Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1004

# GROUND MOTION PREDICTION EQUATIONS FOR CUMULATIVE ABSOLUTE VELOCITY (CAV) USING THE PEER-NGA STRONG MOTION DATABASE

K. W. Campbell[1] and Y. Bozorgnia[2]

## ABSTRACT

Cumulative absolute velocity (CAV), defined as the sum of the absolute acceleration time series, has been shown to be a better predictor of damage than peak ground motion and response spectra parameters. The nuclear industry uses the value of CAV in consecutive one-second intervals in which the acceleration exceeds 0.025g ($CAV_{STD}$) as a check on whether to shut down a nuclear power plant when the response spectra exceed the Operating Basis Earthquake (OBE). The value of CAV exceeding an acceleration threshold of 0.005g ($CAV_5$) has been found to be a better parameter than Arias Intensity or peak ground acceleration (PGA) and magnitude for evaluating liquefaction potential of saturated sands. Most recently, $CAV_{STD}$ has been used to exclude non-damaging ground motions from contributing to the probabilistic seismic hazard analyses (PSHA) of nuclear power plant sites in the central and eastern United States. However, there are very few CAV ground motion prediction equations (GMPEs). To help fill this void, we developed new GMPEs for the geometric mean horizontal component of CAV ($CAV_{GM}$) based on the strong motion database and functional forms used to develop GMPEs for peak ground motion and response spectra parameters for the PEER-NGA Project. We also developed a prediction equation between a modified version of $CAV_{STD}$ ($CAV_S$), which includes all of the USNRC ground motion criteria for shutting down a nuclear power plant, and $CAV_{GM}$ using the PEER-NGA database. We consider our CAV relationships to be valid for magnitudes ranging from 5.0 up to 7.5–8.5 (depending on fault mechanism) and distances ranging from 0 up to 100–200 km (depending on magnitude) for shallow crustal earthquakes in active tectonic regions. We found the standard deviation of both of the CAV parameters to be equal to or smaller than those of any ground motion parameter we have studied thus far.

## Introduction

Cumulative absolute velocity (CAV), which is defined as the integral of the absolute value of the acceleration time series, is calculated from the equation (EPRI 1988):

---

[1]Vice President, EQECAT, Inc., Beaverton, OR, USA, kcampbell@eqecat.com
[2]Executive Director, PEER, University of California, Berkeley, CA, USA, yousef@berkeley.edu

$$\text{CAV} = \int_0^{t_{max}} |a(t)|\, dt \tag{1}$$

where $t$ is time and $t_{max}$ is the total duration of the time series. Fig. 1 shows a hypothetical acceleration time series and the corresponding value of CAV as it evolves over time. In this figure, CAV is the summation of the shaded areas. It is evident from the definition of CAV that its value increases with time until it reaches its maximum value at $t_{max}$. Therefore, CAV includes the cumulative effects of ground motion duration. This is a key advantage of CAV over other peak ground motion and response spectra parameters and is one of the reasons that EPRI (1988) found it to be the instrumental intensity measure that best correlated with the onset of structural damage to buildings of good construction of all of the measures that they studied.

Although it is named the cumulative absolute velocity and it has units of velocity, CAV is not directly related to the ground motion velocity $v(t)$. The name cumulative absolute velocity comes from the recognition that, since $a(t) = dv(t)/dt$, the integral over acceleration in Eq. (1) can be rewritten as the following summation of $N$ incremental (i.e., peak-to-valley and valley-to-peak) velocities, regardless of sign, in the velocity time series (EPRI 1988):

$$\text{CAV} = \sum_{i=1}^{N} |\Delta v_i| \tag{2}$$

CAV was initially developed and proposed by EPRI (1988) as an index to indicate the onset of structural damage to nuclear facilities. Since then several variants of CAV have been proposed that are believed to be better suited to specific engineering applications. EPRI (1991) noted that the calculation of CAV could be overly influenced by time series of long duration that contained small amplitude (non-damaging) accelerations. As a result, EPRI standardized the method of calculating CAV to account for record length. We refer to this standardized version of CAV as $\text{CAV}_{\text{STD}}$ in order to distinguish it from the original definition of CAV. The recommended method to standardize the CAV calculation for a given time series is to window its calculation on a second-by-second basis. Only if the absolute value of acceleration exceeds 0.025g at any time during each non-overlapping one-second time interval of the acceleration time series is the incremental value of CAV for that time interval included in the summation. This calculation is given by the equation (EPRI 2006):

$$\text{CAV}_{\text{STD}} = \sum_{i=1}^{N} \left( H(\text{PGA}_i - 0.025) \int_{t_i}^{t_i+1} |a(t)|\, dt \right) \tag{3}$$

where $a(t)$ has units of g, $N$ is the number of one-second non-overlapping time intervals in the acceleration time series, $\text{PGA}_i$ is the peak ground acceleration (g) in time interval $i$, $t_i$ is the start time of time interval $i$ (sec), and $H(x)$ is the Heaviside Step Function (0 for $x < 0$, 1 for $x \geq 1$). Fig. 1 shows the calculation of $\text{CAV}_{\text{STD}}$ and its relationship to CAV for a hypothetical acceleration time series. As this figure shows, $\text{CAV}_{\text{STD}}$ will always be equal to or less than CAV. This difference can be large for small amplitude recordings. The U.S. Nuclear Regulatory Commission (USNRC 1997) uses $\text{CAV}_{\text{STD}}$ and the response spectra calculated from free-field recordings to determine whether the Operating Basis Earthquake (OBE) has been exceeded and a nuclear power plant must be shut down after an earthquake.

Kramer and Mitchell (2006) investigated several peak, spectral, and energy related ground motion intensity measures, including Arias Intensity and $\mathrm{CAV_{STD}}$, and determined that the measure that best correlated with the peak porewater pressure in saturated liquefiable sands was the value of CAV after application of a 5 cm/sec$^2$ threshold acceleration, which they call $\mathrm{CAV_5}$. Pulses of an acceleration time series whose amplitudes do not exceed this threshold are not included in the calculation of $\mathrm{CAV_5}$. This calculation is given by the equation:

$$\mathrm{CAV_5} = \int_0^\infty H\left(\left|a(t)\right| - 5\right)\left|a(t)\right| dt \tag{4}$$

where $a(t)$ has units of cm/sec$^2$ and $H(x)$ is the Heaviside Step Function defined in Eq. (2).

A summary of studies involving CAV, $\mathrm{CAV_{STD}}$, and $\mathrm{CAV_5}$ and their correlation with macroseismic intensity and instrumental damage index parameters is summarized by Campbell and Bozorgnia (2010a,b).

## Ground Motion Database

In this study, we defined CAV as the geometric mean of the two as-recorded horizontal components of the ground motion. We refer to this former intensity measure as $\mathrm{CAV_{GM}}$ in order to distinguish it from the generic definition of CAV. Our definition of $\mathrm{CAV_{STD}}$, which we refer to as $\mathrm{CAV_S}$, includes all of the USNRC (1997) ground motion criteria for determining whether a nuclear power plant must be shutdown after an earthquake. These criteria state that for any one of the three components (i.e., two horizontal and one vertical) of a free-field recording (1) the 5%-damped pseudo-absolute response-spectral acceleration should exceed 0.2g over the period range 0.1–0.5 sec (the spectral acceleration check) or the 5%-damped pseudo-relative response-spectral velocity should exceed 15.24 cm/sec over the period range 0.5–1 sec (the spectral velocity check), and (2) the value of $\mathrm{CAV_{STD}}$ should exceed 0.16 g-sec (the CAV check).

The strong motion database used for this study was that developed by the Pacific Earthquake Engineering Research Center (Chiou et al. 2008) as part of the Next Generation Attenuation (NGA) Project (Power et al. 2008). We refer to it as the PEER-NGA database. We developed the ground motion prediction equation (GMPE) for $\mathrm{CAV_{GM}}$ from a subset of this database that Campbell and Bozorgnia (2008) used to develop GMPEs for peak ground motion and response spectra parameters. We refer to this subset as the CB08-NGA database. We developed prediction equations between $\mathrm{CAV_S}$ and $\mathrm{CAV_{GM}}$ (see below) from both the PEER-NGA and CB08-NGA databases with and without applying the USNRC spectral velocity check. The prediction equation using the more reliable CB08-NGA database after applying the more inclusive spectral velocity check is presented in this paper. The reader is referred to Campbell and Bozorgnia (2010a) for a description of the other $\mathrm{CAV_S}$ prediction equations.

The full CB08-NGA database used to analyze $\mathrm{CAV_{GM}}$ consists of 1561 recordings from 64 earthquakes with moment magnitudes $\mathbf{M}$ = 4.3–7.9 and rupture distances $R_{RUP}$ = 0.1–199 km. The version of the CB08-NGA database used to analyze $\mathrm{CAV_S}$ (after applying the acceleration and response spectra thresholds) consists of 903 recordings from 53 earthquakes with $\mathbf{M}$ = 4.9–7.9 and $R_{RUP}$ = 0.1–195 km.

## Ground Motion Prediction Equation for $\text{CAV}_{\text{GM}}$

### Median Model

The GMPE for $\text{CAV}_{\text{GM}}$ was developed from the equations (Campbell and Bozorgnia 2008):

$$\overline{\ln \text{CAV}_{\text{GM}}} = f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed} \tag{5}$$

where the magnitude term is given by the expression

$$f_{mag} = \begin{cases} c_0 + c_1\mathbf{M}; & \mathbf{M} \le 5.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M} - 5.5); & 5.5 < \mathbf{M} \le 6.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M} - 5.5) + c_3(\mathbf{M} - 6.5); & \mathbf{M} > 6.5 \end{cases} \tag{6}$$

the distance term is given by the expressions

$$f_{dis} = (c_4 + c_5\mathbf{M})\ln\left(\sqrt{R_{RUP}^2 + c_6^2}\right) \tag{7}$$

the style-of-faulting (fault mechanism) term is given by the expressions

$$f_{flt} = c_7 F_{RV} f_{flt,Z} + c_8 F_{NM} \tag{8}$$

$$f_{flt,Z} = \begin{cases} Z_{TOR}; & Z_{TOR} < 1 \\ 1; & Z_{TOR} \ge 1 \end{cases} \tag{9}$$

the hanging-wall term is given by the expressions

$$f_{hng} = c_9 f_{hng,R} f_{hng,M} f_{hng,Z} f_{hng,\delta} \tag{10}$$

$$f_{hng,R} = \begin{cases} 1; & R_{JB} = 0 \\ \left[\max\left(R_{RUP}, \sqrt{R_{JB}^2 + 1}\right) - R_{JB}\right] \Big/ \max\left(R_{RUP}, \sqrt{R_{JB}^2 + 1}\right); & R_{JB} > 0, Z_{TOR} < 1 \\ (R_{RUP} - R_{JB}) / R_{RUP}; & R_{JB} > 0, Z_{TOR} \ge 1 \end{cases} \tag{11}$$

$$f_{hng,M} = \begin{cases} 0; & \mathbf{M} \le 6.0 \\ 2(\mathbf{M} - 6.0); & 6.0 < \mathbf{M} < 6.5 \\ 1; & \mathbf{M} \ge 6.5 \end{cases} \tag{12}$$

$$f_{hng,Z} = \begin{cases} 0; & Z_{TOR} \ge 20 \\ (20 - Z_{TOR}) / 20; & 0 \le Z_{TOR} < 20 \end{cases} \tag{13}$$

$$f_{hng,\delta} = \begin{cases} 1; & \text{abs}(\delta) \le 70 \\ [90 - \text{abs}(\delta)] / 20; & \text{abs}(\delta) > 70 \end{cases} \tag{14}$$

the shallow site response term is given by the expression

$$f_{site} = \begin{cases} c_{10} \ln\left(\dfrac{V_{S30}}{k_1}\right) + k_2 \left\{ \ln\left[ A_{1100} + c\left(\dfrac{V_{S30}}{k_1}\right)^n \right] - \ln\left[A_{1100} + c\right] \right\}; & V_{S30} < k_1 \\ (c_{10} + k_2 n) \ln\left(\dfrac{V_{S30}}{k_1}\right); & k_1 \le V_{S30} < 1100 \\ (c_{10} + k_2 n) \ln\left(\dfrac{1100}{k_1}\right); & V_{S30} \ge 1100 \end{cases} \tag{15}$$

the basin response (sediment depth) term is given by the expression

$$f_{sed} = \begin{cases} c_{11}(Z_{2.5} - 1); & Z_{2.5} < 1 \\ 0; & 1 \le Z_{2.5} \le 3 \\ c_{12} k_3 e^{-0.75} \left[1 - e^{-0.25(Z_{2.5}-3)}\right]; & Z_{2.5} > 3 \end{cases} \tag{16}$$

and $\mathrm{CAV_{GM}}$ has units of g-sec $\mathbf{M}$ is moment magnitude; $R_{RUP}$ is the closest distance to the coseismic rupture plane (km); $R_{JB}$ is the closest distance to the surface projection of the coseismic rupture plane (km); $F_{RV}$ is an indicator variable representing reverse and reverse-oblique faulting ($F_{RV}$ = 1 for 30° < $\lambda$ < 150°, $F_{RV}$ = 0 otherwise, $\lambda$ is rake angle defined as the average angle of slip measured in the plane of rupture between the strike direction and the slip vector); $F_{NM}$ is an indicator variable representing normal and normal-oblique faulting ($F_{NM}$ = 1 for –150° < $\lambda$ < –30° and $F_{NM}$ = 0 otherwise); $Z_{TOR}$ is the depth to the top of the coseismic rupture plane (km); $|\delta| \le 90°$ is the angle of dip of the rupture plane measured from horizontal; $V_{S30}$ is the time-averaged shear-wave velocity in the top 30m of the site (m/sec); $A_{1100}$ is the median estimate of the geometric mean horizontal component of PGA on a rock outcrop with $V_{S30}$ = 1100 m/sec (g); and $Z_{2.5}$ is the depth to the 2.5 km/sec shear-wave velocity horizon (km).

**Aleatory Uncertainty Model**

The standard deviations of the inter-event variability, intra-event variability, total geometric mean horizontal component, and arbitrary horizontal component (Boore 2005; Baker and Cornell 2006) ($\tau$, $\sigma$, $\sigma_T$, and $\sigma_{Arb}$, respectively) are given by the equations:

$$\tau = \tau_{\ln(\mathrm{CAV_{GM}})} \tag{17}$$

$$\sigma = \sqrt{\sigma^2_{\ln(\mathrm{CAV_{GM}})_B} + \sigma^2_{\ln(\mathrm{AF})} + \alpha^2 \sigma^2_{\ln(\mathrm{PGA})_B} + 2\alpha\rho\sigma_{\ln(\mathrm{CAV_{GM}})_B}\sigma_{\ln(\mathrm{PGA})_B}} \tag{18}$$

$$\sigma_T = \sqrt{\sigma^2 + \tau^2} \tag{19}$$

$$\sigma_{Arb} = \sqrt{\sigma_T^2 + \sigma_C^2} \tag{20}$$

where $\tau_{\ln(\text{CAV}_{\text{GM}})}$ is the standard deviation of the inter-event residuals; $\sigma_{\ln(\text{CAV}_{\text{GM}})}$ is the standard deviation of the intra-event residuals, $\sigma_C$ is the standard deviation of the intra-component variability, $\sigma_{\ln(\text{AF})}$ = 0.3 is the estimated standard deviation of the site amplification factor, ln(AF) = $f_{site,}$ assuming linear site response (see Campbell and Bozorgnia 2008 for a derivation of this value), the subscript B refers to the ground motion at the base of the site profile in which the variance (square of the standard deviation) is reduced by the variance of the site amplification factor (i.e., $\sigma_B^2 = \sigma^2 - 0.3^2$), $\sigma_{\ln(\text{PGA})}$ is the estimated intra-event standard deviation of ln(PGA), $\rho$ is the correlation coefficient between the intra-event variability (residuals) of ln($\text{CAV}_{\text{GM}}$) and ln(PGA), and $\alpha$ is the linearized functional relationship between $f_{site}$ and ln($A_{1100}$), which is estimated from the partial derivative $\partial f_{site}/\partial \ln(A_{1100})$ according to the expression:

$$\alpha = \begin{cases} k_2 A_{1100}\left\{\left[A_{1100} + c\left(V_{S30}/k_1\right)^n\right]^{-1} - \left(A_{1100} + c\right)^{-1}\right\} & V_{S30} < k_1 \\ 0 & V_{S30} \geq k_1 \end{cases} \tag{21}$$

## Ground Motion Prediction Equation for $\text{CAV}_\text{S}$

### Median and Aleatory Uncertainty Models

Because of the strict criteria that were used to define $\text{CAV}_\text{S}$, there were too few recordings to develop a GMPE directly from the data. Instead, a prediction equation was developed in terms of $\text{CAV}_{\text{GM}}$ based on the equation:

$$\overline{\ln(\text{CAV}_\text{S})} = c_0 + c_1 \ln(\text{CAV}_{\text{GM}}) + c_2(\mathbf{M} - 6.5)H(\mathbf{M} - 6.5) + c_3 R_{RUP} \tag{22}$$

When the value of $\text{CAV}_{\text{GM}}$ is unknown, ln($\text{CAV}_{\text{GM}}$) should be replaced by its median predicted value from Eqs. (5)–(16).

When $\text{CAV}_{\text{GM}}$ is known, the standard deviations of ln($\text{CAV}_\text{S}$) are obtained directly from the regression analysis (i.e., $\tau = \tau_{\ln(\text{CAV}_\text{S})}$ and $\sigma = \sigma_{\ln(\text{CAV}_\text{S})}$). When $\text{CAV}_{\text{GM}}$ is unknown (i.e., predicted), the standard deviations are calculated from the equations:

$$\tau = \sqrt{\tau^2_{\ln(\text{CAV}_\text{S})} + c_1^2 \tau(\text{CAV}_{\text{GM}})^2} \tag{23}$$

$$\sigma = \sqrt{\sigma^2_{\ln(\text{CAV}_\text{S})} + c_1^2 \sigma(\text{CAV}_{\text{GM}})^2} \tag{24}$$

where $\tau(\text{CAV}_{\text{GM}})$ and $\sigma(\text{CAV}_{\text{GM}})$ are the values of $\tau$ and $\sigma$ for $\text{CAV}_{\text{GM}}$ from Eqs. (17) and (18) and $c_1$ is the linearized functional relationship (partial derivative) between ln($\text{CAV}_\text{S}$) and ln($\text{CAV}_{\text{GM}}$) from Eq. (22). The above equations do not include a covariance term [the term involving $\rho$ in Eq. (18)] because the residuals of ln($\text{CAV}_\text{S}$) and ln($\text{CAV}_{\text{GM}}$) were found to be uncorrelated. Because $\text{CAV}_\text{S}$ is defined as the maximum of the three ground motion components, it does not have an intra-component standard deviation. Note that in no case can the value of $\text{CAV}_\text{S}$ predicted from its probability density function (PDF) be less than 0.16 g-sec by definition.

## Results

The empirical coefficients $c_i$ and the theoretical coefficients $k_1$ and $k_2$ were determined using nonlinear random-effects regression (Abrahamson and Youngs 1992). Coefficient $k_3$ was arbitrarily assigned a value of 1.0 because no theoretical value was available. It was included as a parameter to be consistent with the original GMPE of Campbell and Bozorgnia (2008). Table 1 lists the model coefficients, standard deviations (in natural log units), and correlation coefficients required to evaluate the median and aleatory uncertainty models. Also included in this table are the model parameters for the PGA GMPE of Campbell and Bozorgnia (2008), which is needed to estimate $A_{1100}$ and its uncertainty. The standard deviations of $\ln(\mathrm{CAV_S})$ when $\mathrm{CAV_{GM}}$ is predicted are given in parentheses in Table 1.

Fig. 2 shows the median attenuation and magnitude scaling characteristics predicted by the CAV GMPEs for $F_{RV} = F_{NM} = 0$, $\delta = 90°$, $Z_{TOR} = 0$, $V_{S30} = 760$ m/sec, and $Z_{2.5} = 2$ km. Fig. 3 shows the predicted median shallow site response and basin response effects in terms of NEHRP site classes B ($V_{S30} = 1070$ m/sec), C ($V_{S30} = 525$ m/sec), D ($V_{S30} = 255$ m/sec), and E ($V_{S30} = 150$ m/sec). Fig. 4 shows the estimated inter-event, intra-event, and total standard deviations. Fig. 2 clearly shows the effect of the acceleration and response spectral filters on the GMPEs. Figs. 3 and 4 show the significant effects of soil nonlinearity on the predicted site amplification and intra-event and total standard deviations. In the case of the $\mathrm{CAV_S}$ plots, $\mathrm{CAV_{GM}}$ was predicted from the median and aleatory uncertainty models described previously.

## Conclusions

CAV has found important applications in the U.S. nuclear industry, where one of its variants is used in conjunction with the response spectrum to determine whether a nuclear power plant should be shut down after an earthquake (USNRC 1997), and in geotechnical engineering, where another of its variants is used to assess the liquefaction potential of saturated sands (Kramer and Mitchell 2006). The first variant has been used as a means of preventing small magnitude (non-damaging) earthquakes from contributing to the PSHAs of several nuclear power plants in the central and eastern U.S (EPRI 2006; Watson-Lamprey and Abrahamson 2007). CAV has also been shown to correlate strongly with macroseismic intensity and other instrumental damage indices. However, there are very few GMPEs available with which to estimate CAV (see Campbell and Bozorgnia 2010a,b for a list of these GMPEs and for a summary of relationships between CAV and other proposed damage indices). In this study, we help to fill this void by developing a consistent set of GMPEs for two variants of CAV using the PEER-NGA strong motion database. The standard deviations of these GMPEs are equal to or less than the smallest we have found thus far for peak ground motion and response spectra parameters. The GMPEs are valid for magnitudes ranging from 5.0 up to 7.5 (normal faulting), 8.0 (reverse faulting), or 8.5 (strike-slip faulting), for distances ranging from 0 up to 100 km (for **M** < 7) or 200 km (for larger **M**), and for shallow crustal earthquakes in active tectonic regions. Valid ranges of the other predictor variables are given by Campbell and Bozorgnia (2010a,b).

## Acknowledgments

This project was partially sponsored by the International Atomic Energy Agency (IAEA) as part of the activities of Seismic Working Group 1 (WG1) of the Extra Budgetary Program (EPB). Dr. Bozorgnia's participation was partially sponsored by 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 sponsors.

## References

Abrahamson, N. A., and R. R. Youngs, 1992. A stable algorithm for regression analyses using the random effects model, *Bull. Seismol. Soc. Am.* **82**, 505-510.

Baker, J. W., and C. A. Cornell, 2006. Which spectral acceleration are you using?, *Earthq. Spectra* **22**, 293-312.

Boore, D. M., 2005. Erratum: equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: a summary of recent work, *Seismol. Res. Lett.* **76**, 368-369.

Campbell, K. W., and Y. Bozorgnia, 2008. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s, *Earthq. Spectra* 24, 139-171.

Campbell, K. W., and Y. Bozorgnia, 2010a. Analysis of cumulative absolute velocity (CAV) and JMA instrumental seismic intensity ($I_{JMA}$) using the PEER-NGA strong motion database, *Report No. 2010/102*, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Campbell, K. W., and Y. Bozorgnia, 2010b. A ground motion prediction equation for the horizontal component of cumulative absolute velocity (CAV) based on the PEER-NGA strong motion database, *Earthq. Spectra*, in press.

Chiou, B., R. Darragh, N. Gregor, and W. Silva, 2008. NGA project strong-motion database, *Earthq. Spectra* 24, 23-44.

Electrical Power Research Institute (EPRI), 1988. A criterion for determining exceedance of the Operating Basis Earthquake, *Report No. EPRI NP-5930*, Palo Alto, California.

Electrical Power Research Institute (EPRI), 1991. Standardization of the cumulative absolute velocity, *Report No. EPRI TR-100082-T2*, Palo Alto, California.

Electrical Power Research Institute (EPRI), 2006. Program on technology innovation: use of cumulative absolute velocity (CAV) in determining effects of small magnitude earthquakes on seismic hazard analyses, *Report No. 1014099*, Palo Alto, California.

Kramer, S. L., and R. A. Mitchell, 2006. Ground motion intensity measures for liquefaction hazard evaluation, *Earthq. Spectra* 22, 413–438.

Power, M., B. Chiou, N. Abrahamson, Y. Bozorgnia, T. Shantz, and C. Roblee, 2008. An overview of the NGA project, *Earthq. Spectra* 24, 3-21.

U.S. Nuclear Regulatory Commission (USNRC), 1997. Pre-earthquake planning and immediate nuclear power plant operator postearthquake actions, *Regulatory Guide 1.166*, Washington, D.C., 8 pp.

Watson-Lamprey, J. A., and N. A. Abrahamson, 2007. Use of minimum CAV in seismic hazard analyses, in *Proc., 9th Canadian Conference on Earthquake Engineering*, Ottawa, 352-358.

Table 1   Model coefficients, standard deviations, and correlation coefficients

| Param. | $c_0$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | $c_6$ | $c_7$ | $c_8$ | $c_9$ | $c_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PGA | -1.715 | 0.500 | -0.530 | -0.262 | -2.118 | 0.170 | 5.60 | 0.280 | -0.120 | 0.490 | 1.058 |
| $CAV_{GM}$ | -4.354 | 0.942 | -0.178 | -0.346 | -1.309 | 0.087 | 7.24 | 0.111 | -0.108 | 0.362 | 2.549 |
| $CAV_S$ | 0.0691 | 1.151 | -0.173 | -0.00265 | – | – | – | – | – | – | – |
| | | | | | | | | | | | |
| Param. | $c_{11}$ | $c_{12}$ | $k_1$ | $k_2$ | $k_3$ | $\tau$ | $\sigma$ | $\sigma_T$ | $\sigma_C$ | $\sigma_{Arb}$ | $\rho$ |
| PGA | 0.040 | 0.610 | 865 | -1.186 | 1.839 | 0.219 | 0.478 | 0.526 | 0.166 | 0.551 | 1.000 |
| $CAV_{GM}$ | 0.090 | 1.277 | 400 | -2.690 | 1.0 | 0.196 | 0.371 | 0.420 | 0.089 | 0.429 | 0.735 |
| $CAV_S$ | – | – | – | – | – | 0.101 (0.247) | 0.130 (0.446) | 0.165 (0.510) | – | – | – |

Note: $c$ = 1.88, $n$ = 1.18, and $\sigma_{\ln(AF)}$ = 0.3; PGA has units of g; $CAV_{GM}$ and $CAV_S$ have units of g-sec; standard deviations are in natural log units; $k_3$ was arbitrarily set to 1.0 because no theoretical constraint was available (see text); standard deviations in parentheses are used when $CAV_{GM}$ is predicted rather than being known; standard deviations assume linear site response (see text for calculating standard deviations for nonlinear site response).

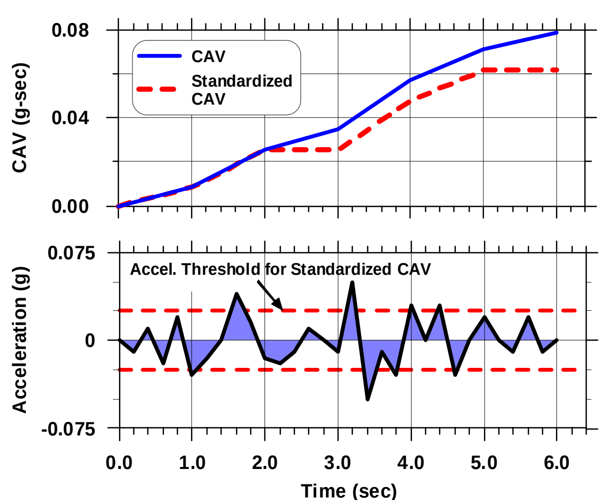


Figure 1.   Illustration of the definitions of CAV and Standardized CAV ($CAV_{STD}$) showing their evolution with time. Modified from EPRI (1988, 1991).

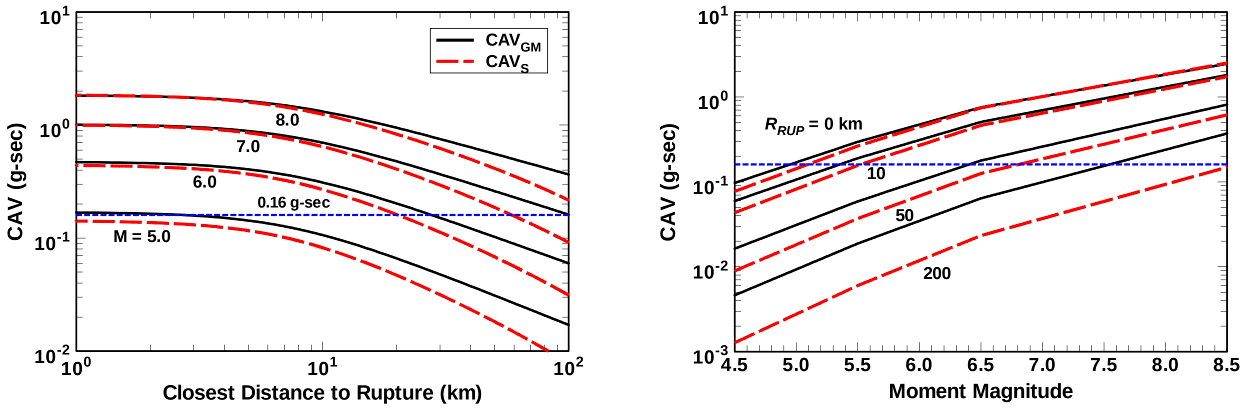


Figure 2. Median attenuation and magnitude scaling characteristics predicted by the GMPEs developed in this study. The threshold value of 0.16 g-sec used in the nuclear industry is shown for reference.

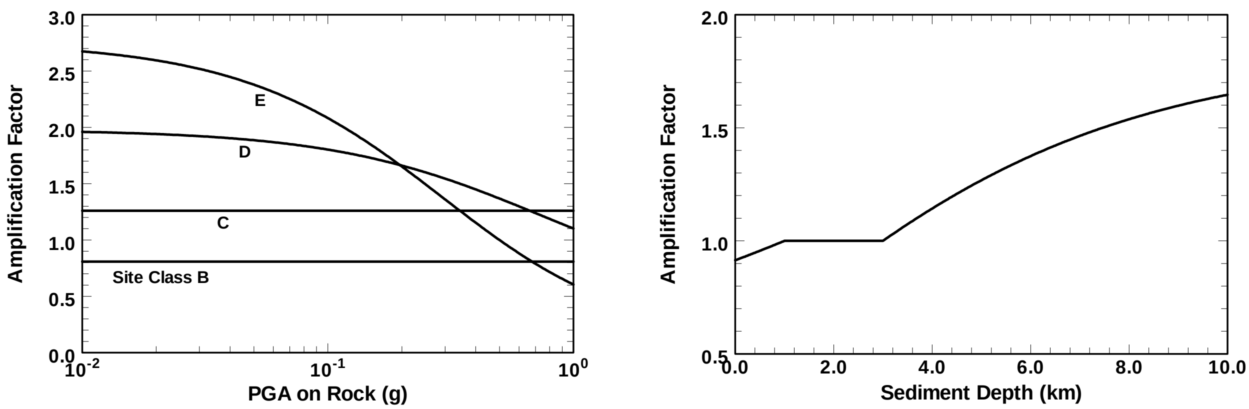


Figure 3. Median shallow site response and basin response (sediment depth) effects predicted by the GMPEs developed in this study.

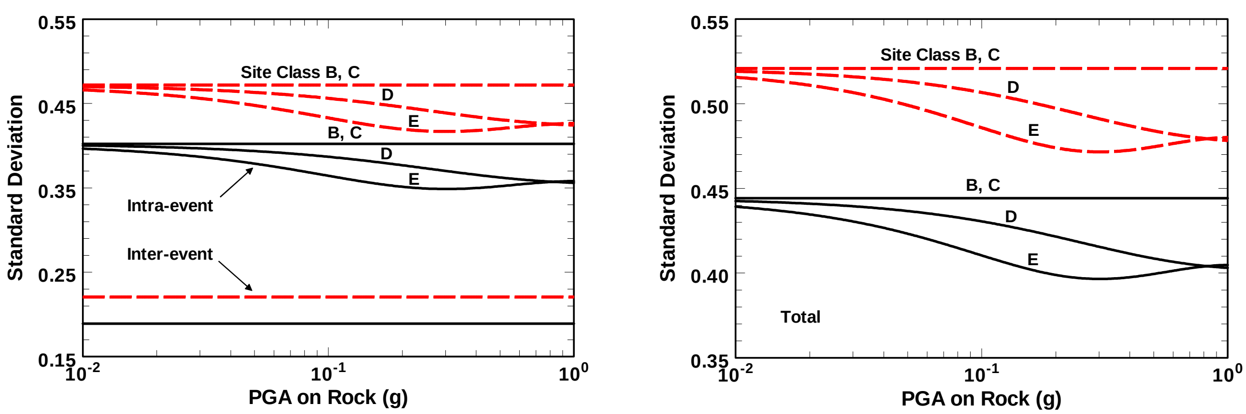


Figure 4. Inter-event, intra-event, and total standard deviations predicted by the GMPEs developed in this study.