



Reference Rock Site Condition for Central and Eastern North America

Youssef M. A. Hashash¹, Albert R. Kottke², Kenneth W. Campbell³, Jonathan P. Stewart⁴,
Byungmin Kim⁵, Cheryl Moss⁶, Sissy Nikolaou⁷, Ellen M. Rathje⁸, and Walter J. Silva⁹

¹ Professor, Dept. of Civil and Environmental Engineering,

University of Illinois at Urbana-Champaign, IL (hashash@illinois.edu)

² Engineer, Bechtel Corporation, San Francisco, CA (akottke@bechtel.com)

³ Vice President, EQECAT, Inc., Oakland, CA

⁴ Professor, Dept. of Civil and Environmental Engineering, University of California at Los Angeles, CA

⁵ Postdoctoral Researcher, Dept. of Civil and Environmental Engineering,

University of Illinois at Urbana-Champaign, IL

⁶ Senior Geologist, Mueser Rutledge Consulting Engineers, New York, NY

⁷ Senior Associate, Mueser Rutledge Consulting Engineers, New York, NY

⁸ Professor, Dept. of Civil, Architectural and Environmental Engineering,

University of Texas, Austin, TX

⁹ Pacific Engineering and Analysis, Inc., El Cerrito, CA

ABSTRACT

The reference rock site condition is defined by the shear (S)- and compression (P)-wave velocities, as well as a site attenuation parameter (κ_0). The significance of the reference rock is that it represents the site condition for which ground motions will be estimated using semi-empirical ground motion prediction equations (GMPEs). Moreover, it is the site condition where site amplification are referenced to (i.e., site amplification is unity for reference rock). This paper presents the recommendation of a reference S-wave velocity, a reference P-wave velocity, and S-wave site attenuation parameter, κ_0 , associated with a reference rock site condition in Central and Eastern North America (CENA), supported by results of a comprehensive literature search and additional studies. The work is part of the Next Generation Attenuation Relationships for Central and Eastern North America (NGA-East) Project. The recommended S- and P-wave velocities are 3,000 and 5,500 m/sec, respectively. Considering a $\pm 5\%$ impact on the site amplification, ranges for the reference S- and P-wave velocities of 2,700 to 3,300 m/sec and 5,000 to 6,100 m/sec, respectively, are recommended. The recommended reference rock site kappa is 0.006 sec. The uncertainty in the site kappa is described using a log-normal distribution with an aleatory standard deviation of 0.43, and epistemic standard deviations of 0.12, when uncertainty in source, path, and site-amplification effects are included in simulations used to develop ground motion prediction equations, and 0.20, when they are not.

INTRODUCTION

Site amplification represents the altering of ground motions for a particular site condition relative to a reference condition, hereby referred to as the reference rock site condition. The reference rock site condition is defined by the S-wave velocity (V_s), P-wave velocity (V_p), and a site attenuation parameter (κ_0) that is used in stochastic ground motion simulation tools (e.g., Anderson and Hough 1984; Boore 1983). The reference rock site condition varies significantly between active tectonic regions, such as Western North America (WNA), and mid-plate regions, such as Central and Eastern North America (CENA) (Boore and Joyner 1997). These differences result in the need for the reference rock site condition to be region specific (Nikolaou *et al.* 2012). As part of the Next Generation Attenuation Relationships for Central and Eastern North America (NGA-East) Project, a comprehensive literature

review has been conducted, as well as additional studies that support the recommendation of a best estimate and uncertainty of the reference site condition (i.e., $V_{s,ref}$, $V_{p,ref}$, and $\kappa_{0,ref}$).

The EPRI (1993) report established the state-of-practice for defining ground motions in the CENA region for nuclear facilities. The report identified 16 crustal structure regions within CENA, which were developed using P-wave inversions. Using an assumed Poisson's ratio of 0.25, V_s was estimated from V_p and was not based on direct measurements. The estimated V_s of the surface layer ranges from 2.31 to 2.83 km/sec with a value of 2.83 km/sec for 12 of 16 profiles. Additionally, the EPRI (1993) study reported a median $\kappa_{0,ref}$ of 0.006 sec and initially proposed to model the uncertainty with a natural log standard deviation of 0.40. Eventually, EPRI (1993) used three equally weighted values (0.003, 0.006, and 0.012 sec) to define the total uncertainty in $\kappa_{0,ref}$ in the development of a ground motion prediction equation (GMPE) using the point-source stochastic simulation method (EPRI 1993; Toro *et al.* 1997). The U.S. Nuclear Regulatory Commission (NRC) recommended $V_{s,ref}$ of 2.8 km/sec (9,200 ft/s) (NRC 2007). This recommendation of 2.8 km/sec (9,200 ft/s) in NUREG-1.208 was adopted by the NRC to maintain compatibility with contemporaneous ground motion prediction equations used in the nuclear industry (e.g. Toro *et al.* 1997), which are based on the estimated $V_{s,ref}$ values from EPRI (1993). Reference shear-wave velocities range from 2.00 to 2.88 km/sec for a number of GMPEs applicable to the CENA region (Atkinson and Boore 2006; Campbell 2003; Pezeshk *et al.* 2011; Toro *et al.* 1997). Those models are based on simulations, and hence the reference velocities reflect conditions at the top of assumed crustal profiles used during the simulation process. It is important to recognize the divergence in reference site conditions in GMPEs does not reflect varying interpretations of available profiles derived from data. In fact, since the seminal EPRI (1993) work, no systematic data compilation has been undertaken to support a defensible definition of reference rock. The work described in this study addresses this need using prescribed protocols applied to high quality data in a transparent, reviewable manner.

The purpose of this study is two-fold: (1) to review and evaluate, within the framework of a Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 process, the data and studies that have been conducted since the original Electric Power Research Institute (EPRI) (1993) report was released, and (2) to evaluate whether the distribution describing the reference rock site condition for hard-rock site in CENA should be revised and make recommendations of the reference rock site condition. Further details and background information can be found in the upcoming reports by (Campbell *et al.* 2013; Hashash *et al.* 2013).

REFERENCE VELOCITY

In this study, S- and P-wave velocity profiles that penetrate intact hard rock were collected from published reports (Beresnev and Atkinson 1997; Daniels *et al.* 1983; Dorman and Smalley 1994; Kafka and Skehan 1990; Luetgert *et al.* 1994; Moos and Zoback 1983) and Nuclear Power Plant (NPP) license applications (U.S. Nuclear Regulatory Commission 2013) at CENA sites.

Definition of Reference Velocity

We have found that velocity profiles from the CENA region having a sufficiently large sampling depth to penetrate intact bedrock show some common characteristics. For example, as illustrated in Figure 1 from Bell Bend NPP, S- and P-velocities increase with depth as the materials transition from soils into weathered rock and eventually intact rock. A striking feature of profiles from a significant majority of the available sites is the lack of increase with depth of shear wave velocity within firm materials encountered near the bases of profiles. Defining the reference rock site condition on the basis of written descriptions of relatively intact rock from boring logs is not sufficient, because highly variable conditions in the rock V_s profile can be present even for materials logged as intact rock. This is thought to result in part from the wide range of rock types sampled in our data set. Instead, visual inspection of the profiles revealed key features that are commonly encountered, and which have been used to develop criteria to define reference

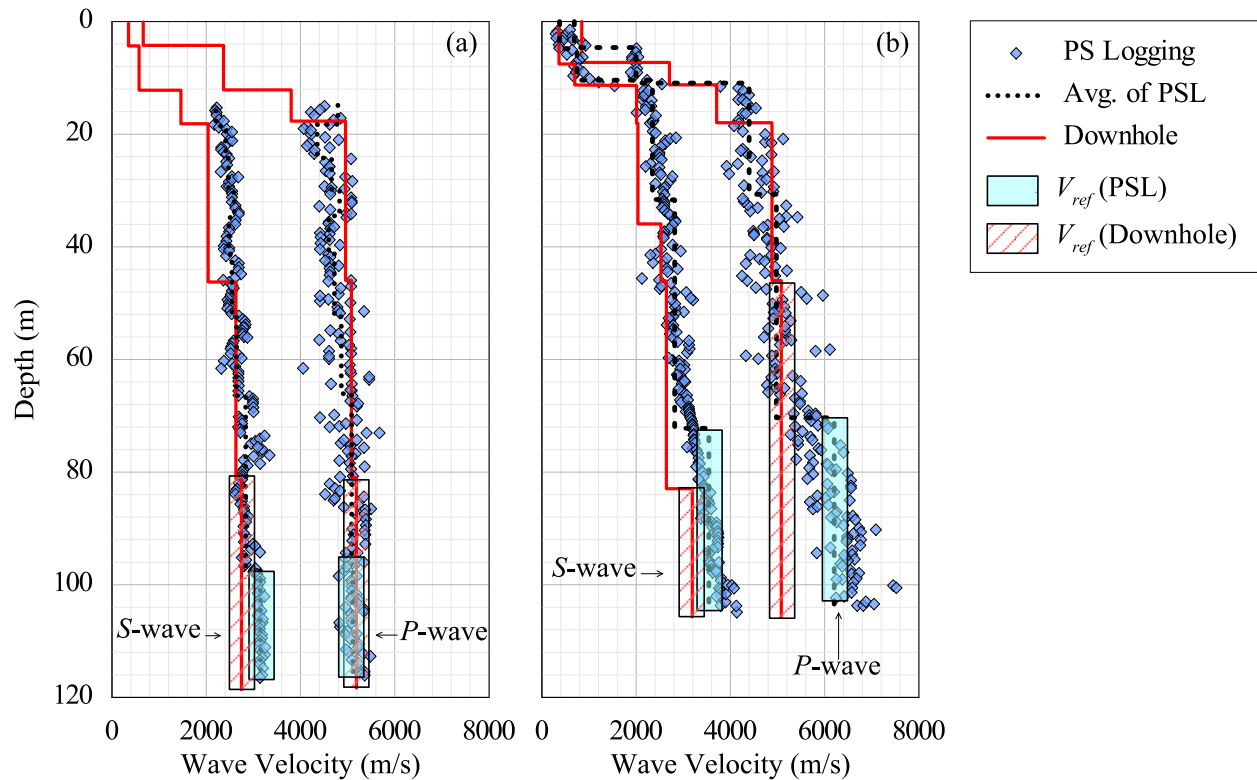


Figure 1 Wave velocities measured using P- and S-wave suspension logging (PSL) and downhole methods at Bell Bend NPP from (a) Figure 2.5-151 and (b) Figure 2.5-152 in UniStar Nuclear Services LLC (2010).

rock based on the velocity, measurement penetration, velocity gradient, and geologic age (details in Hashash *et al.* 2013).

Evaluation of Reference Velocity

The total number of profiles examined in this work was 283, of which 128 satisfied the reference rock velocity conditions. Those 128 profiles were digitized and the mean reference rock velocity was computed over the interpreted depth range. This process yielded 68 S-wave velocities at 27 different locations and 60 P-wave velocities at 22 different locations. Figure 2 shows the locations of the sites with reference velocities. The sites with reference rock velocities occur throughout the study region, but there is limited coverage along the Gulf Coast, Western Plains, and Appalachian regions. The velocity profiles from three Gulf-Coast nuclear plants (Levy County, South Texas, and Victoria County) were not sufficiently deep to sample the reference rock condition despite measurements at depths of 1400 to 4000 m. Of the 68 S-wave measurements, 58 are from direct measurements of the in-situ S-wave velocity. The remaining 10 values have estimated V_s using measured V_p and an assumed Poisson's ratio. The selected S- and P-wave reference velocities show essentially no trend with depth as shown in Figure 3.

Discussion

The data collected in this study provide information on the aleatory uncertainty at three different scales: profile, site, and region. At each of these scales, the data are used to quantify the expected value and uncertainty, as well as to test statistical distributions. A normal distribution is selected, principally because it is more representative of the within-site and within-region distributions.

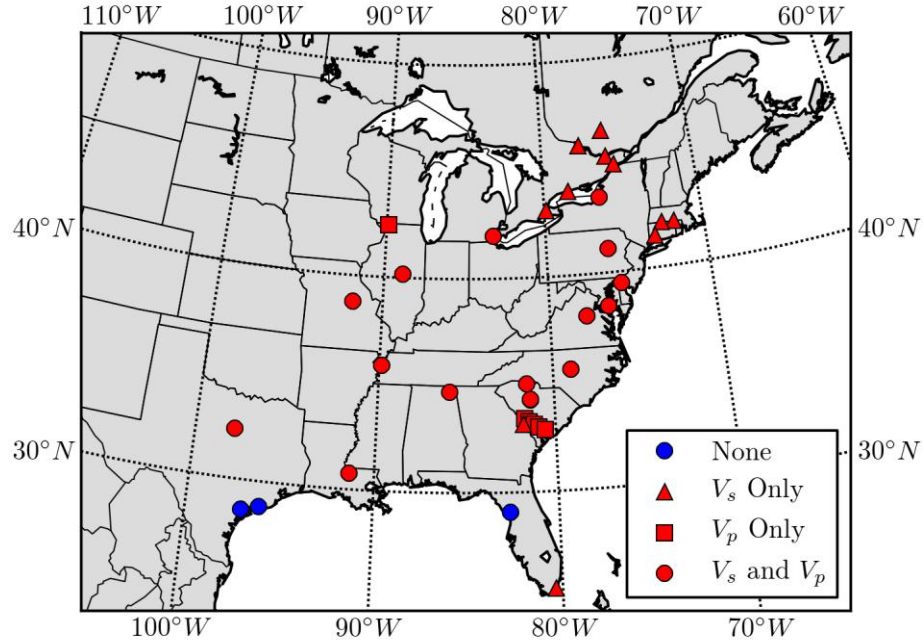


Figure 2 Locations of the reference S- and P-wave velocity measurements.

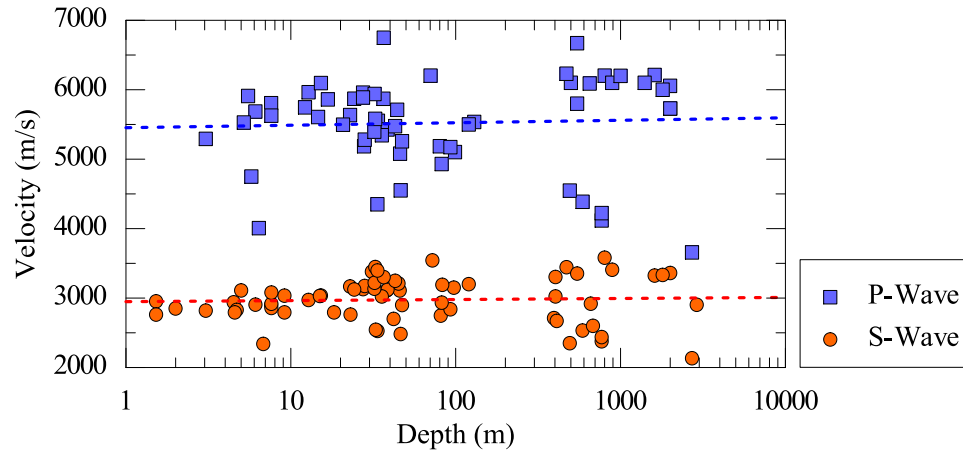


Figure 3 Influence of depth on the reference P - and S -wave velocities with semilog-linear fits through the S - and P -wave velocity data.

Each of the profiles have a mean reference velocity, $(\bar{v}_{s,ref})_{pr}$ and $(\bar{v}_{p,ref})_{pr}$, and within-profile standard deviations, $\sigma_{vs,ref}^{pr}$ and $\sigma_{vp,ref}^{pr}$, that ranges from 52 to 612 m/sec. There is a slight trend in within-profile standard deviation with mean profile velocity, thus dispersion is again represented with a coefficient of variation (COV) instead of standard deviation, shown in Figure 4. The within-profile coefficients of variation range from 0.02 to 0.18 for $\sigma_{vs,ref}^{pr}$ and 0.02 to 0.09 for $\sigma_{vp,ref}^{pr}$. The average of S - and P -wave values (0.067) is used as the estimate of within-profile coefficient of variation ($COV^{profile}$).

The mean S -wave velocities at each of the profiles range from 2,134 m/sec at River Bend NPP located in Louisiana to 3,581 m/sec at Calvert Cliffs NPP located in Maryland. For sites with multiple

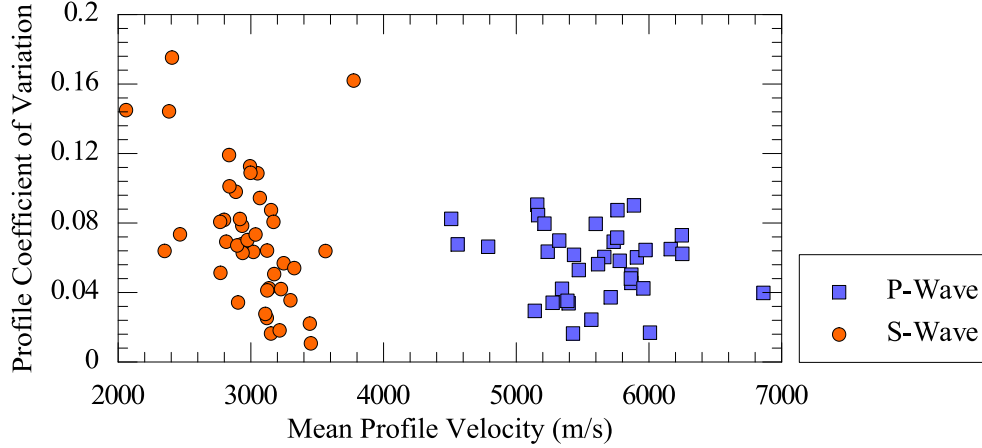


Figure 4: Influence of mean profile velocity on the variation of the within-profile coefficients of variation.

profiles, the mean can be taken across the data sets for the site as a whole, $(\bar{V}_{s,ref})_{site}$ and $(\bar{V}_{p,ref})_{site}$, and an between-profile standard deviation of reference velocity can be computed, $\sigma_{Vs,ref}^{site}$ and $\sigma_{Vp,ref}^{site}$. This between-profile variability is evaluated from four sites with 8 to 12 profiles (i.e., Bell Bend NPP, Bellefonte NPP, V.C. Summer NPP, and William States Lee NPP). The between-profile coefficients of variation range from 0.033 to 0.127 for $COV_{Vs,ref}^{site}$ and 0.017 to 0.114 for $COV_{Vp,ref}^{site}$. Given the similar range in coefficients of variations and the relationship between S- and P-wave velocities, a single coefficient variation of 0.063 is recommended for both $COV_{Vs,ref}^{site}$ and $COV_{Vp,ref}^{site}$, which is quite similar to $COV^{profile}$ of 0.067.

Considering site-to-site variability of mean reference velocities, a regional weighted mean is computed with weights taken as proportional to the reciprocal of the standard error, defined by the $COV_{Vs,ref}^{site}$ and $COV_{Vp,ref}^{site}$ values divided by the square root of the number of profiles, to provide a maximum likelihood estimate of the mean (denoted as $(\bar{V}_{s,ref})_{reg}$ and $(\bar{V}_{p,ref})_{reg}$). For the four well-sampled sites, the site specific standard deviations are used for weighting. For more sparsely sampled sites (having one to three profile means), the standard deviation is computed from mean COV^{site} of 0.063. Weighted standard deviations are similarly computed (denoted as $COV_{Vs,ref}^{reg}$ and $COV_{Vp,ref}^{reg}$), which represent regional site-to-site variability of the mean velocity. Combining site-to-site and between-profile standard deviations yields a total standard deviation of $COV_{Vs,ref}^{reg}$ and $COV_{Vp,ref}^{reg} = 0.144$ and 0.128 , respectively. These mean values and their 95% confidence intervals are $(\bar{V}_{s,ref})_{reg} = 2,951 \pm 831$ m/sec (i.e., 2,120 to 3,782 m/sec) and $(\bar{V}_{p,ref})_{reg} = 5,517 \pm 1,380$ m/sec (i.e., 4,137 to 6,897 m/sec).

We did not find evidence for regional dependence of the reference velocities, which are derived principally from three general geographic regions: (1) Atlantic coast; (2) continental interior; and (3) Appalachian Mountains. Our data do not provide reference velocities for the Gulf Coast region (details in Hashash *et al.* 2013). In this region the depth to the CENA reference rock condition is much greater than other CENA regions due to several kilometers of overlying sediments. Therefore, a reference rock condition is not provided for the Gulf Coast.

Recommended Reference Velocity

As previously described, the mean regional reference velocities for CENA, with their 95% confidence intervals, were derived from the data assembled in this study. For application purposes, we recommend the use of mean values having no more than two significant digits, which gives the following values: $V_{s,ref} = 3,000$ m/sec or 9,800ft/sec, and $V_{p,ref} = 5,500$ m/sec or 18,000 ft/sec. Note, that the formal statistical nomenclature has been dropped for these recommendations, because they are interpreted (and slightly modified) from the formal statistics.

The data gathered in this study reveal substantial site-to-site variability of mean reference velocities. This is important for site-specific ground motion studies, where geotechnical and geophysical logging to depths corresponding to the reference conditions may be required by regulatory agencies. Given the evident site-to-site variability, we do not advocate strict adherence to reaching the $V_{s,ref}$ and $V_{p,ref}$ values given above. Our principal recommendation is that the depth of exploration be sufficiently large that the reference condition is demonstrated by the collected data.

With that said, it is recognized that often in practical applications the articulation of a specific (or at least a range of) reference velocity is required. In these cases, the selected velocity range is more rationally defined from its impact on the site amplification rather than by the width of confidence intervals. For this reason, the velocity range is based on its impact on site amplification. The amplification in a vertically-propagating horizontally-polarized S-wave between two layers is related to the mass density (ρ) and velocity (V) in the layers (Joyner et al. 1981) as:

$$A = \sqrt{\frac{\rho_1 V_1}{\rho_2 V_2}} \quad (1)$$

If the layers have the same mass densities, then the amplification across those two layers is equal to the square root of the velocity ratio ($\sqrt{V_1/V_2}$). An admittedly subjective limit on amplification change of 5% is selected, which implies that for a given soil layer velocity the range in reference rock velocity is 0.907 to 1.108 of the central value. This corresponds to a computed range of 2,700 to 3,300 m/sec for $V_{s,ref}$ and 5,000 to 6,100 m/sec for $V_{p,ref}$. The range is somewhat smaller than the 95% confidence interval given above. The EPRI (1993) recommendation for $V_{s,ref}$ falls within this range, which means that prior seismic hazard analyses for nuclear power plants utilizing this value are not incompatible with our recommendations. However, the P-wave reference velocity from EPRI (1993) of $V_{p,ref} = 4,900$ m/sec falls outside the recommended range. Based on the above reasoning, the recommended range of $V_{s,ref}$ is 2,700 to 3,300 m/sec (8,900 to 10,800 ft/sec) and of $V_{p,ref}$ is 5,000 to 6,100 m/sec (16,400 to 20,000 ft/sec).

REFERENCE SITE ATTENUATION

For the purposes of characterizing the reference rock site condition, the site attenuation parameter (κ_0) is of interest as attenuation that is independent of distance and dependent on the characteristics of the subsurface geological structure. Since introduced, κ_0 has become the preferred parameter for incorporating site attenuation in the calculation of seismological site amplification (e.g., Anderson 1986; Anderson 1991; Halldorsson and Papageorgiou 2005; Joyner et al. 1981; Silva and Darragh 1995).

At present, there are various interpretations of κ_0 . In this study, κ_0 is defined as local attenuation that is in addition to the crustal damping (Q), and thus is bounded by zero. A complete description on the background on site attenuation parameter (κ_0) can be found in in Campbell (2009) and Campbell et al. (2013).

Published Models of Site attenuation

The mean values of published estimates of hard-rock κ_0 in Central and Eastern North America range from 0.002 to 0.009 sec (Atkinson and Boore 2006; Atkinson 1984;1996; Campbell 2009;

Chapman *et al.* 2003; Silva and Darragh 1995; Silva *et al.* 1988; Toro and McGuire 1987). In order to show that the small values of κ_0 reported for CENA hard-rock sites are no unrealistic, it is useful to compare them with estimates for hard-rock sites in the Western North America (WNA) from regions where estimates of κ_0 are somewhat analogous to the hard-rock environment of CENA. Two such regions where estimates of κ_0 are available are the granitic pluton of the Anza region in southern California and the cordillera of southwestern British Columbia. The mean κ_0 values range from 0.0003 to 0.01 sec (Anderson 1991; Atkinson 1996; Campbell 2009; Hough *et al.* 1988; Silva and Darragh 1995) which is quite similar with the range in mean values observed in the CENA data (i.e., 0.002 to 0.009 sec).

Another method of estimating κ_0 is by empirically correlating it to the time-averages S-wave velocity in the top 30 m of a site (V_{s30}). Figure 5 summarizes κ_0 estimates from the κ_0 – V_{s30} relationships of Silva *et al.* (1999) for northern California, Chandler *et al.* (2006) for global active and stable tectonic regimes, Edwards *et al.* (2011) as modified by Edwards (2012) (using three relationships between κ_0 and V_{s30} : log-linear; log-log; and linear-linear) for Switzerland, and Van Houtte *et al.* (2011) for Japan, California, and Taiwan. Except for Switzerland, all of the equations give similar estimates of κ_0 for $V_{s30} < 1500$ m/sec, after which they begin to diverge due to their different databases and functional forms and greater uncertainty. The Switzerland equations systematically predict smaller estimates in this velocity range for reasons that are not known at this time. One possible reason is that Edwards *et al.* (2011) and Edwards (2012) allowed negative values of κ_0 in their inversions, thus reducing the average value for each station compared to an analysis for which all values of κ_0 are found or constrained to be greater than zero. However, the Swiss estimates become more similar to those from the other relationships at higher values of V_{s30} . All of the relationships provide estimates of κ_0 for $V_{s30} > 2,000$ m/sec that are comparable to the values for CENA hard-rock sites, whether or not they explicitly include data from stable continental regions or, for that matter, from hard-rock sites. For $V_{s30} > 1,500$ m/sec, the estimates of κ_0 from the κ_0 – V_{s30} relationships are found to range from 0.004–0.016 sec, which are consistent with those reported for British Columbia hard-rock sites (0.007–0.015 sec) (Atkinson 1996) with similar near-surface velocities. The Edwards (2012) linear-linear relationship is excluded from this comparison because of its extreme curvature at large values of V_{s30} .

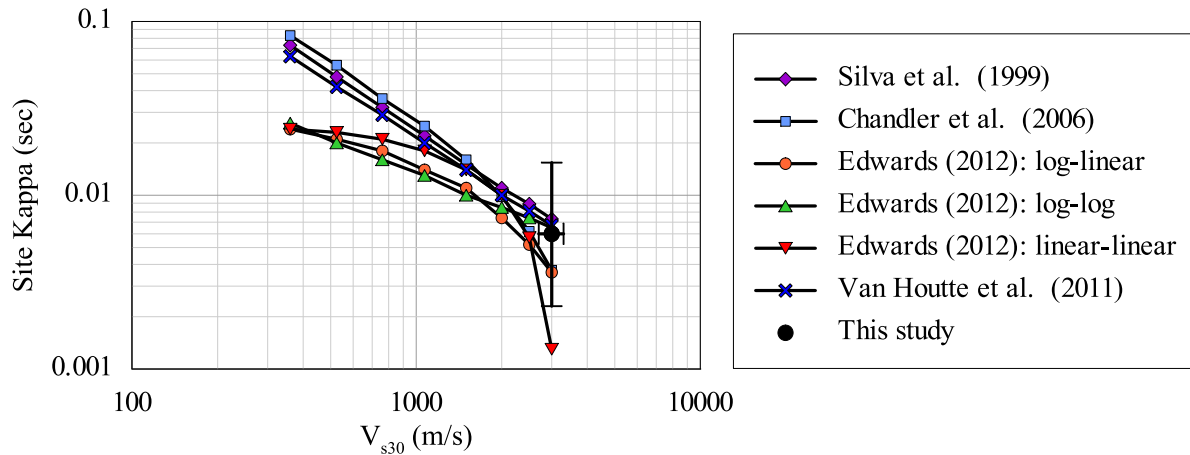


Figure 5 A comparison of estimates of site kappa (κ_0) from selected κ_0 – V_{s30} relationships with the values recommended in this study for the reference rock S-Wave velocity ($V_{s,ref}$) of 3000 ± 300 m/sec. The vertical error bar represents the 95th-percentile (plus and minus two standard deviations) of the total distribution of the reference rock site kappa ($\kappa_{0,ref}$) that includes epistemic uncertainty in source, path, and site-amplification effects.

Recommended Values

Based on the results of this study and careful deliberation, the NGA-East Geotechnical Working Group recommend that the reference rock site kappa ($\kappa_{0,ref}$) should be represented by a lognormal distribution with a median value ($\bar{\kappa}_{0,ref}$) of 0.006 sec. This approach was chosen because (1) it has been used to represent the distribution of κ_0 in several previous studies and, therefore, has precedence in the literature and (2) it did not allow for the unphysical prediction of negative values. The selection of the median value was straightforward, based on the values presented in this study.

Considering the standard deviation derived from the estimates for CENA, as well as Schneider *et al.* (1993) and Silva and Darragh (1995) studies, an aleatory natural log standard deviation $\phi_{\ln \kappa_{0,ref}}$ of 0.43 for $\kappa_{0,ref}$ is recommended. Two different epistemic uncertainties are recommended for $\kappa_{0,ref}$. If the uncertainties of seismological and geophysical parameters are incorporated in the simulations used to develop ground motion prediction equations, then an average natural log standard error of 0.12 is recommended based on the Schneider *et al.* (1993) and Silva and Darragh (1995) studies. When uncertainty in seismological input parameters are not incorporated in the simulations that are used to develop ground motion prediction equations, then an average natural log standard error 0.20 based on Edwards *et al.* (2011).

CONCLUSIONS

This study provides recommendations for the S- and P-wave velocity, site attenuation (κ_0), and unit weight of the reference rock for Central and Eastern North America. The reference rock condition defines the boundary between the site specific amplification and the regional ground motion model. A consistent definition of this boundary across models allows for models of site amplification and ground motion to be developed independently.

The reference S- and P-wave velocity recommendations are based on values reported in site investigations reported at nuclear power plants, as well as investigation results published in the literature. Profiles were collected at sites across the study region and used to examine the variation in reference velocities within a profile, between profiles, and across the region. The recommended mean values of $V_{s,ref}$ and $V_{p,ref}$ are 3,000 and 5,500 m/sec, respectively. The recommended range in values is 2,700 to 3,300 m/sec and 5,000 to 6,100 m/sec for $V_{s,ref}$ and $V_{p,ref}$, respectively. This range is based on a presumed change in site amplification of 5%, rather than the observed variation in collected data.

The reference site attenuation ($\kappa_{0,ref}$) is based on values published values both within the study region, as well as in the relationships between κ_0 and V_{s30} for other regions. A median value of 0.006 sec is recommended. The recommended model for the aleatory variability of $\kappa_{0,ref}$ is a log-normal distribution with natural log standard deviation of 0.43. The recommended epistemic uncertainty of $\kappa_{0,ref}$ is a log-normal distribution with a natural log standard deviation of 0.20. If variability of the seismological parameters is included elsewhere in the model, then the epistemic uncertainty should be reduced to a natural log standard deviation of 0.12.

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