Use of Cumulative Absolute Velocity (CAV) in Damage Assessment

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SUMMARY:
Cumulative absolute velocity (CAV) has been proposed as an instrumental index to quantify the potential earthquake damage to structures. We explore this idea further by developing a relationship between the standardized version of CAV and the Japan Meteorological Agency (JMA) and Modified Mercalli (MMI) instrumental seismic intensities in order to correlate standardized CAV with the qualitative descriptions of damage in the corresponding macroseismic intensity scales. Such an analysis statistically identifies the threshold values of standardized CAV associated with the onset of damage to buildings of good design and construction that is inherent in these scales. Based on these results, we suggest that CAV might be used to rapidly assess the potential damage to a general class of conventional structures after an earthquake.

Keywords: cumulative absolute velocity, CAV, intensity, ground motion, damage

1. INTRODUCTION

In 1988, the Electric Power Research Institute (EPRI) introduced cumulative absolute velocity (CAV) as a potential damage-related ground motion intensity measure (IM). CAV is mathematically defined by the equation (EPRI, 1988; Reed and Kassawara, 1990):

$$CAV = \int_0^{t_{max}} |a(t)|\, dt \tag{1.1}$$

where $|a(t)|$ is the absolute value of acceleration at time t and t_{max} is the total duration of the ground motion record. In 1991, EPRI introduced a standardized version of CAV, which we refer to as $\mathrm{CAV_{STD}}$ in order to distinguish it from the original definition of CAV, that prevents low-amplitude non-damaging ground motions from contributing to the value of CAV. $\mathrm{CAV_{STD}}$ is mathematically defined by the equation (EPRI, 2006):

$$CAV_{STD} = \sum_{i=1}^{N} \left(H(PGA_i - 0.025) \int_{i-1}^{i} |a(t)|\, dt \right) \tag{1.2}$$

where N is the number of non-overlapping one-second time intervals, PGA_i is the peak ground acceleration (g) in time interval i (inclusive of the first and last points), and $H(x)$ is the Heaviside Step Function defined as $H(x) = 0$ for $x < 0$ and 1 otherwise.

EPRI (1991) provided a different mathematical expression for $\mathrm{CAV_{STD}}$ that gives identical results. Fig. 1.1 shows a hypothetical acceleration record and the corresponding values of CAV and $\mathrm{CAV_{STD}}$ as they evolve over time. According to Eqns. 1.1 and 1.2, CAV and $\mathrm{CAV_{STD}}$ are the values obtained at the end of the record. As this figure shows, $\mathrm{CAV_{STD}}$ will always be equal to or less than CAV. This difference can be quite large for long-duration small-amplitude records.

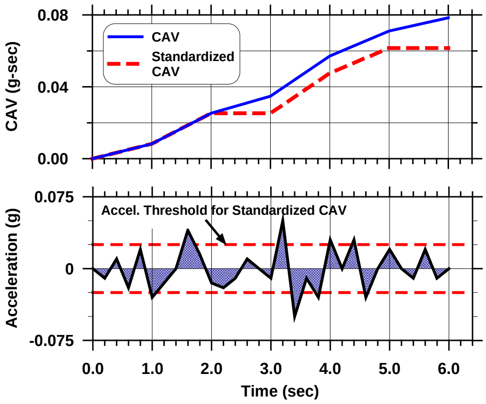

Figure 1.1. Definitions of CAV and CAV_{STD} showing their evolution with time (modified from EPRI, 1991)

Since their introduction, CAV, CAV_{STD}, and several other proposed versions of CAV have been extensively studied for use as potential damage-related IMs. Most of these studies have correlated these IMs with instrumental or macroseismic intensities and, by inference, to the qualitative levels of structural damage that are inferred from these intensities. A few studies have gone a step further and related these IMs directly to observed damage or to the computed nonlinear structural response of model buildings. Others have used these parameters to develop ground motion prediction equations. A review of these studies is available in Campbell and Bozorgnia (2010a,b, 2011a, 2012).

Based on the engineering characteristics of ground motion and the investigations of earthquake records and associated damage summarized in EPRI (1988) and Reed and Kassawara (1990), a panel of experts convened by EPRI recommended a two-level criterion for determining when ground motion is expected to be potentially damaging to buildings of good design and construction. This two-level criterion was defined in terms of a response spectrum check, in which the 5%-damped value of pseudo-absolute acceleration (PSA) at a site, at frequencies between 2 and 10 Hz, exceeds 0.20 g and a CAV check, in which the value of CAV is greater than 0.30 g-s. The CAV check was later revised by EPRI (1991) to trigger when the value of CAV_{STD} is greater than 0.16 g-s.

At the recommendation of EPRI (1988, 1991) and after considerable review, the U.S. Nuclear Regulatory Commission (USNRC) adopted the use of CAV_{STD} (the CAV check) and the response spectrum (the response spectrum check) in its post-event procedures to determine whether the Operating Basis Earthquake (OBE) response spectrum is exceeded and a nuclear power plant must be shut down for inspection after an earthquake. However, unlike EPRI, the response spectrum check was further subdivided into a spectral acceleration (PSA) check and a spectral velocity (PSV) check, in which either the value of PSA (2–10 Hz) is greater than 0.20 g (or exceeds the OBE) or the value of PSV (1–2 Hz) is greater than 15.34 cm/s (or exceeds the OBE) in order for the OBE response spectrum to be exceeded. A more detailed description of these checks are given in USNRC (1997) and in Campbell and Bozorgnia (2010a, 2011a, 2012). We have used the USNRC shutdown criteria to define a another CAV parameter called CAV_{DP}, where the DP stands for damage parameter (Campbell and Bozorgnia, 2011a, 2012).

We selected CAV_{DP} as the CAV-related IM to statistically evaluate in this study because of its direct relationship to the damage threshold criterion recommended by EPRI (1988, 1991) and Reed and Kassawara (1990) for buildings of good design and construction and its adoption by the USNRC to conservatively indicate the potential damage to nuclear facilities. We also evaluated the original version of CAV_{DP} recommended by EPRI (1991) that excludes the PSV check in order to show the sensitivity of the results to this check.

2. RELATIONSHIP BETWEEN SEISMIC INTENSITY AND DAMAGE

Macroseismic intensity is typically determined subjectively from observations of the effects of an earthquake on humans, man-made structures, and the natural environment (e.g., Musson et al., 2010). However, the proliferation in the number of strong motion instruments over the last few decades and the need for a quick assessment of damage after an earthquake has spawned the development of instrumental measures of the JMA and MMI seismic intensity scales. In this section, we summarize the qualitative descriptions of damage inferred in the JMA, MMI, and EMS macroseismic intensity scales and relate these descriptions to the potential damage threshold criteria for CAV proposed by EPRI and USNRC, based on the strong correlation between the macroseismic and instrumental measures of these intensity scales.

2.1. JMA Intensity

The JMA macroseismic intensity scale (also known as the shindo scale) has been used in Japan as a measure of earthquake ground shaking effects since 1949. In 1996, the scale was revised to 10 categories and each category was defined in terms of an instrumental parameter, which was calibrated to coincide with the effects described in the macroseismic version of the scale (Japan Meteorological Agency, 1996; Earthquake Research Committee, 1998). This instrumental seismic intensity is calculated from either ground motion acceleration records or specially designed seismic intensity meters. We refer to this new instrumental seismic intensity measure as I_{JMA} (Campbell and Bozorgnia 2011b).

The revised 10-degree JMA macroseismic intensity scale is described in terms of the effects of an earthquake on humans, indoor and outdoor objects, wooden houses, reinforced-concrete (RC) structures, ground and slopes, utilities and infrastructure, and large-scale structures (http://www.jma.go.jp/jma/en/Activities/inttable.pdf, last accessed June 2011). For purposes of this study, we have chosen to use the qualitative effects of an earthquake on RC structures as described in this seismic intensity scale to demonstrate the correlation of I_{JMA} with damage. These effects, along with the ranges of I_{JMA} that correspond to each JMA macroseismic intensity category, are summarized in Campbell and Bozorgnia (2012). Qualitative levels of damage are given for RC structures of both high and low earthquake resistance. According to this scale, there is no visible damage (i.e., formation of cracks) to RC structures of low earthquake resistance at JMA 5 Lower (5L), corresponding to $4.5 \le I_{JMA} < 5.0$, and to RC structures of high earthquake resistance at JMA 5 Upper (5U), corresponding to $5.0 \le I_{JMA} < 5.5$. According to the online table, earthquake resistance tends to be higher for newer construction. It is generally considered to be low for Japanese structures built prior to 1982 and high for structures built after this date, based on a major revision of the Japanese building code at that time. However, earthquake resistance is not dependent only on the age of construction.

2.2. Modified Mercalli Intensity

Since its development in 1931 and revision in 1956 (Musson et al., 2010), there has been a long history of studies that have correlated MMI to strong motion IMs, mostly for the purpose of estimating PGA, PGV, and PSA for engineering evaluation and design. A review of these studies is given in Campbell and Bozorgnia (2012). Because of the well-defined correlation between I_{JMA} and the qualitative description of damage to RC structures given in the JMA intensity scale, it is useful to correlate I_{JMA} with MMI, or more specifically, to an instrumental measure of this intensity, which we refer to as I_{MM}. This is done using a relationship developed by Shabestari and Yamazaki (2001), which was calibrated using MMI assessments of three well-recorded earthquakes in California and shown to be consistent with similar relationships between MMI and both Community Internet Intensity (CII) and peak-amplitude measures of I_{MM} estimated from PGA and PGV used in the development of the USGS ShakeMap (Wald et al., 1999). According to this equation, the median values of I_{MM} that are consistent with the threshold values of JMA intensity for which visible damage (i.e., the formation of cracks) to RC structures of low earthquake resistance is seen is $I_{MM} = 6.84 \pm 0.28$ or MMI VII, and for which visible damage to RC structures of high earthquake resistance is seen is $I_{MM} = 7.82 \pm 0.28$ or

MMI VIII.

One drawback of the MMI scale is that it gives only a very general qualitative description of damage, which is biased towards masonry structures. According to the USGS (1986), there are four classes of structures: (1) specially designed structures (Masonry A), (2) buildings of good design and construction (Masonry B), (3) ordinary substantial structures (Masonry C), and (4) poorly built structures (Masonry D). The assignment of a USGS structure class to a specified masonry type is that of the authors and not that of the USGS. The USGS describes the degree of damage as negligible, slight, and considerable. Fortunately, this shortcoming has been addressed in the recently developed European Macroseismic Scale (EMS) described in the next section. For this study, we use the more detailed descriptions of damage to RC structures in the EMS scale to describe the damage inferred by the same intensity category in the MMI scale, based on a study by Musson et al. (2010) that found that the two scales are generally equivalent to one another up to at least intensity X.

2.3. European Macroseismic Scale

The European Macroseismic Scale (EMS-98 or simply EMS) is an update of the Medvedev-Sponheuer-Kárník (MSK) scale, which itself is an update based on experiences available in the early 1960s from the application of the Mercalli-Cancani-Sieberg (MCS) scale commonly used in Italy, the MMI scale commonly used in the United States, and the Medvedev (GEOFIAN) scale commonly used in Russia and countries of the former Soviet Union (Grünthal, 1998). The EMS scale was specifically designed to describe the damage to structures of different construction types and vulnerability classes. Continuing with our example, RC structures fall into the EMS structure type described as RC frames and walls with levels of earthquake-resistant design (ERD) described as none, moderate, or high. Each of these levels of earthquake resistance is assigned a range of vulnerability classes from A to F with the higher letters corresponding to the less vulnerable and more earthquake-resistant structures. In order to account for uncertainty, each level of earthquake resistance is assigned a most likely vulnerability class as well as less likely stronger and weaker vulnerability classes. Vulnerability Class F represents the strongest of those RC frames and walls that are described as having a high level of earthquake resistance. We refer to this vulnerability class as having a very high level of earthquake resistance and consider it to correspond to the vulnerability associated with the most rugged of structures, such as safety related nuclear structures and other critical structures located in high seismic areas.

According to the qualitative descriptions of damage to RC structures in the EMS scale as summarized in Campbell and Bozorgnia (2012), the onset of slight structural damage to structures of with no specific ERD begins at EMS VII ($I_{MM} \geq 6.5$) and increases one degree of intensity for each increase in vulnerability class (Grünthal, 1998). For example, the onset of structural damage to structures of very high ERD, described as cracks in columns and beams, begins at EMS X ($I_{MM} \geq 9.5$). This is generally consistent with the JMA intensity scale for which the onset of damage to RC structures of low earthquake resistance, which is assumed to be similar to EMS structures with no specific ERD, begins at JMA 5U and for which the onset of damage to RC structures of high earthquake resistance, which is conservatively assumed to be similar to EMS structures with moderate ERD, begins at JMA 6L. These JMA intensities correspond to EMS/MMI VII and VIII, respectively.

3. PREDICTION EQUATIONS

The purpose of developing relationships between CAV_{DP} and the instrumental intensity measures I_{JMA} and I_{MM} is twofold: (1) to evaluate the values of I_{JMA} and I_{MM} that correspond to the CAV_{DP} damage threshold criterion of 0.16 g-sec representing the potential onset of damage to buildings of good design and construction as described in the MMI intensity scale, no specific earthquake-resistant design as described in the EMS intensity scale, and low earthquake resistance as described in the JMA intensity scale and (2) to statistically correlate CAV_{DP} with the qualitative descriptions of damage to RC structures and other buildings of good design and construction that are described in the JMA, MMI, and EMS macroseismic intensity scales.

The definition of CAV_{DP} embodies all of the EPRI (1988, 1991) and USNRC (1997) damage threshold criteria within a single IM. However, we note that EPRI did not include the PSV check in its original recommendations, which was later added by the USNRC in the formulation of its nuclear power plant shutdown criteria. Campbell and Bozorgnia (2010b) performed an analysis of the CB08-NGA (Campbell and Bozorgnia, 2008) and PEER-NGA (Chiou et al., 2008) databases and found that inclusion of the PSV check allows ground motions at relatively long distances from large-magnitude earthquakes to exceed the response spectrum check when the PSA and CAV checks would not. Such ground motions are generally not of concern if the primary use of CAV_{DP} is to screen out non-damaging near-source high-acceleration records from small-magnitude earthquakes, which was EPRI's original intent when defining the response spectrum check. Nevertheless, in order to demonstrate the impact of including the PSV check in the definition of CAV_{DP}, and to potentially broaden the applicability of CAV_{DP} as a potential damage index parameter, we provide results with and without this check. In the remainder of the paper, we refer to these databases as CB08-NGA-PSV, CB08-NGA-NoPSV, PEER-NGA-PSV, and PEER-NGA-NoPSV, where the terms PSV and NoPSV refer to whether the PSV check is applied when selecting the records. These databases are summarized in Campbell and Bozorgnia (2012).

The strong motion database used in this study was developed by the Pacific Earthquake Engineering Research Center (PEER) for use in the Next Generation Attenuation (now called the NGA-West1) Project (Power et al., 2008; Chiou et al., 2008). To show the sensitivity of the results to the database selection criteria, we also used the subset of the PEER-NGA database that we previously used to develop GMPEs for peak ground motion and linear elastic response spectral parameters (Campbell and Bozorgnia, 2007, 2008), inelastic response spectral parameters (Bozorgnia et al., 2010), CAV (Campbell and Bozorgnia, 2010b), I_{JMA} (Campbell and Bozorgnia, 2011b), and CAV_{DP} (Campbell and Bozorgnia, 2011a, 2012). It is referred to in this paper as the CB08-NGA database and is described in detail by Campbell and Bozorgnia (2007, 2008).

The median relationship between CAV_{DP} and instrumental seismic intensity is given by the equation:

$$\mu_{\ln CAV_{DP}} = c_0 + c_1 X \tag{3.1}$$

where $\mu_{\ln CAV_{DP}}$ is the predicted median value of $\ln CAV_{DP}$ (g-s) and X is either I_{JMA} or I_{MM}. Analyses were performed using the random-effects regression algorithms of Abrahamson and Youngs (1992). These relationships are restricted to intensities in the range $I_{JMA} \geq 4.5$ and $I_{MM} \geq 5.5$ for reasons explained in the next section. The results of the analyses are listed in Table 3.1. We also tested bi-linear and quadratic functional forms of the above equation, but hypothesis tests indicated that the additional coefficients were not significantly different from zero at the 90% confidence level.

Aleatory uncertainty is modelled by the random-effects equation (Abrahamson and Youngs, 1992, Campbell and Bozorgnia, 2008):

$$\ln CAV_{DP,ij} = \mu_{\ln CAV_{DP},ij} + \eta_i + \varepsilon_{ij} \tag{3.2}$$

where η_i is the inter-event (between-earthquake) residual for event i and the parameters $\mu_{\ln CAV_{DP},ij}$, $\ln CAV_{DP,ij}$, and ε_{ij} are the predicted median value, observed value, and intra-event (within-earthquake) residual for recording j of event i. The independent normally distributed variables η_i and ε_{ij} have zero means and estimated inter-event, intra-event, and total standard deviations of $\tau_{\ln CAV_{DP}}$, $\sigma_{\ln CAV_{DP}}$, and $\sigma_T^2 = \tau_{\ln CAV_{DP}}^2 + \sigma_{\ln CAV_{DP}}^2$. These standard deviations are given in terms of natural log units in Table 3.1.

Table 3.1. Summary of Regression Results

Database	PSV	c_0	c_1	$\sigma_{\ln CAV_{DP}}$	$\tau_{\ln CAV_{DP}}$	σ_T	R^2
JMA Instrumental Intensity ($I_{JMA} \geq 4.5$)							
CB08-NGA-PSV	Yes	–5.207	0.943	0.329	0.279	0.431	0.657
CB08-NGA-NoPSV	No	–5.165	0.935	0.329	0.281	0.433	0.648
PEER-NGA-PSV	Yes	–5.527	0.987	0.346	0.294	0.454	0.699
PEER-NGA-NoPSV	No	–5.484	0.979	0.348	0.295	0.456	0.692
MMI Instrumental Intensity ($I_{MM} \geq 5.5$)							
CB08-NGA-PSV	Yes	–3.859	0.493	0.295	0.302	0.422	0.740
CB08-NGA-NoPSV	No	–3.829	0.489	0.296	0.306	0.426	0.725
PEER-NGA-PSV	Yes	–4.034	0.505	0.309	0.316	0.442	0.768
PEER-NGA-NoPSV	No	–4.024	0.504	0.311	0.318	0.445	0.759

An initial regression analysis using all of the data indicated that there was a bias in the residuals for $I_{JMA} < 4.5$ and $I_{MM} < 5.5$ due to the filtering effects of the PSA and CAV_{STD} thresholds used to define CAV_{DP}. As a result, we restricted the analysis to those records with intensities larger than these values. This did not impact any of the conclusions of our study, since no damage is expected to RC structures classified as having low earthquake resistance at JMA 5L ($I_{JMA} < 5.0$) or as having no specific earthquake-resistant design at EMS/MMI VI ($I_{MM} < 6.5$). Visual inspection of the residuals (observed value minus predicted value) indicated no visible biases or trends, which further justified our use of a linear relationship between $\mu_{\ln CAV_{DP}}$ and $\ln CAV_{DP}$. There are, however, notable biases and trends between the residuals and the physical parameters of the earthquakes for both intensity measures (Campbell and Bozorgnia, 2012). Whether these biases are important depends on the potential use of the prediction equations. One likely use of these equations is to statistically evaluate CAV_{DP} as a tentative criterion for rapidly assessing whether conventional structures might have sustained damage after an earthquake. In this case, the physical parameters of an earthquake might not be known with any reliability at the time these criteria are applied, which precludes the use of physical earthquake parameters in Eqn. 3.1. If an unbiased relationship between CAV_{DP} and I_{JMA} is desired, one can be obtained from the GMPEs of these IMs (Campbell and Bozorgnia, 2010b, 2011a,b) as demonstrated in Campbell and Bozorgnia (2012). There is no available GMPE for I_{MM}, but we would expect similar results to those found for I_{JMA} considering the strong correlation between I_{JMA} and I_{MM}.

4. CORRELATION OF CAV_{DP} WITH DAMAGE

In Table 4.1, we present the statistical correlation of CAV_{DP} with qualitative descriptions of damage to generic RC structures, and by analogy to other buildings of good design and construction, by relating estimates of CAV_{DP} with values of I_{JMA} and JMA macroseismic intensity from the sources described previously and summarized in Campbell and Bozorgnia (2012). This analysis assumes that damage to such structures begins at JMA 5U ($I_{JMA} = 5.0$). Table 4.2 gives similar results by relating estimates of CAV_{DP} with values of I_{MM} and EMS/MMI macroseismic intensity, assuming that damage begins at EMS/MMI VII ($I_{MM} = 6.5$). In these tables, $P_{ne}(0.16)$ is the probability that $CAV_{DP} < 0.16$ g-s (the EPRI damage threshold criterion) given the specified median estimate of I_{JMA} or I_{MM}, $P_{ne}(0.16)_{5U}$ and $P_{ne}(0.16)_{VII}$ are the nonexceedance probabilities corresponding to the lower boundary of JMA intensity category 5U (i.e., $I_{JMA} = 5.0$) and EMS/MMI VII (i.e., $I_{MM} = 6.5$) corresponding to the onset of damage, and σ_T is the total standard deviation in natural log units. These probabilities are an indication of the likelihood that CAV_{DP} will be less than that required to exceed the recommended EPRI damage threshold criteria given the potential level of damage indicated in the macroseismic intensity scales. Also listed in these tables are the predicted values of CAV_{DP} that correspond to nonexceedance probabilities of 1% and 5%. It should be noted that the probabilities given in Tables 3.1 and 3.2 only account for the aleatory uncertainty associated with the empirical prediction of CAV_{DP} and do not account for the epistemic uncertainty associated with the relationships between macroseismic intensity and damage or between instrumental and macroseismic intensity. Some insight into this epistemic uncertainty can be gained by comparing the results listed in the two tables.

Table 4.1. Statistical Correlation Between CAV_{DP} and JMA Macroseismic Intensity Assuming the Onset of Damage to Buildings of Good Design and Construction Begins at Intensity 5U

JMA	EMS/ MMI	NGA Database	PSV Check	Median (g-s)	σ_T	$P_{ne}(0.16)$ ($\times 10^{-4}$)	CAV_{DP} (g-s) P_{ne}=5%	P_{ne}=1%	$P_{ne}(0.16)_{5U}$
5U	VII	CB08	Yes	0.611	0.431	9.65	0.301	0.224	0.160
5U	VII	CB08	No	0.613	0.433	9.65	0.301	0.224	0.160
6L	VIII	CB08	Yes	0.980	0.431	0.131	0.482	0.359	0.256
6L	VIII	CB08	No	0.978	0.433	0.146	0.480	0.357	0.255
6U	IX	CB08	Yes	1.570	0.431	0.000584	0.773	0.576	0.411
6U	IX	CB08	No	1.560	0.433	0.000720	0.766	0.570	0.408
7	X	CB08	Yes	2.516	0.431	0.000000817	1.238	0.923	0.658
7	X	CB08	No	2.491	0.433	0.00000115	1.222	0.910	0.650
5U	VII	PEER	Yes	0.553	0.418	3.14	0.262	0.192	0.160
5U	VII	PEER	No	0.555	0.425	3.19	0.262	0.192	0.160
6L	VIII	PEER	Yes	0.906	0.418	0.668	0.429	0.315	0.262
6L	VIII	PEER	No	0.905	0.425	0.772	0.428	0.313	0.261
6U	IX	PEER	Yes	1.484	0.418	0.00463	0.703	0.516	0.429
6U	IX	PEER	No	1.477	0.425	0.00547	0.698	0.511	0.426
7	X	PEER	Yes	2.431	0.418	0.0000103	1.152	0.846	0.703
7	X	PEER	No	2.410	0.425	0.0000136	1.138	0.834	0.695

Table 4.2. Statistical Correlation Between CAV_{DP} and EMS/MMI Macroseismic Intensity Assuming the Onset of Damage to Buildings of Good Design and Construction Begins at Intensity VII

JMA	EMS/ MMI	NGA Database	PSV Check	Median (g-s)	σ_T	$P_{ne}(0.16)$ ($\times 10^{-4}$)	CAV_{DP} (g-s) P_{ne}=5%	P_{ne}=1%	$P_{ne}(0.16)_{VII}$
5U	VII	CB08	Yes	0.520	0.422	26.2	0.260	0.195	0.160
5U	VII	CB08	No	0.522	0.426	27.6	0.259	0.194	0.160
6L	VIII	CB08	Yes	0.851	0.422	0.375	0.425	0.319	0.262
6L	VIII	CB08	No	0.851	0.426	0.438	0.422	0.316	0.261
6U	IX	CB08	Yes	1.393	0.422	0.00146	0.696	0.522	0.429
6U	IX	CB08	No	1.387	0.426	0.00198	0.689	0.515	0.425
7	X	CB08	Yes	2.281	0.422	0.00000152	1.139	0.855	0.702
7	X	CB08	No	2.263	0.426	0.00000251	1.123	0.840	0.694
5U	VII	PEER	Yes	0.473	0.442	70.9	0.229	0.169	0.160
5U	VII	PEER	No	0.473	0.445	74.0	0.228	0.168	0.160
6L	VIII	PEER	Yes	0.784	0.442	1.79	0.379	0.280	0.265
6L	VIII	PEER	No	0.783	0.445	1.79	0.377	0.278	0.265
6U	IX	PEER	Yes	1.299	0.442	0.0108	0.628	0.465	0.439
6U	IX	PEER	No	1.297	0.445	0.0129	0.624	0.461	0.438
7	X	PEER	Yes	2.152	0.442	0.0000205	1.040	0.770	0.728
7	X	PEER	No	2.147	0.445	0.0000269	1.033	0.762	0.726

Tables 4.1 and 4.2 indicate that, depending on the database, the probabilities that CAV_{DP} is less than 0.16 g-s [$P_{ne}(0.16)$], given the onset of damage consistent with macroseismic intensities of JMA 5U and EMS/MMI VII and their assumed relationship to I_{JMA} and I_{MM}, are found to range from (rounding to a single significant digit) 0.1–0.3% for the relationship based on I_{JMA} (Table 4.1) and 0.3–0.7% for the relationship based on I_{MM} (Table 4.2). These probabilities are calculated based on the threshold values of instrumental intensities that correspond to the lower end of the ranges of values that define intensity categories JMA 5U (i.e., $I_{JMA} = 5.0$) and EMS/MMI VII (i.e., $I_{MM} = 6.5$). This is consistent with how EPRI (1988, 1991) originally selected the CAV and CAV_{STD} damage threshold values and confirms that these threshold values are appropriately conservative for buildings of good design and construction. The values of $P_{ne}(0.16)$ decrease to less than 0.02% for an assumed onset of damage consistent with JMA 6L (i.e., $I_{JMA} = 5.5$) or EMS/MMI VIII ($I_{MM} = 7.5$), which generally corresponds to the onset of damage to industrial and conventional power facilities (EPRI, 1988), specially designed structures (MMI scale), and structures with levels of earthquake-resistant design described as moderate (EMS scale) or high (JMA scale).

Table 4.3 summarizes the mean threshold values of CAV_{DP} and their standard deviations based on the results listed in Tables 4.1 and 4.2. The standard deviations represent the epistemic uncertainty corresponding to the four databases (including whether the PSV check is applied) and the two instrumental intensity measures. The levels of earthquake-resistant design that are assigned to the given JMA, MMI, and EMS macroseismic intensity categories and their correspondence to the values of instrumental seismic intensity used to calculate CAV_{DP} are based on our interpretation of the qualitative descriptions of earthquake resistance and damage provided in these intensity scales. Others might interpret these descriptions differently, which is an additional element of epistemic uncertainty not included in the analysis. RC structures described as having no specific earthquake-resistant design in the EMS scale include both engineered and non-engineered construction. Non-engineered structures of this type are typically found in regions of low seismicity where seismic design regulations are nonexistent or are only recommended. They are considered to be similar to buildings of good design and construction as described in the MMI scale and defined by EPRI (1988). The threshold values of CAV_{DP} in the column labeled $P_{ne}(0.16)_{5U,VII}$ correspond to the estimated nonexceedance probabilities that are inferred from the conservative approach used by EPRI (1988, 1991) to establish the original CAV threshold criterion (i.e., $0.35 \pm 0.25\,\%$) and represent the nonexceedance probability corresponding to the lower boundary of intensity categories JMA 5U ($I_{JMA} = 5.0$) or EMS/MMI VII ($I_{MM} = 6.5$). We also give results for less conservative nonexceedance probabilities of 1% and 5%. All of the CAV_{DP} threshold values are found to increase by about 60–65% with each increase in intensity level.

Table 4.3. Threshold Values of CAV_{DP} and Their Epistemic Uncertainty Below Which Structures of Various Levels of Earthquake-Resistant Design are not Expected to be Damaged

Level of Earthquake-Resistant Design			Seismic Intensity		CAV_{DP} (g-s)			
MMI	EMS	JMA	EMS/MMI	JMA	Median	P_{ne}=5%	P_{ne}=1%	$P_{ne}(0.16)_{5U,VII}$
Good Design & Const.	None	Low	VII	5U	0.54±0.05	0.26±0.03	0.19±0.02	0.16±0.00
Specially Designed	Moderate	High	VIII	6L	0.88±0.08	0.43±0.04	0.32±0.03	0.26±0.00
Specially Designed	High	High	IX	6U	1.43±0.11	0.70±0.05	0.52±0.04	0.43±0.01
Specially Designed	Very High	High	X	7	2.34±0.15	1.14±0.07	0.84±0.06	0.69±0.03

As indicated in EPRI (1988, 1991) and summarized in Campbell and Bozorgnia (2012), there is a fair amount of conservatism in the EPRI and USNRC damage threshold criteria. According to Table 4.3, the minimum observed values of CAV_{STD} that EPRI found was associated with structural damage correspond to a probability of nonexceedance of over 5% instead of 0.35% and an MMI level that is about one degree higher than that associated with the recommended EPRI criterion. This conservatism would appear to mitigate any lack of consideration of the uncertainty associated with interpreting the damage descriptions in the seismic intensity scales.

Continuing with the example of a generic RC structure, the EMS scale indicates that a structure with no ERD will have slight structural damage beginning at EMS (MMI) VII. If one accepts a 5% probability that damage will be less than this given the estimated threshold value of CAV_{DP} for this intensity level, this threshold value is estimated to be approximately 0.3 g-s, according to the summary results listed in Table 4.3. Following this same logic, a similar structure would begin to sustain moderate structural damage (MMI/EMS VIII) at approximately 0.4 g-s, heavy structural damage (MMI/EMS IX) at approximately 0.7 g-s, and very heavy structural damage or collapse (MMI/EMS X) at approximately 1.1 g-s. Given these threshold values, a ShakeMap could be produced that would identify those geographic regions where the above levels of damage to generic RC structures without earthquake-resistant design (but of good design and construction) might be expected. Similar assessments could be made for other nonexceedance probabilities, types of structures, and vulnerability classes depending on the intended purpose. One potential purpose of such a map would be to assist in determining where to focus emergency response activities. This would be particularly useful if the potential damage map were overlain on an inventory map of the structures of interest in a manner similar to ShakeCast (e.g., Wald et al., 2008).

A potential issue with using CAV_{DP} to assess and map the damage potential of a general class of structures is the necessity to be able to spatially interpolate the instrumentally derived values. Unlike peak-amplitude and response spectral values, NEHRP site factors (BSSC, 2009) cannot be used to spatially interpolate CAV_{DP}, or for that matter any other version of CAV, to other site conditions due in part to their dependence on duration. However, similar site factors for CAV_{DP} can be derived from site terms such as those included in the CAV GMPE of Campbell and Bozorgnia (2010b) and imputed to CAV_{DP} through the relationship between $\ln CAV_{DP}$ and $\ln CAV_{GM}$ developed by Campbell and Bozorgnia (2011a). These same two relationships could also be used to estimate CAV_{DP} when no instrumental values are available in the vicinity of a site, similar to the procedure currently used to develop ShakeMap for peak-amplitude and response spectral values (Wald et al., 1999).

5. CORRELATION OF CAV_{DP} WITH DAMAGE

We present prediction equations between a variant of the standardized version of CAV, which we refer to as CAV_{DP}, and instrumental measures of JMA seismic intensity (I_{JMA}) and MMI (I_{MM}), both of which have been calibrated to the macroseismic versions of these intensity scales and, therefore, to the qualitative descriptions of structural damage embodied in these scales. CAV_{DP} incorporates in a single parameter all of the ground motion criteria that EPRI used to establish the threshold of damage to conventional buildings of good design and construction and that USNRC conservatively used to establish its nuclear power plant shutdown criteria. We used I_{JMA} and its relationship to the JMA macroseismic intensity scale and I_{MM} and its relationship to the MMI and EMS macroseismic intensity scales to derive threshold values of CAV_{DP} that correspond to the onset of damage associated with a generic class of RC structures of different degrees of earthquake-resistant design, as inferred from the macroseismic effects described in these intensity scales. Other classes of structures can be evaluated in a similar manner. Our prediction equations can be used to statistically quantify and select an appropriate set of damage threshold criteria for CAV_{DP} that takes into account both aleatory and, too a limited extent, epistemic uncertainty. However, our estimate of epistemic uncertainty does not include the additional uncertainty that corresponds to the association of a specific level of macroseismic intensity with the expected level of structural damage. This is not necessarily an issue considering the demonstrated conservatism in this association based on actual, albeit relatively old, damage data collected by EPRI (1988).

Our analysis estimates that the probability of nonexceedance of the 0.16 g-s EPRI and USNRC threshold criteria, assuming the onset of damage at EMS/MMI VII (JMA 5U), is $0.35 \pm 0.25\,\%$, depending on the version of the database and instrumental intensity measure that is used in the analysis. Given similarly small nonexceedance probabilities, this conservative threshold criterion increases to 0.26, 0.43, and 0.69 g-s for damage thresholds corresponding to EMS/MMI VIII, IX, and X (JMA 6L, 6U, and 7), respectively, consistent with structures described as having moderate, high, and very high earthquake resistance in the EMS intensity scale. Higher acceptable probabilities of nonexceedance result in even higher values of CAV_{DP}. For example, for a 5% probability of nonexceedance, all of the CAV_{DP} damage threshold values increase by about 65%, consistent with both the increase in CAV_{DP} that corresponds to an increase of one degree of intensity and the conservatism in the CAV_{STD} threshold criteria estimated by EPRI (1988, 1991) from actual damage data.

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