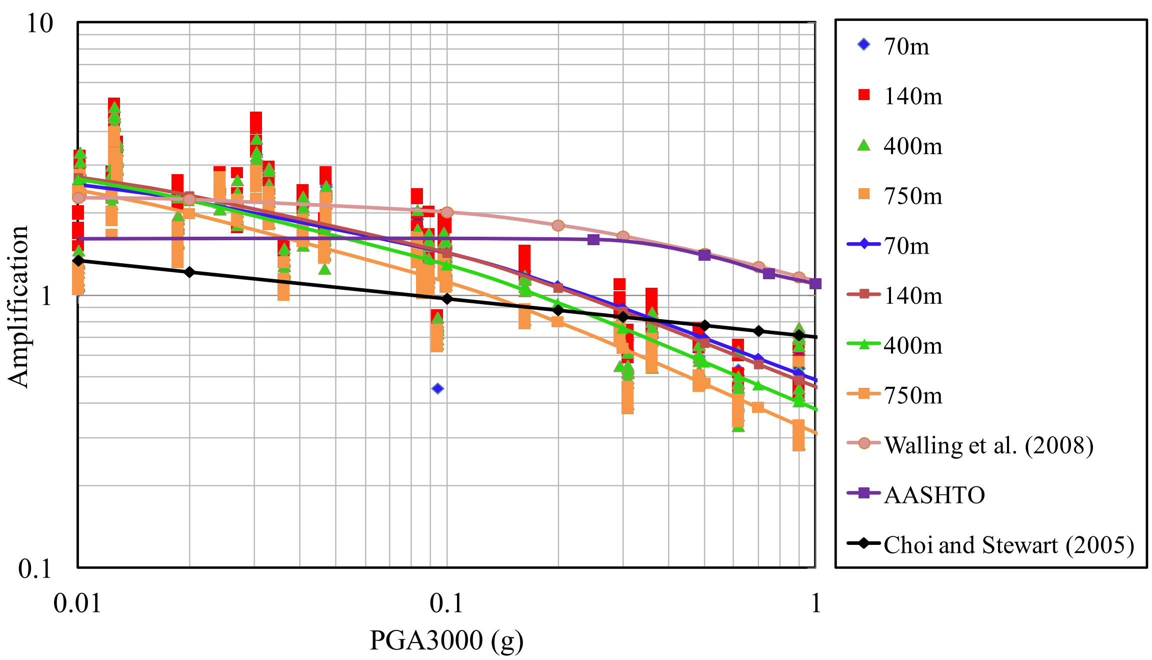
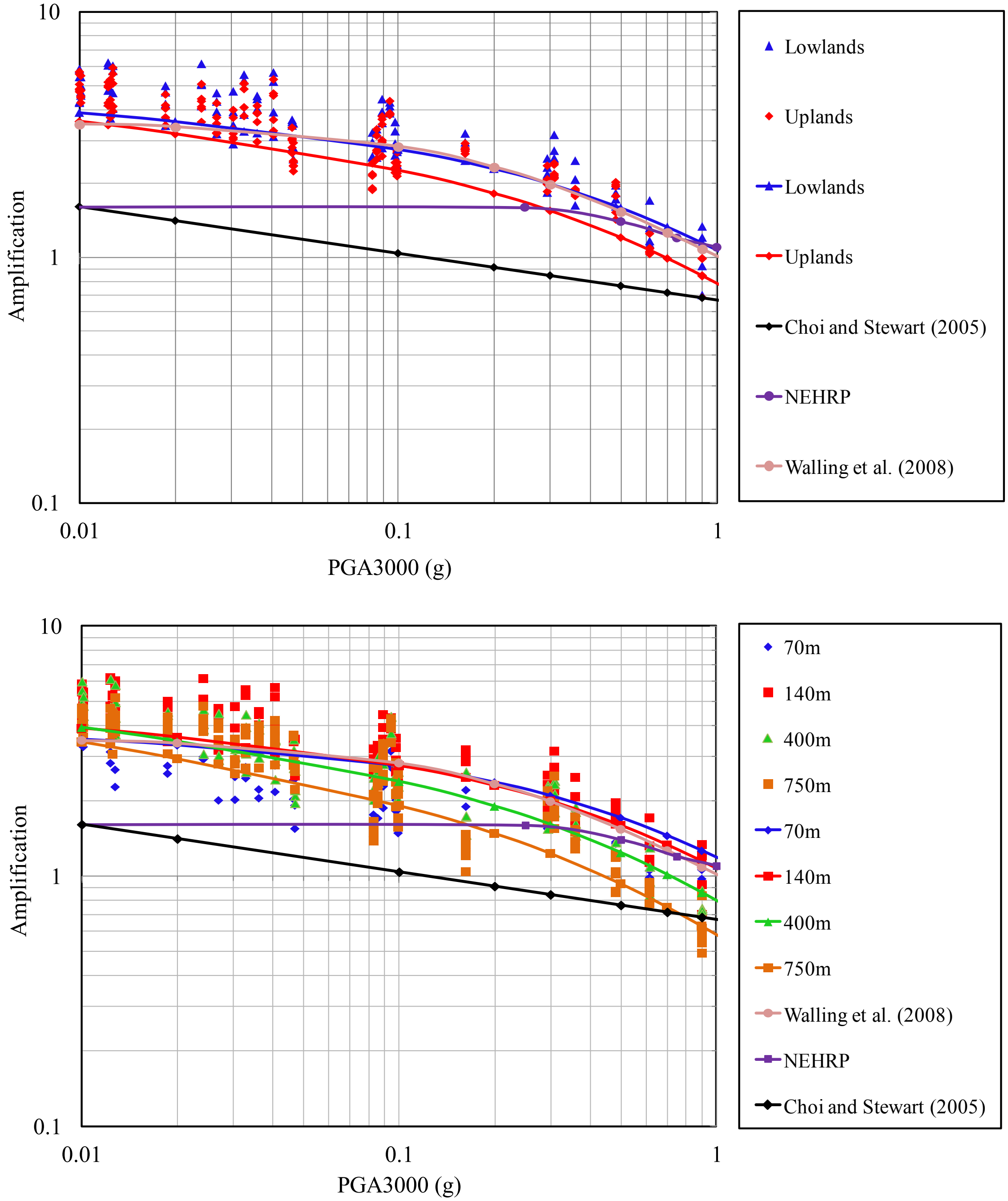
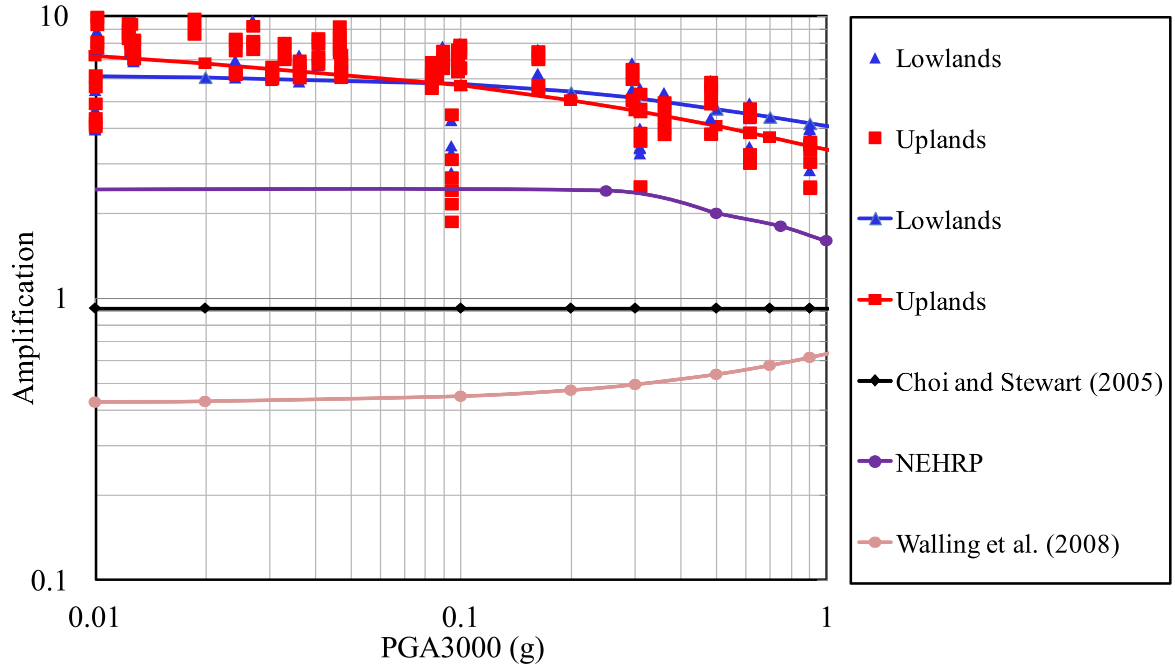

10
1
0.1
0.01
0.1
1
Amplification
PGA3000 (g)
70m
140m
400m
750m
70m
140m
400m
750m
Walling et al. (2008)
AASHTO
Choi and Stewart (2005)

Figure 7.

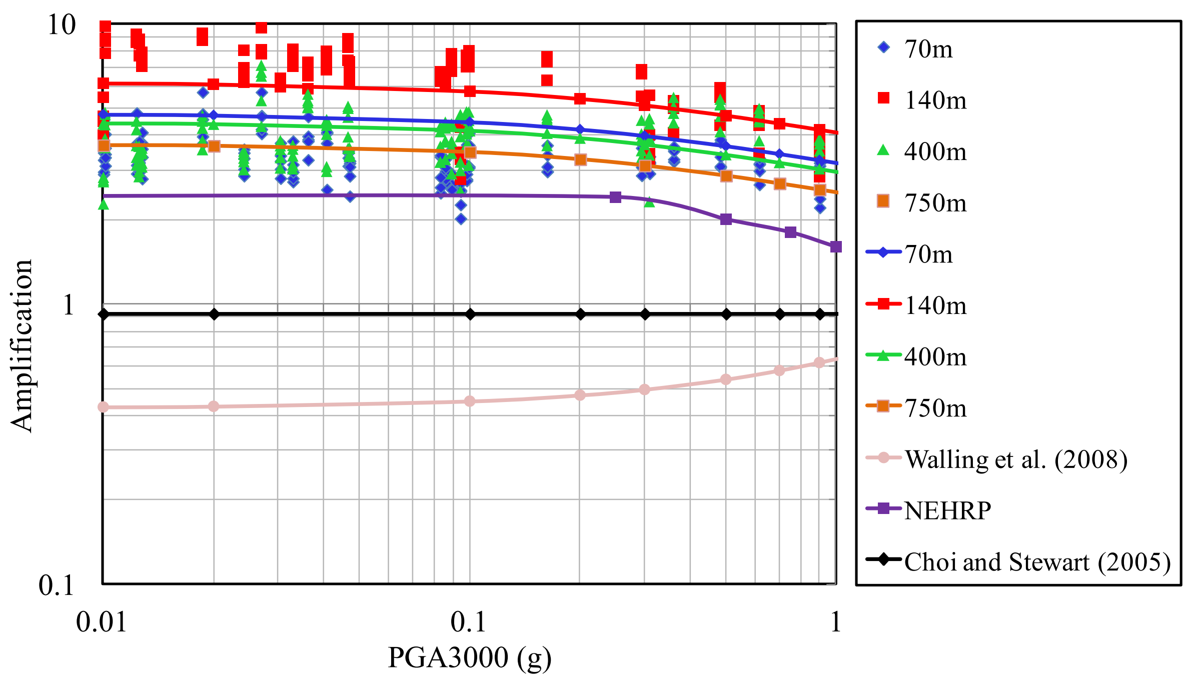


10
1
0.1
0.01
0.1
1
Amplification
PGA3000 (g)
Lowlands
Uplands
Lowlands
Uplands
Choi and Stewart (2005)
NEHRP
Walling et al. (2008)
10
1
0.1
0.01
0.1
1
Amplification
PGA3000 (g)
70m
140m
400m
750m
70m
140m
400m
750m
Walling et al. (2008)
NEHRP
Choi and Stewart (2005)

Figure 8.



10
1
0.1
Amplification
0.01
0.1
1
PGA3000 (g)
Lowlands
Uplands
Lowlands
Uplands
Choi and Stewart (2005)
NEHRP
Walling et al. (2008)



10
1
0.1
Amplification
0.01
0.1
1
PGA3000 (g)
70m
140m
400m
750m
70m
140m
400m
750m
Walling et al. (2008)
NEHRP
Choi and Stewart (2005)

Figure 9.

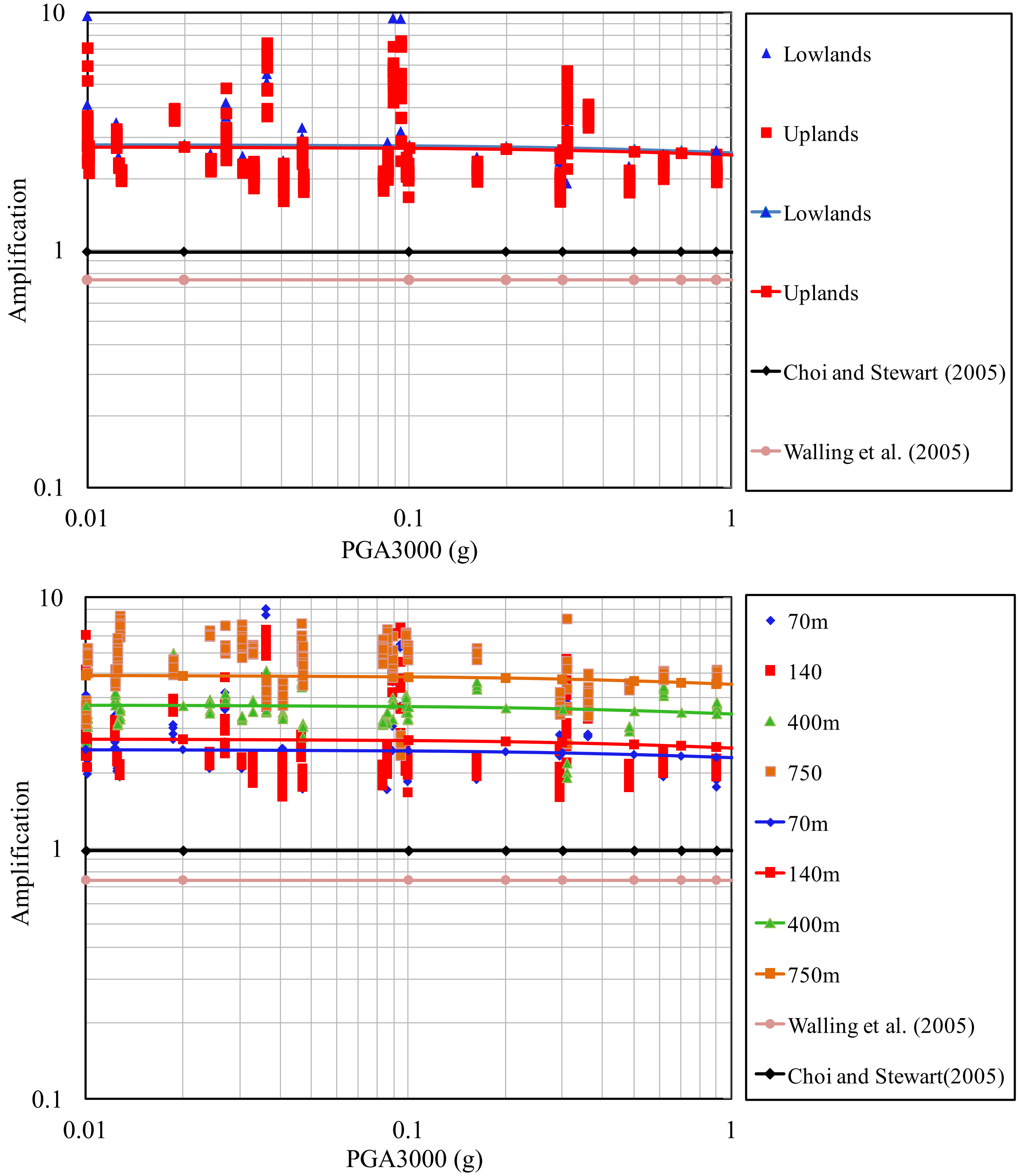

10
1
0.1
0.01
0.1
1
Amplification
PGA3000 (g)
Lowlands
Uplands
Lowlands
Uplands
Choi and Stewart (2005)
Walling et al. (2005)
10
1
0.1
0.01
0.1
1
Amplification
PGA3000 (g)
70m
140
400m
750
70m
140m
400m
750m
Walling et al. (2005)
Choi and Stewart(2005)

Figure 10.