Title

Influence of shear wave velocity reversals on one-dimensional site response of spatially varied profiles

Authors

Pehlivan, M

Hashash, YMA

Harmon, JA

et al.

Publication Date

2023-12-10

Peer reviewed

6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch. New Zealand

Influence of Shear Wave Velocity Reversals on One-Dimensional Site Response of Spatially Varied Profiles

M. Pehlivan[1], Y. Hashash[2], J. A. Harmon[3], E. M. Rathje[4], J. P. Stewart[5], W. J. Silva[6], K. W. Campbell[7], S. Nikolaou [8]

ABSTRACT

Spatial variability and uncertainties that exist in natural deposits are often modeled in one-dimensional (1D) site response analysis through multiple spatially varied shear wave velocity (V_S) profiles. These spatially varied V_S profiles usually exhibit V_S reversals that might not be observed in the natural deposits. This study investigates the consequences of allowing V_S reversals in spatially varied V_S on the 1D site response characteristics. Two sets of sixty (60) spatially varied V_S profiles, with and without V_S reversals, were generated. Results of the 1D site response analysis showed that allowing V_S reversals in spatially varied V_S profiles can lower the median surface response up to 10% at periods shorter than the fundamental site period. The difference in surface response becomes more significant for the higher intensity input motions. The variability in the median surface response was not significantly influenced by the presence of V_S reversals.

Introduction

Site response analyses are performed to evaluate the influence of the local soil deposit on strong ground shaking, with the resulting surface response being used in seismic design. The main soil properties required for site response analysis are the shear-wave velocity (V_S) profile and the nonlinear modulus reduction and damping curves. The spatial variability and the uncertainties in these soil properties should be taken into account in seismic design. In one-dimensional (1D) site response analyses, the spatial variability and the uncertainty in the V_S that might exist in natural deposits is commonly accounted for by analyzing multiple spatially varied 1D V_S profiles. Spatially varied 1D V_S profiles are usually generated via Monte Carlo simulations, based on a representative 1D V_S profile and statistical parameters such as standard deviation (σ_{lnVs}) and interlayer correlation coefficient (ρ_{IL}). Often times, in order to allow for interlayer variability in the V_S profile ρ_{IL} is assumed to be less than unity. This assumption might lead to spatially varied V_S profiles with V_S reversals, where the V_S of a deeper layer is lower than the V_S of the overlying layer. These V_S reversals might be observed at any depth within the profile. As the V_S is usually expected to increase with depth, the presence of extreme V_S reversals at greater depths

[1]Geotechnical Eng., Mueser Rutledge Consulting Eng, New York, NY, USA, menzerpehlivan@utexas.edu
[2]Prof., Civil and Env. Eng. Dept., Univ. of Illinois at Urbana-Campaign, IL, USA, hashash@illinois.edu
[3]PhD Candidate, Civil and Env. Eng. Dept., Univ. of Illinois at Urbana-Campaign, IL, USA, harmon4@illinois.edu
[4]Prof., Civil, Arch., and Env. Eng. Dept., Univ. of Texas at Austin, TX, USA, e.rathje@mail.utexas.edu
[5]Prof., Civil and Env. Eng. Dept., Univ. of California Los Angeles, CA, USA, jstewart@seas.ucla.edu
[6]President, Pacific Engineering and Analysis, El Cerrito, CA, Country, pacificengineering@juno.com
[7]Vice President, CoreLogic EQECAT, Oakland, CA, USA, kcampbell@corelogic.com
[8]Senior Assoc., Mueser Rutledge Consulting Eng, New York, NY, USA, snikolaou@mrce.com

might constitute unrealistic 1D V_S profile realizations for natural deposits. This study investigates the consequences of the presence of V_S reversals on 1D surface response of spatially varied V_S profiles as part of the Next Generation Attenuation Relationships for Central and Eastern America (NGA-East) Geotechnical Working Group (GWG), which is focused on development of site amplification models for the Central and Eastern North America (CENA). For this purpose, two (2) sets of sixty (60) spatially varied V_S profiles, with and without V_S reversals, were generated for a deep CENA site. This paper discusses the generation of these two sets of spatially varied V_S profiles and compares the associated 1D surface response predictions.

Spatially Varied Shear Wave Velocity Profiles

The objective of this study is to develop soil amplification functions for the CENA region, as a part of the NGA-East GWG. The current study investigates the consequences of having V_S reversals in the spatially varied V_S profiles generated to model 1D site response of CENA site conditions. We developed ten (10) generalized characteristic V_S profiles to represent CENA site conditions. We used the generalized characteristic V_S profile developed for the Residual Sediment (RR) site conditions (Kottke et al., 2012) as the baseline V_S profile to generate the spatially varied V_S profiles (Figure 1 and 3) and the V_S of the bedrock was assumed to be 3000 m/s (Hashash et al., 2012). As shown in Figures 1 and 3, baseline V_S increases from 240 m/s at the ground surface to 600 m/s at 100 m and reaches up to 960 m/s at 1000 m below the ground surface. The average V_S of the baseline profile is 760 m/s and the predominant period of the site is around 5.3 s.

Spatially varied V_S profiles are generated using the Toro (1995) random field models as implemented in the computer program Strata (Kottke and Rathje, 2008). These variable layer thickness and velocity models were used to generate the spatially variable V_S profiles based on the baseline V_S profile. The variable layering model simulates layering thickness as a non-homogenous Poisson process with a depth-dependent rate. For this study, custom model parameters were used for the Toro (1995) depth-dependent rate model (i.e., a = 1.98, b = 10.86, c = -0.89) to model the uncertainty in the stratigraphy of RR site conditions across CENA. The spatially variable V_S values were generated for each layer using the variable velocity model, which assumes that V_S is log-normally distributed at any given depth and correlated between adjacent layers. The statistical parameters required for generation of the spatially variable V_S profiles are the standard deviation of the natural logarithm of the shear wave velocity (σ_{lnVs}) and the interlayer correlation (ρ_{IL}). For this study, spatially variable V_S profiles without reversals ($V_{S,NR}$) were generated using a depth-independent σ_{lnVs} of 0.2 and a ρ_{IL} of 1.0. The interlayer correlation coefficient of 1.0 was used for $V_{S,NR}$ profiles to maximize the spatial correlation between the adjacent layers so that generated spatially variable V_S profiles would not exhibit V_S reversals. Spatially variable V_S profiles with reversals ($V_{S,WR}$) were generated using a depth-independent σ_{lnVs} of 0.2 and a ρ_{IL} of 0.8. To ensure the generation of reasonable V_S profiles in accordance with the regional CENA site conditions, the generalized characteristic V_S profiles developed for Minimum and maximum site conditions of the CENA for the NGA-East GWG were introduced as minimum and maximum bounds for the spatially variable V_S profiles, respectively.

Figure 1a and Figure 1b present sixty (60) spatially variable V_S profiles generated with and without V_S reversals, respectively, together with the baseline and the minimum and maximum V_S profiles. Figure 1 shows that the medians across the 60 simulations of the $V_{S,NR}$ and $V_{S,WR}$ profiles show some deviation from the baseline RR profile. The median $V_{S,NR}$ is up to 18% higher than the baseline profile around the surface, whereas the difference between the median $V_{S,WR}$ is up to 9% higher than the baseline profile. In the top 100 m, the average difference between the baseline profile and the median $V_{S,NR}$ and $V_{S,WR}$ profiles is around 5% and 2%, respectively. A comparison of the generated $V_{S,NR}$ and $V_{S,WR}$ profiles shown in Figure 1 illustrates that $V_{S,NR}$ profiles have stiffer V_S realizations at most depths. These stiffer V_S realizations in spatially variable NR profiles are due to the full spatial correlation between adjacent layers that preserves the rate of increase observed between the V_S of the adjacent layers in the baseline V_S profile.

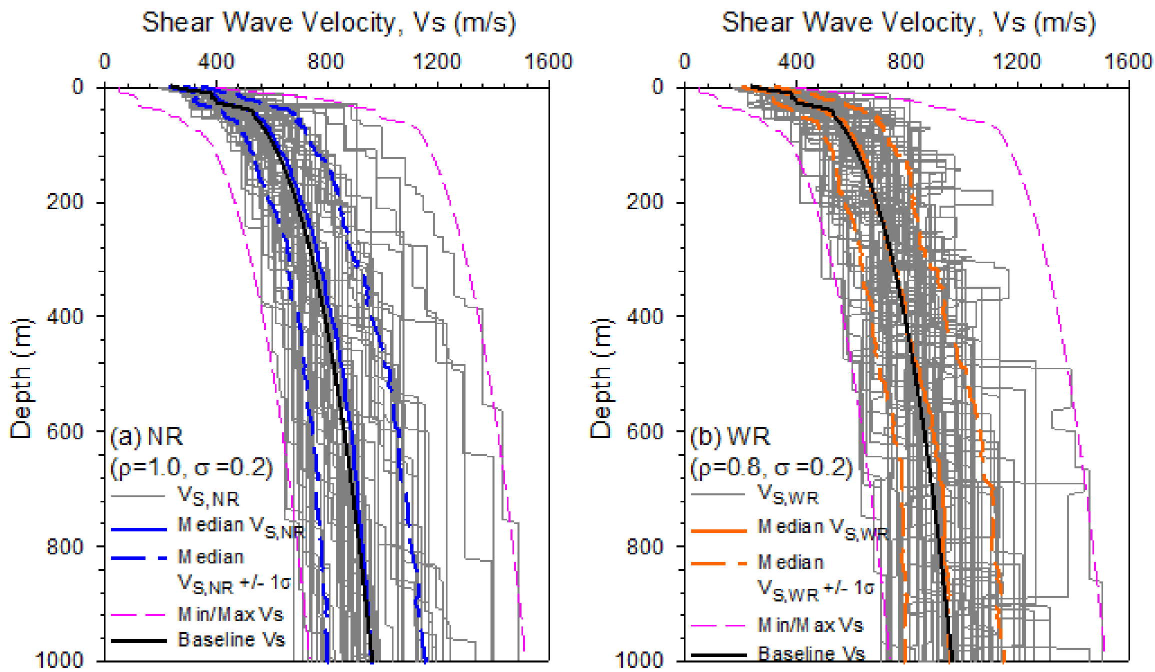

Figure 1. Sixty (60) spatially variable V_S profiles together with the baseline, minimum, and maximum V_S profiles: (a) without V_S reversals, $V_{S,NR}$ (σ_{lnVs}= 0.2, ρ_{IL}= 1.0) (b) with V_S reversals, $V_{S,WR}$ (σ_{lnVs}= 0.2, ρ_{IL}= 0.8)

The observed difference between the median profiles and the baseline profile in Figure 1 is partially due to the introduced layer thickness variation. To further discuss the influence of layer thickness variation, Figure 2 presents a single V_S profile simulation of a generic baseline V_S profile, which is generated by varying only the layer thickness, without varying the V_S of the layers. The layers of the single V_S profile simulation are thicker than the layers of the baseline profile. When the variability in V_S is introduced, the median V_S of simulations generated with varying layer thickness is calculated at layer midpoints of the baseline profile and used as the baseline profile. In the case of Figure 2, even though V_S has not been randomized, the median of Layer 1 is biased by the V_S generated from Layer 2. Therefore, the median V_S profile of the spatially varied V_S simulations might show deviation from the baseline V_S profile.

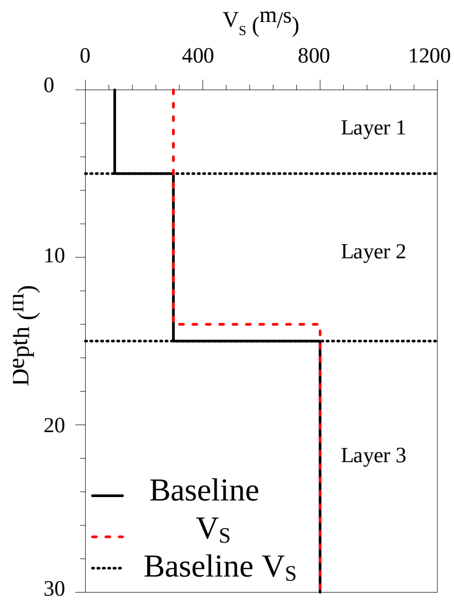

Figure 2. Generic baseline profile and associated single V_S simulation generated with only Toro (1995) variable layer thickness model

Figure 3a compares the median profiles of $V_{S,NR}$ and $V_{S,WR}$ shown in Figure 1; the median $V_{S,WR}$ profile shows a better overall match to the baseline profile for most depths when compared to the median $V_{S,NR}$ profile. Figure 3b plots the residuals (difference between the median simulated V_S estimates and the baseline V_S values) for the median $V_{S,NR}$ and $V_{S,WR}$ profiles, which further illustrate the difference in the median V_S predictions. The observed difference in the median profiles is mainly due to the lower interlayer correlation coefficient in the spatially variable $V_{S,WR}$ profiles that allows V_S reversals. Figure 1 shows that in the $V_{S,NR}$ profiles, a high V_S realization at the surface cause even higher V_S with depth as opposed to the $V_{S,WR}$ profiles, where a high V_S realization at the surface did not necessarily cause higher V_S with depth (at least for shallow depths) due to low spatial correlation. Therefore, the median $V_{S,NR}$ profile has higher V_S than the median $V_{S,WR}$ profile at most depths. At shallow depths close to the surface, the median $V_{S,NR}$ profile can be up to 10% higher than the median $V_{S,WR}$ and baseline profiles. Although small, the observed difference in the median profiles might constitute a bias in the evaluation of the V_S reversals influence on 1D site response results. In order to eliminate such bias, the simulated $V_{S,WR}$ profiles were adjusted so that the median $V_{S,WR}$ profile matched the median $V_{S,NR}$ profile. Figure 3c illustrates the adjusted spatially varied WR profiles that were used in the site response analysis.

Results

Equivalent-linear site response analysis of $V_{S,NR}$ and $V_{S,WR}$ profiles were performed using the computer program Strata (Kottke and Rathje, 2008). Strain-dependent soil properties were defined based on the Darendeli (2001) nonlinear soil property curves. Site response analyses were performed for a set of 104 ground motions selected that represent CENA seismological conditions. Eighty four (84) motions come from NUREG-6728 (McGuire et al., 2001) and twenty (20) motions come from the finite-fault simulations of Hashash and Moon (2011). Input motions evenly cover a range of input Peak Ground Acceleration (PGA) from 0.01 g to 1.4 g.

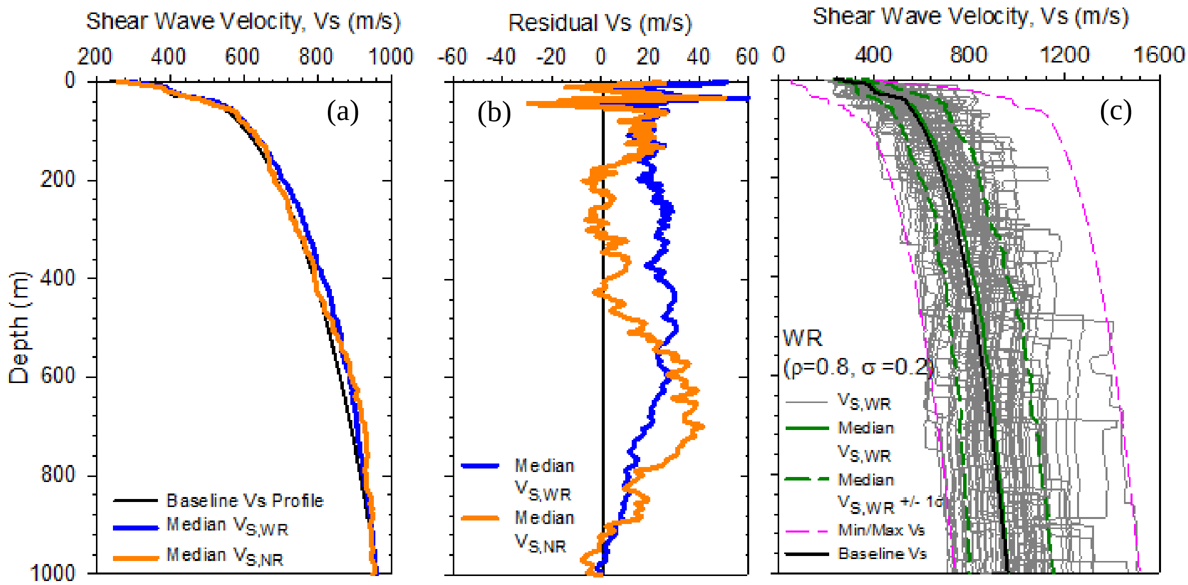

Figure 3. (a) Comparison of median $V_{S,NR}$ and $V_{S,WR}$ profiles with the baseline Vs profile, (b) residuals of the median $V_{S,NR}$ and $V_{S,WR}$ profiles with respect to the baseline Vs profile, (c) adjusted spatially variable $V_{S,WR}$ profiles used in the site response analyses

Surface response spectra obtained for the $V_{S,NR}$ and adjusted $V_{S,WR}$ profiles are shown in Figures 4a and 4b, respectively. Figure 4 shows that the range of surface response obtained from the site response analyses of the two sets of profiles have similar characteristics, with PGA ranging from 0.02 g to 1.0 g. The variation around the median response spectra is found to be similar for the surface response obtained for both the $V_{S,NR}$ and adjusted $V_{S,WR}$ profiles.

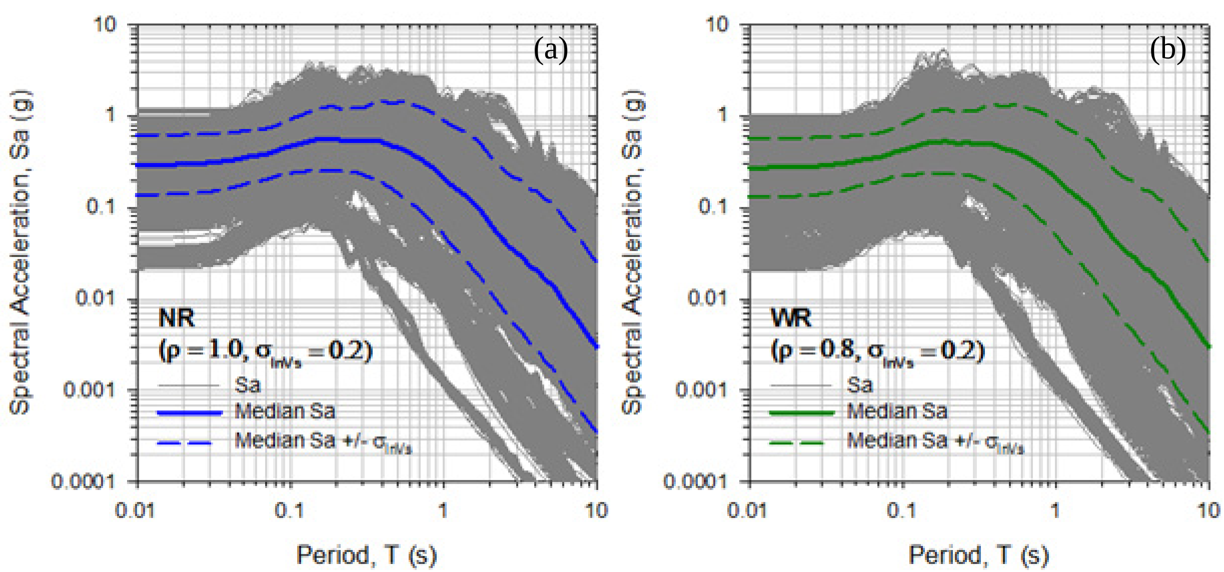

Figure 4. Surface accelerations obtained for 60 spatially variable (a) $V_{S,NR}$ and (b) adjusted $V_{S,WR}$ profiles.

Figure 5a compares the median surface response and the 68% confidence bounds obtained from the site response analyses of the baseline V_S profile (without any spatial variation) with the surface response obtained from the median surface response spectra of the $V_{S,NR}$ (Sa_{NR}) and adjusted $V_{S,WR}$ profiles (Sa_{WR}) (shown in Figure 4). Figure 5a shows that the median Sa_{NR} is very similar to the surface response spectra of the baseline V_S profile and that the median Sa_{NR} is higher the median Sa_{WR} for periods less than T = 1.5 s. Surface acceleration predictions of spatially variable $V_{S,NR}$ profiles can be up to 9.5 % higher than that of the $V_{S,WR}$ profiles at short periods of around T = 0.1 s. Figure 5a also shows that the variability around the median Sa_{NR}, $Sa_{WR,}$ and the baseline profile are similar, indicating that the presence of the V_S reversals in spatially variable V_S profiles does not have a significant effect on the variability of the surface response. Figure 5b illustrates the influence of the input intensity level on the median Sa_{NR} and Sa_{WR}. As illustrated in the Figure 5b, the median Sa_{NR} and Sa_{WR} are similar under low intensity input motions and becomes more evident with increasing input motion intensity.

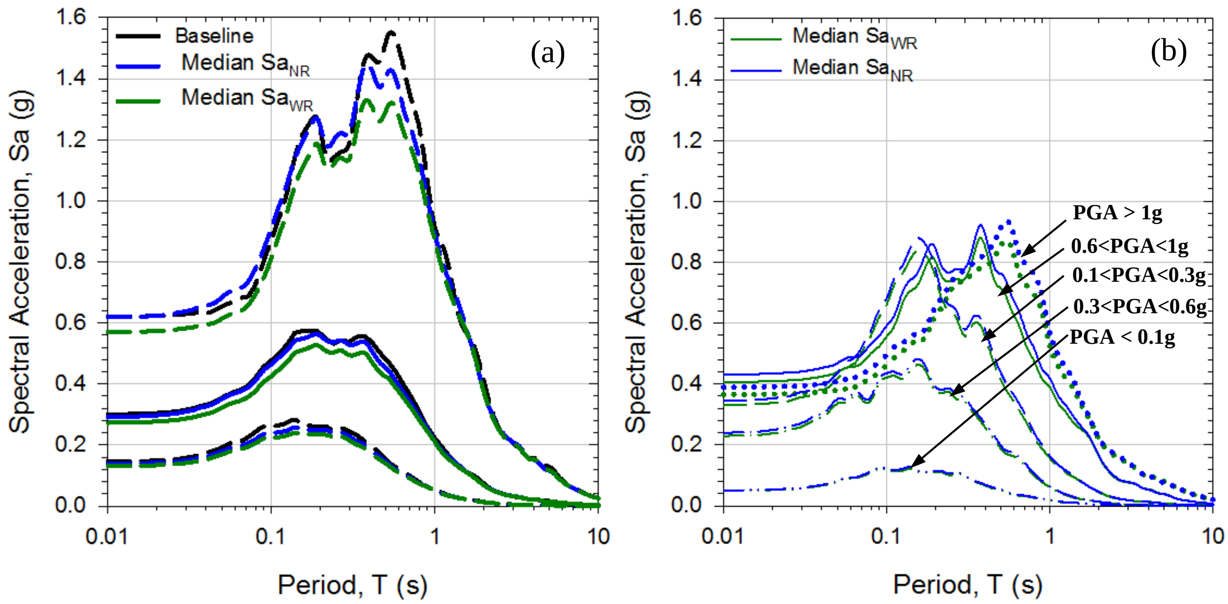

Figure 5. (a) Median spectral acceleration of $V_{S,NR}$ and adjusted $V_{S,WR}$ profiles, (b) median spectral acceleration predictions as a function of input motion intensities

Figure 5b shows that as the input intensity increases the presence of V_S reversals in the spatially variable V_S profiles tend to reduce the surface response predictions at periods less than T = 1.5 s. For input PGA over 1 g, the presence of V_S reversals in the spatially variable V_S profiles can reduce the median surface accelerations for about 9.4 % at periods of around T = 0.7 s. Figure 6 plots the percent difference observed between the median Sa_{NR} and Sa_{WR} profiles that more clearly shows higher surface response of the $V_{S,NR}$ profiles at periods less than T = 1.5 s. Figure 6 also shows that around the predominant site period (i.e., T = 5.3 s) the Sa_{WR} is observed to be slightly (up to 3%) higher than the Sa_{NR} for motions with input PGA higher than 0.3 g.

The lower median Sa_{WR} for the high intensity motions can be a result of higher shear strains (γ) mobilized due to the presence of V_S reversals in the simulated profiles (Figure 3c) that can cause higher damping. The amplitude of mobilized γ is highly dependent on the input motion intensity.

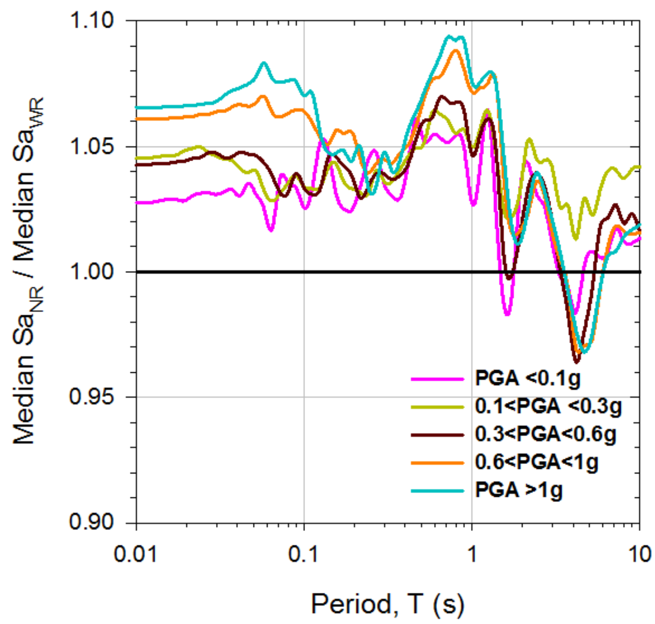

Figure 6. Ratio of the median Sa_{NR} to Sa_{WR} for different input motion intensities.

Figure 7a shows that high intensity input ground motion mobilizes larger shear strains in the spatially variable profiles. Figure 7b presents the ratio of the median γ of $V_{S,NR}$ profiles (γ_{NR}) to median γ of $V_{S,WR}$ profiles (γ_{WR}) and shows that the $V_{S,NR}$ profiles mobilize higher amplitudes of shear strain (i.e., median γ_{NR} > median γ_{WR}) at most depths along the profile for most of the input intensities. The adjusted $V_{S,WR}$ profiles are found to mobilize higher amplitudes of shear strain at depths greater than 760 m under input motions with intensities higher than 0.6 g (i.e., median γ_{WR} > median γ_{NR}).

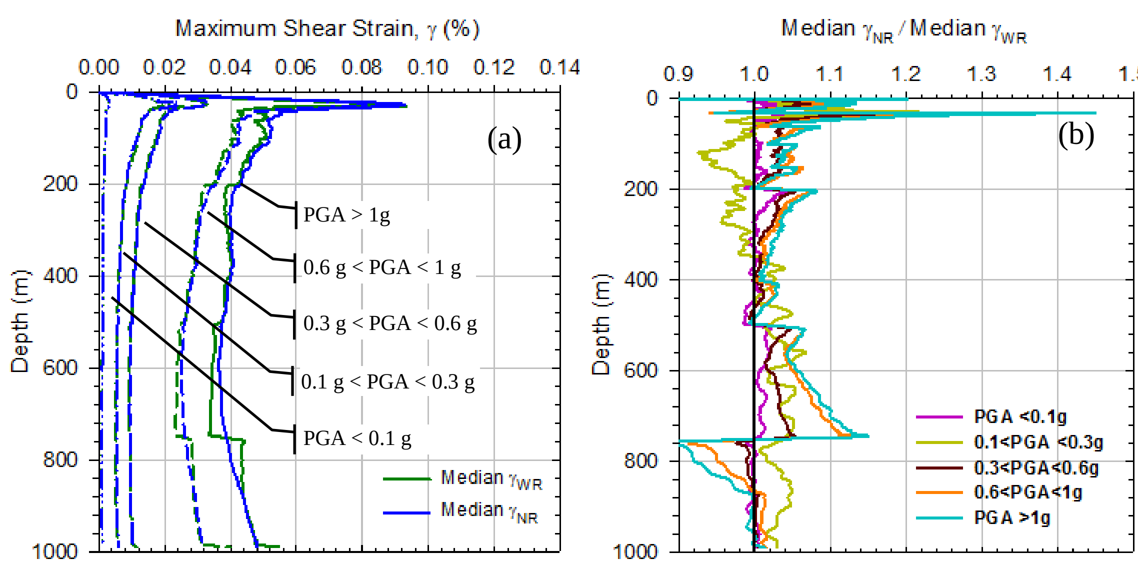

Figure 7. (a) Comparison of maximum shear strain profiles of spatially variable $V_{S,NR}$ and adjusted $V_{S,WR}$ profiles as a function of input intensity and (b) ratio of median maximum shear strain profiles of spatially variable $V_{S,NR}$ and adjusted $V_{S,WR}$ profiles.

Conclusions

In one-dimensional (1D) site response analyses, the spatial variability and the uncertainty in V_S profiles are commonly taken into account by analyzing multiple spatially variable 1D V_S profiles. Often these spatially variable V_S profiles exhibit V_S reversals. This study investigated the influence of the presence of V_S reversals on 1D surface response of spatially variable V_S profiles as a part of the NGA-East GWG that focuses on the development of site amplification models for CENA. Two (2) sets of sixty (60) spatially variable V_S profiles, with and without V_S reversals, were analyzed using equivalent-linear 1D site response analysis. The results of the study showed that the presence of V_S reversals reduces the median surface response spectra up to 9.5% at periods of shorter than 0.1 s, but did not significantly affect the median surface predictions around the site period. The variability in the median surface spectral acceleration was not influenced by the presence of V_S reversals. Influence of V_S reversals was more pronounced for the surface response of high-intensity motions. Similarly, the maximum shear strains developed within the profiles due to high input intensity motions were found to be influenced by the presence of V_S reversals. Profiles with V_S reversals predicted about 10% higher maximum shear strains about 760 m below the ground surface, while profiles without V_S reversals predicted higher maximum shear strains at shallower depths.

Acknowledgments

This work was done as part of the NGA-East project Geotechnical Working Group activities under the auspices of the Pacific Earthquake Engineering Research Center (PEER). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsoring agencies.

References

Darendeli, M. B. (2001). *Development of a New Family of Normalized Modulus Reduction and Material Damping Curves*, Ph.D. Dissertation, The University of Texas at Austin, 362 pp.

Hashash, Y. M. A., Kottke, A. R., Campbell, K. W., Kim, B., Moss, C., Nikolaou, S., Rathje, E.M., Silva, W. J., and Stewart, J. P. (2013). *Reference rock site condition for central and eastern North Americ*a, in Transactions, 22nd Conference on Structural Mechanics in Reactor Technology, SMiRT-22, Division IV, San Francisco.

Hashash, Y. M. A., and Moon, S. (2011). *Site amplification factors for deep deposits and their application in seismic hazard analysis for central U.S.*, U.S. Geological Survey, NEHRP Grant Award G09AP00123, final report, 91 pp.

Kottke A. R., Hashash, Y. M. A., Stewart, J. P., Moss, C., Nikolaou, S., Rathje, E.M., Silva, W. J., and Campbell, K. W. (2012). *Development of geologic site classes for seismic site amplification for central and eastern North America*, in Proceedings, 15th World Conference in Earthquake Engineering, Paper 4557, Lisbon, Portugal.

Kottke A. R., and Rathje, E. M. (2008). *Technical Manual for Strata*, Pacific Earthquake Engineering Research Center, University of California, Berkeley. PEER Report 2008/10

McGuire, R. K., Silva, W. J., and Costantino, C. J. (2001). *Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-consistent Ground Motion Spectra Guidelines*, NUREG/CR-6728, U.S. Nuclear Regulatory Commission, Gathersburg, Maryland.

Toro, G. R. (1995). *Probabilistic models of site velocity profiles for generic and site-specific ground-motion amplification studies*, report prepared by Risk Engineering, Inc. for Brookhaven National Laboratory, Upton, New York.