On the use of Arias Intensity as a lower bound in the hazard integration process of a PSHA

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SUMMARY:

Traditionally, in a probabilistic seismic hazard assessment a minimum earthquake magnitude (m_{min}) is defined with a view to restricting attention only to scenarios that are potentially damaging. However, the use of m_{min} as the lower bound in the hazard integration process is not necessarily the most efficient way to differentiate damaging from non-damaging earthquake scenarios. Additionally, the somewhat arbitrary definition of what constitutes an appropriate value of m_{min} can have significant influence on the seismic hazard results, particularly for high-frequency ground motions at short return periods.

As an alternative to m_{min}, the use of other ground-motion parameters, which have been recognised as better predictors of damage, has been proposed. Hardy et al. (2006) proposed a framework within which a cumulative absolute velocity (CAV) of 0.16g-s is used to define when damage can start to occur. In this paper, the use of an Arias Intensity (I_a) threshold of 0.06m/s is examined, as alternative to the CAV threshold of 0.16g-s, within the framework proposed by Hardy et al. (2006). It should be noted, however, that these thresholds should be structure specific.

Keywords: Arias Intensity, PSHA, Ground-motion equation

1. INTRODUCTION

Traditionally, in a probabilistic seismic hazard assessment (PSHA) a minimum earthquake magnitude (m_{min}) must be defined. The purpose of this minimum magnitude is to eliminate from consideration all events that are so small that they would not cause any damage to engineered structures. However, the use of earthquake magnitude as the lower bound in the hazard integration process is not necessarily the most efficient way to distinguish between damaging and non-damaging earthquake scenarios. The main issue being that ground motions, rather than earthquakes, cause damage. Unfortunately, the subjective selection of m_{min} can have a significant influence on the seismic hazard results associated with high-frequency spectral ordinates (or other high-frequency measures of ground-motion, such as effective peak ground acceleration) for short return periods.

As an alternative to m_{min}, the use of other ground motion parameters, which have been recognised as better predictors of damage than earthquake magnitude (e.g., Cabañas et al., 1997; Hancock & Bommer, 2006; Reed et al., 1988), has been proposed. For example, Hardy et al. (2006) proposed to use cumulative absolute velocity (CAV) with a threshold value of 0.16g-s as way of defining potentially damaging earthquake scenarios.

In this paper, the use of Arias Intensity (I_a) is examined as alternative to CAV. In particular, a threshold value of 0.06m/s for Arias intensity is identified and compared to the corresponding CAV value of 0.16g-s. To this end, a model for predicting I_a as a function of peak ground acceleration (PGA), moment magnitude ($\mathbf{M}$) and shear-wave velocity (V_{s30}) is developed. This model is then incorporated into the framework proposed by Hardy et al. (2006). As a case study, seismic hazard curves are derived for different ground-motion parameters for the city of Dubai, UAE. In order to remove from the hazard calculations earthquake scenarios considered as non-damaging, the following criteria are considered: a m_{min} of **M**4.9, a CAV value of 0.16g-s and an I_a of 0.06m/s. Finally, the disaggregated results are presented and discussed.

2. THE HARDY ET AL. (2006) CAV-FILTER FRAMEWORK

As previously mentioned, many ground-motion parameters have been shown to be better predictors of damage than earthquake magnitude. In addition to this, the subjective selection of m_{min} has important effects on the results of hazard calculations due to the mechanics of PSHA. In particular, the fact that frequently occurring small-magnitude events can generate large ground-motions (even with low likelihood) results in them contributing to the rates of exceedance of ground-motion values corresponding to relatively short return periods. In order to overcome this problem, Hardy et al. (2006), in a study sponsored by the Electric Power Research Institute (EPRI), proposed the use of the cumulative absolute velocity (CAV) as an alternative parameter for identifying which earthquake scenarios should be included in the hazard integration process.

Hardy et al. (2006) proposed to use a CAV value of 0.16g-s as the lower bound to define potentially damaging earthquake scenarios. That is, only earthquake scenarios generating ground motions that exceed CAV = 0.16g-s are included in the seismic hazard calculations. Hardy et al. (2006) re-write the hazard integral to include CAV as lower bound of the integration process as follows:

$$\gamma(SA > z, CAV > CAV_{\min}) = \sum_{i=1}^{N_{source}} v_i \int_{m_{\min}}^{m_{\max}} \int_{r=0}^{\infty} \int_{\varepsilon=-\infty}^{\infty} f_{mi}(M) f_{ri}(r) f_{\varepsilon}(\varepsilon) \\ P(SA > z, CAV > CAV_{\min} \mid M, r, \varepsilon) dM dr d\varepsilon \tag{2.1}$$

where SA is the spectral acceleration, z is the target ground-motion level (in terms of spectral acceleration), v_i is the rate of earthquakes with magnitude equal to or larger than m_{min} for the i^{th} source, and $f_{mi}(M)$, $f_{ri}(r)$ and $f_{\varepsilon}(\varepsilon)$ are the probability density functions for magnitude, distance and epsilon, respectively. Epsilon is the number of standard deviations above the mean of ground motion as predicted by the ground-motion prediction equation.

The difference of Equation 2.1 with respect to the original hazard integral is that instead of considering the probability of SA > z for a given M and r, it is now the joint probability of SA > z and CAV > CAV_{min} for a given M and r that is considered. Given that some correlation between CAV and SA is expected, Hardy et al. (2006) decompose the joint probability by accounting for this dependence. The joint probability can be expressed as:

$$P(SA > z, CAV > CAV_{\min} \mid M, r, \varepsilon) = P(SA > z \mid M, r, \varepsilon) \\ P(CAV > CAV_{\min} \mid SA > z, M, r) \tag{2.2}$$

Incorporating Equation 2.2 into Equation 2.1 and explicitly integrating over the ground-motion variability, Hardy et al. (2006) re-write the hazard integral as:

$$\gamma(SA > z, CAV > CAV_{\min}) = \sum_{i=1}^{N_{source}} v_i \int_{m_{\min}}^{m_{\max}} \int_{r=0}^{\infty} \int_{\varepsilon=-\infty}^{\infty} f_{mi}(M) f_{ri}(r) f_{\varepsilon}(\varepsilon) \\ P(SA > z \mid M, r, \varepsilon) P(CAV > CAV_{\min} \mid SA(M, r, \varepsilon), M, r) dM dr d\varepsilon \tag{2.3}$$

As can be appreciated from Equation 2.3, the probability of CAV > CAV_{min} is dependent upon the values of SA, M and r. Therefore, the development of ground-motion prediction models for estimating CAV based on these parameters is required. Hardy et al. (2006) went further to develop two empirical models to estimate CAV as function of SA, *M* and *r* in order to implement the proposed framework; however, these models are not discussed herein as it is beyond the scope of this paper.

In principle, the framework proposed by Hardy et al. (2006) can be applied to filter out non-damaging earthquake scenarios from the hazard calculations using any ground-motion parameter deemed to be a good predictor of damage. However, this will require ground-motion prediction models that account for the correlation between the ground-motion parameter chose as predictor of damage and SA in addition to *M* and *r*.

In addition to the approach outlined above in which one uses a model for CAV which is a function of SA, it is also possible to make use of independent models for predicting the CAV, or Arias Intensity, directly. However, in this case one also needs to develop a model for the correlation among the relevant ground-motions measures. This approach also requires a check that this correlation model is conditionally independent of the magnitude and distance. That is, the correlations between SA and CAV are the same for all combinations of magnitude and distance. This alternative approach is equivalent to performing a vector-valued probabilistic seismic hazard analysis (Bazzurro & Cornell, 2002).

The development of a new model for predicting I_a as function of PGA (SA at zero period), moment magnitude (**M**) and shear-wave velocity for the uppermost 30m of soil deposit (V_{s30}) is presented in Section 4. Then, in Section 5, the proposed I_a model is used to filter the seismic hazard results of the case study. The reasoning behind the use of I_a = 0.06m/s as the lower bound for the hazard integration process is discussed in Section 3.

3. ARIAS INTENSITY (I_A) AS PREDICTOR OF DAMAGE

Arias Intensity (I_a) has been shown to be a good estimator of damage, particularly for the prediction of the response of short-period structures (Travasarou et al., 2003), and the assessment of liquefaction potential and landslide susceptibility (e.g., Cabañas et al., 1997 and Kayen & Mitchell, 1997).

In order to estimate an I_a threshold to distinguish between damaging and non-damaging scenarios, comparable to the use of a CAV value of 0.16g-s, the relation between the inter-storey drifts of the various floors of a six-storey building and CAV and the relation between these drifts for the same structure and I_a were examined. This was done by using the results of a structural response analysis of a six-storey building carried out by Nicola Buratti (Buratti et al., 2008). Figure 3.1 shows the correlation between CAV and I_a and the relative drifts of the upper storey of the six-storey building. Similar correlations were observed for the remaining storeys.

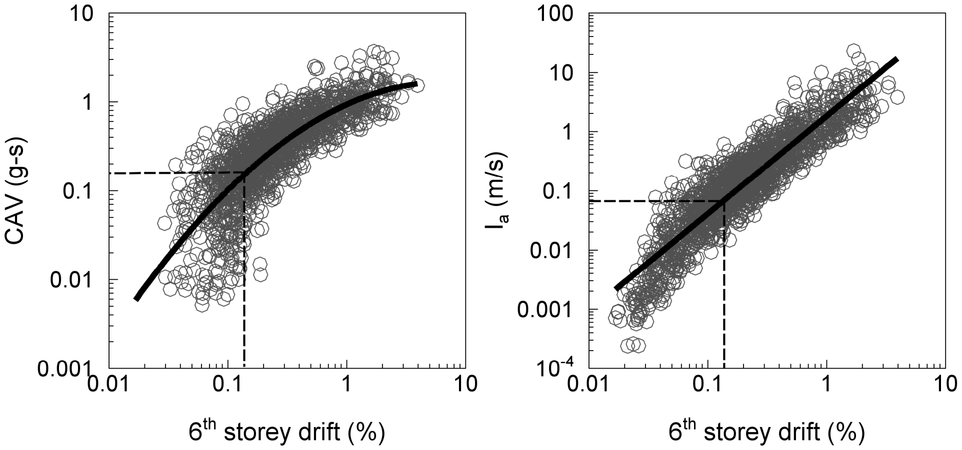

Figure 3.1. Correlations between CAV (left) and I_a (right) and the relative drifts for the 6th storey of the studied building. Black solid lines are the best-fit curve to the data; dashed black lines shown the drift level for CAV value of 0.16g-s and the I_a value corresponding to the same drift level.

Based on the correlations observed between CAV and the inter-storey drifts of the six-storey building, a CAV value of 0.16g-s can be regarded as being appropriate damage threshold for the structure used in this analysis, as it is essentially at this point that a break in the linearity of the inter-storey drifts can be observed with increasing CAV (indicating the onset of non-linear behaviour of the structure). A similar break is seen to occur in the plot with respect to Arias intensity. Additionally, some researchers have suggested that damage to non-structural elements initiate at drift ratios between 0.1% and 0.3% (Crowley et al., 2004), which is consistent with the drift ratio identified for this case of around 0.13% for CAV values of 0.16g-s.

Given this, an I_a value of 0.06m/s, which corresponds to a drift ration of 0.13%, was selected as the lower bound to the seismic hazard calculations, instead of the CAV value of 0.16g-s. Both threshold values (i.e., I_a = 0.06m/s and CAV = 0.16g-s) can be regarded as equivalent predictors for the same level of damage for the studied structure. However, the variance of drift values for these identified threshold values is slightly lower for the case of Arias intensity.

Buratti et al. (2008) used a subset of ground motion records from the Next Generation Attenuation (NGA) project database (Power et al., 2008) consisting of 1666 observations (833 recordings with two horizontal components) from 53 earthquakes. To define this subset, all records from the Chi-Chi sequence were excluded, as well as records with only one horizontal component and records for which **M**, r_{jb} or V_{s30} were not available.

It should be noted that an I_a = 0.06m/s threshold is proposed herein in order to be able to compare against the hazard results using a CAV threshold of 0.16g-s, only. However, any other threshold value of interest could be used instead depending on the type of structure of interest and the level of I_a at which damage is expected to initiate (e.g., different threshold values may apply for liquefaction or slope stability). This raises an important point. While the use of a generic minimum magnitude value has its shortcomings, one of its advantages is that is does not require consideration of the structural characteristics. However, while this is an advantage from an ‘ease-of-application’ perspective, the fact that it does not depend upon the structural characteristics obviously implies that it cannot distinguish between damaging and non-damaging scenarios.

4. I$_A$ MODEL

In this section, a model for predicting I_a as function of PGA, **M** and V_{s30} is developed. This model was derived using the same strong motion data set used for the structural response analysis carried out by Buratti et al. (2008) and described in the previous section. The distribution of **M** and r_{jb} from the data set used to develop the I_a model is shown in Figure 4.1. The dataset consists primarily of earthquakes with magnitudes between **M**5.5 and **M**7.5 and r_{jb} distances between 4 and 200km.

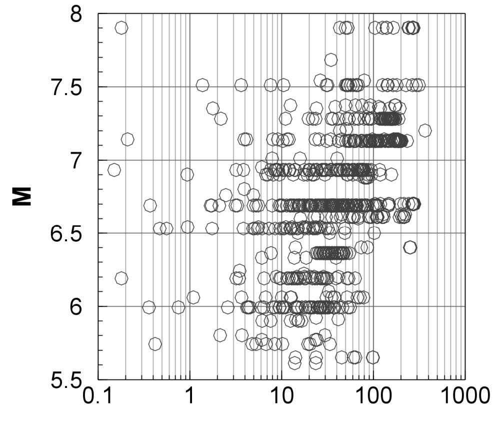

Figure 4.1. Distribution of the magnitudes (**M**) and distances (r_{jb}) of the earthquake dataset used to derive the I_a model.

Figure 4.2 shows the I_a values from the data set as function of PGA, **M**, r_{jb} and V_{s30}. A good linear correlation and small variability is observed between I_a and PGA. Also, a clear correlation between I_a and r_{jb} can be observed, even without accounting for the inherent correlation between magnitude and distance in the underlying dataset. Less evident are the correlations between I_a and **M**, and I_a and V_{s30}; however, it should be noted that the trends are hidden by the fact that the plot I_a vs **M** is for all distances and it is not easy to visually separate out the magnitude-distance correlation of the underlying data set.

Since PGA has a direct correlation with the source-to-site distance, considering I_a as function of PGA will incorporate in some way the dependence of I_a on r_{jb}. Based on this, an initial I_a model is proposed as a function of PGA and **M** only:

$$\log_{10}(I_a) = c_0 + c_1 \log_{10}(PGA) + c_2 M \tag{4.1}$$

where I_a is in units of m/s, PGA is in units of g, c_0 = -0.843, c_1 = 1.643 and c_2 = 0.251. The standard deviation of Equation 4.1 is 0.193 in $\log_{10}$ units.

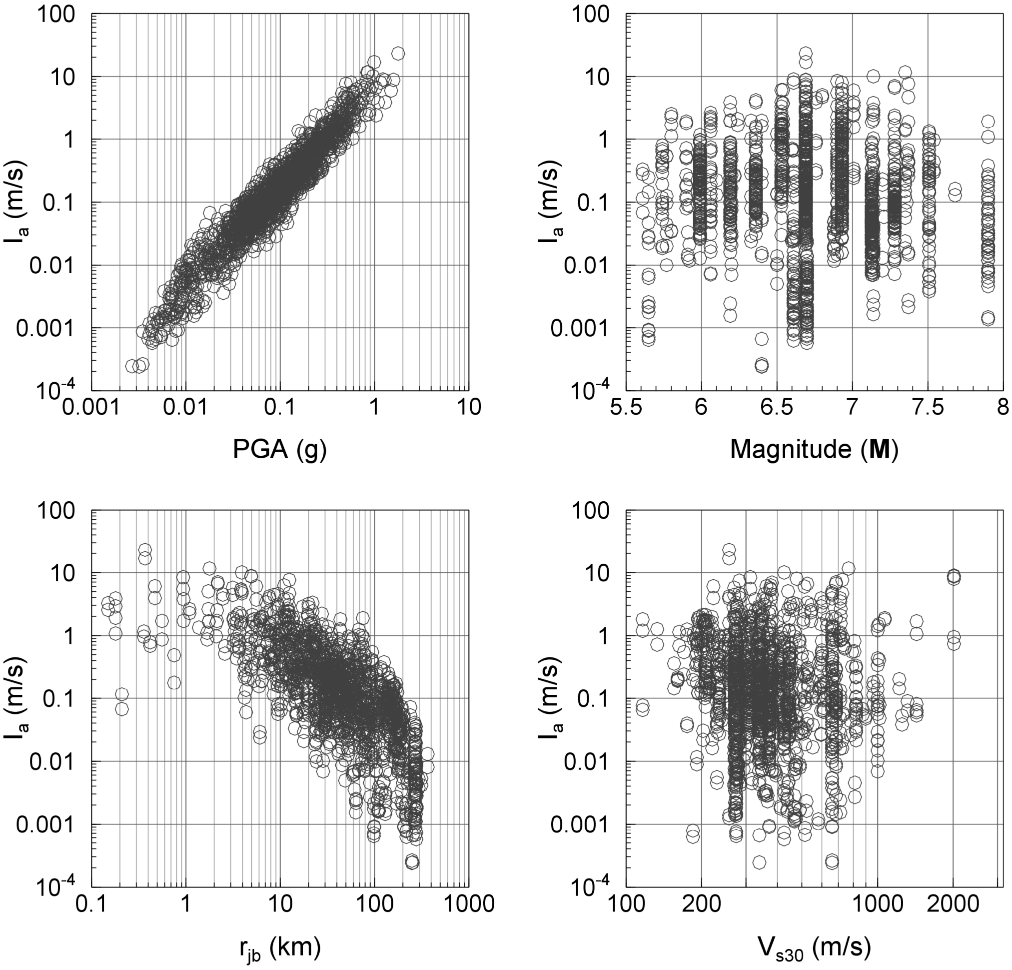

Figure 4.2. Dependence of Arias intensity (I_a) on peak ground acceleration (PGA), moment magnitude (**M**), Joyner-Boore distance (r_{jb}) and shear-wave velocity for the uppermost 30m of soil deposit (V_{s30})

From the evaluation of the residuals for I_a of Equation 4.1, a trend with respect to $\log_{10}(V_{s30})$ was observed showing a linear dependence with a negative slope. Therefore, the $\log_{10}$ of V_{s30} was incorporated in the model. Thus a final I_a model is proposed:

$$\log_{10}(I_a) = b_0 + b_1 \log_{10}(PGA) + b_2 M + b_3 \log_{10}(V_{s30}) \quad (4.2)$$

Coefficients b_0 to b_3 from Equation 4.2 and its standard deviation (σ) are given in Table 4.1

Table 4.1. Coefficients for the final I_a model (Equation 4.2)

Coefficient	Estimate
b_0	0.0459
b_1	1.6500
b_2	0.2591
b_3	-0.3615
σ	0.179

The coefficients for the I_a model were obtained using a non-linear model fit by maximum likelihood. Random effects were not considered in the regression analysis. The residuals for the final I_a model (Equation 4.2) are shown in Figure 4.3. As can be seen in Figure 4.3, no significant trends can be observed in the residuals of Equation 4.2. This model is then incorporated into the framework proposed by Hardy et al. (2006) instead of the CAV model to remove non-damaging earthquakes from the hazard results of the case study.

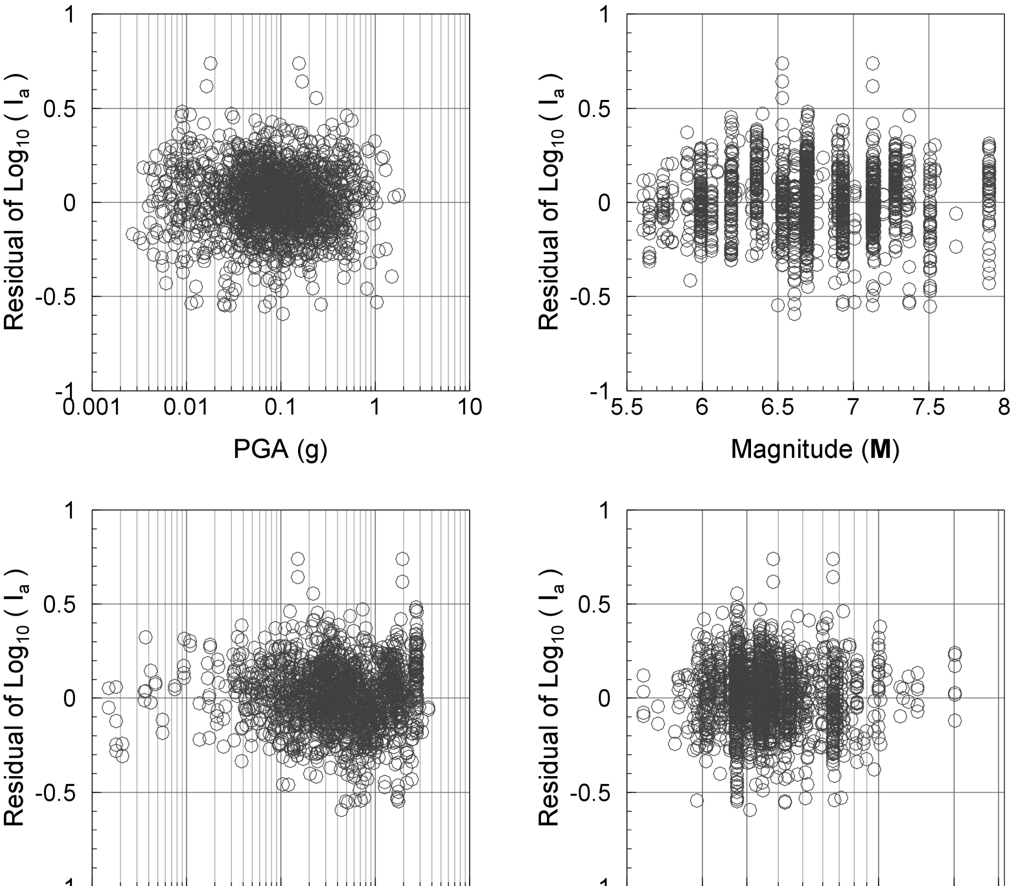

Figure 4.3. Dependence of the residuals of the final I_a model (Equation 4.2) on PGA, **M**, r_{jb} and V_{s30}.

5. CASE STUDY

Aldama-Bustos et al. (2009) developed a probabilistic seismic hazard analysis for three sites in the United Arab Emirates (UAE), including the city of Dubai. Using Aldama-Bustos et al. (2009) as the basis, seismic hazard estimates were obtained considering the framework proposed by Hardy et al. (2006) and using as lower bound of the hazard integration process I_a = 0.06m/s (I_a06) and CAV = 0.16g-s (CAV16). For details on the seismicity model, selection of ground-motion prediction equations and logic tree considered in the seismic hazard analysis for the case study the reader is referred to Aldama-Bustos et al. (2009).

In Figure 5.1, the seismic hazard curves obtained by Aldama-Bustos et al. (2009) for the city of Dubai using a m_{min} of **M**4.9 are compared against the hazard curves using I_a06 and CAV16 thresholds to remove non-damaging earthquake scenarios from the hazard integration process. Seismic hazard curves are presented for PGA and spectral amplitudes at response periods of 0.2s, 1.0s and 3.0s.

Uniform Hazard Spectra for return periods of 2,500 years and 10,000 years are shown in Figure 5.2. It is important to note that for the 2,500-year return period, spectral amplitudes are zero for the shorter periods, less than 1.0s. This is an important point. Once the CAV or Arias intensity filters are applied, if the level of seismicity is relatively low then it becomes possible to have ordinates of the UHS with values of zero. While this is technically also possible for traditional hazard analyses, the seismicity level must be extremely low before this can happen.

Disaggregated results in terms of magnitude and distance are presented in Figure 5.3 for different ground motion parameters at the 10,000-year return period. On the left-hand-side the disaggregated results from the study of Aldama-Bustos et al. (2009) are shown, while on the right-hand-side results from using the I_a06 threshold are presented.

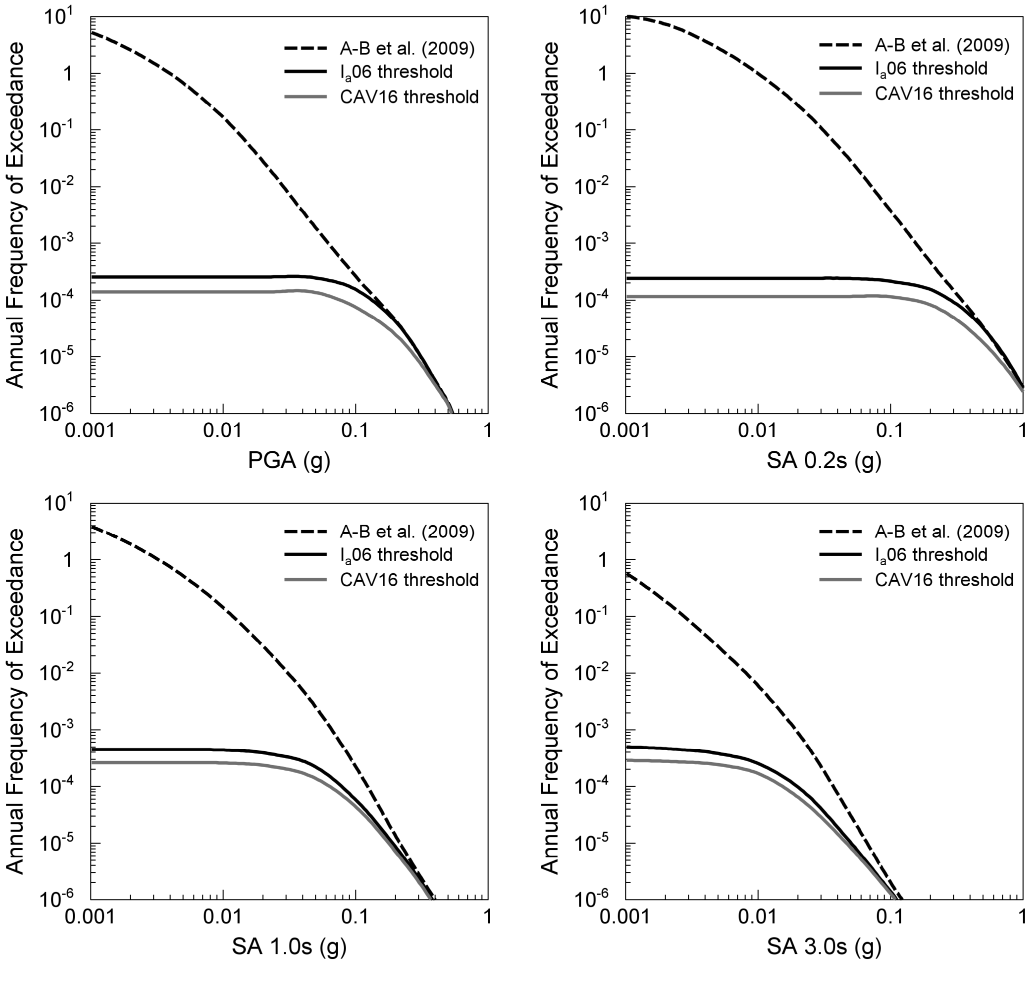

Figure 5.1. Seismic hazard curves for the city of Dubai as reported by Aldama-Bustos et al. (2009) [A-B et al. (2009)] using m_{min} = **M**4.9 and after removing non-damaging earthquake scenarios from the integration process using I_a = 0.06m/s [I_a06 threshold] and CAV = 0.16g-s [CAV16 threshold].

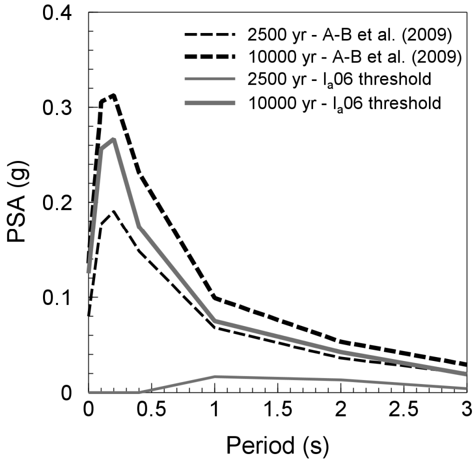

Figure 5.2. Response spectra for the city of Dubai for the 2,500- and 10,000-year return periods as reported by Aldama-Bustos et al. (2009) [A-B et al. (2009)] and after filtering using I_a = 0.06m/s [I_a06 threshold] as lower bound of the integration process.

6. DISCUSSION AND CONCLUSIONS

A significant reduction in the seismic hazard levels is observed from applying the I_a06 threshold to differentiate between damaging and non-damaging earthquake scenarios in the integration of the seismic hazard. From the hazard curves shown in Figure 5.1, it is observed that the reduction in the hazard levels from using the CAV16 or the I_a06 thresholds is very similar, but with those corresponding to the I_a06 threshold being consistently higher. This difference is a reflection of the different variances of the CAV and I_a values for a given drift level. As the variance of I_a values for a given drift level are lower, the result is the more rapid convergence of the filtered hazard curve to the unfiltered curves shown in Figure 5.1.

Regarding the uniform hazard spectra, at a return period of 2,500 years the spectral amplitudes for response periods below 1.0s are zero, and for longer periods the spectral amplitudes are so small that they can be disregarded for practical purposes. However, at the 10,000-year return period, the reduction in the spectral amplitudes is relatively small.

It is important to observe in the disaggregated results, Figure 5.3, that when using the I_a06 threshold not only contributions from small-magnitude events were reduced, but also contributions from medium-to-large events at long distances (>200km).

The framework proposed by Hardy et al. (2006) has been shown to be efficient in removing earthquake scenarios that are deemed to not produce damage to engineered structures and that potentially lead to an inflation of the seismic hazard. As shown in this study, alternative ground-motion parameters can be incorporated within this framework; however, it is necessary to develop ground-motion models that incorporate the correlation between the ground-motion parameter selected as predictor of damage and spectral amplitudes. In conclusion, the approach proposed by Hardy et al. (2006) is able to deal with the major short-coming of the current m_{min} prescription.

It is important to highlight that the results of a seismic hazard study were either the CAV16 threshold or I_a06 threshold are used represent the annual probability of exceeding both the target ground motion (e.g., PGA = 0.2g) and a value of I_a = 0.06m/s for the case when the I_a06 is being used, or the target ground motion and a CAV value of 0.16g-s if the CAV16 threshold is being considered.

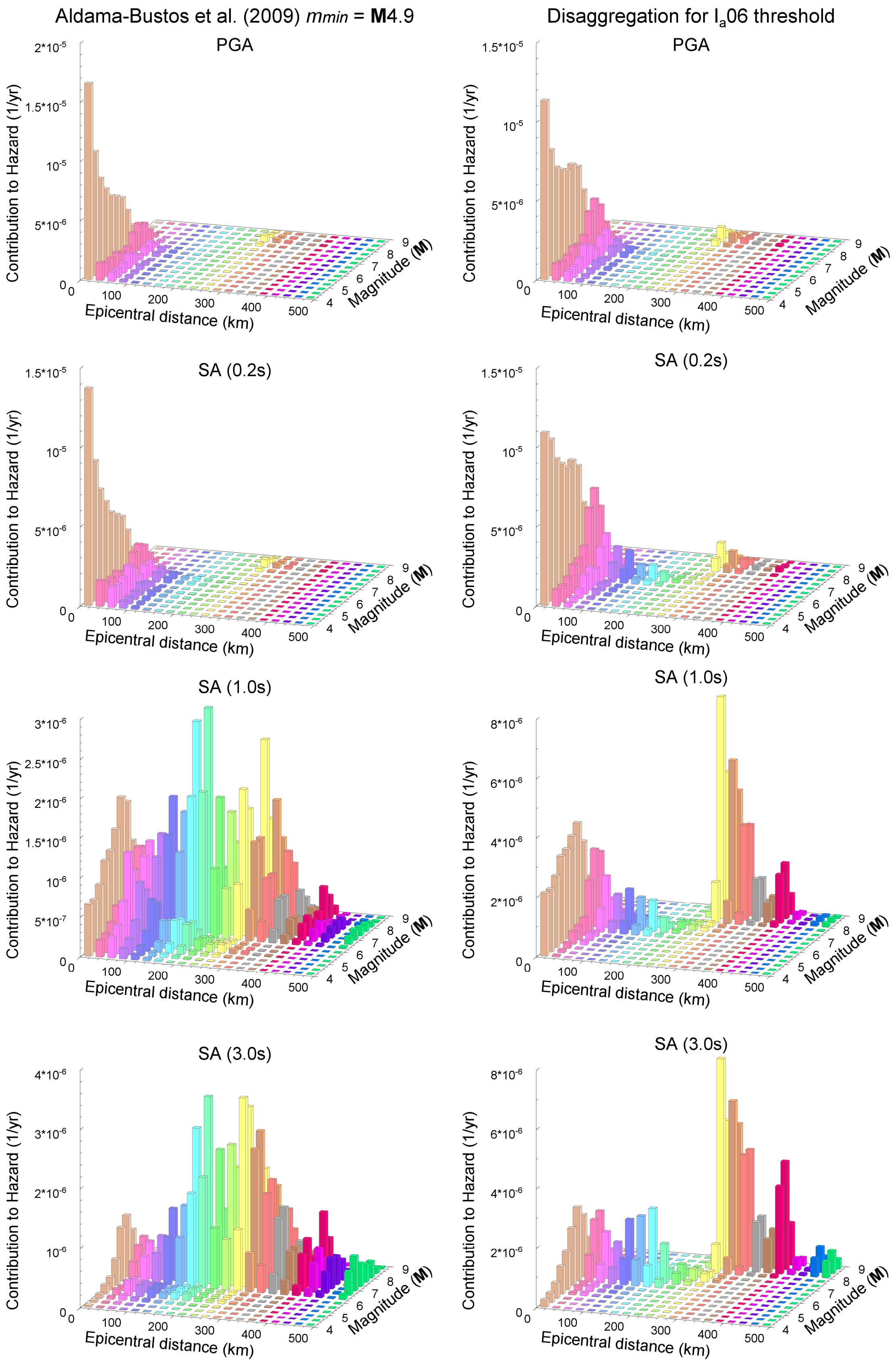

Figure 5.3. Disaggregated results for the city of Dubai for PGA and SA at 0.2, 1.0 and 3.0s response period at the 1,000-year return period. On the left-hand-side the results from Aldama-Bustos et al. (2009) for a m_{min} of **M**4.9 are presented, while on the right-hand-side the results considering the I_a06 threshold in the hazard calculations are shown.

Hazard results obtained using a lower bound for the hazard calculations within the framework proposed by Hardy et al. (2006) such as CAV16 or I_a06 should be understood as the joint probability of two events happening. In other words, the probability that two threshold values (e.g., PGA=0.2 and I_a=0.06m/s) are being exceeded. These results must be interpreted with caution as they could easily be misunderstood; for instance, the hazard results presented herein for the city of Dubai indicate zero hazard for return periods less than ~2,000 years. This should not be understood as that the probability of an earthquake being felt in Dubai in the next 2,000 years, or in any 2,000-year period, is zero, but that seismic resistant design is not required for structures whose design return periods are less than ~2,000 years.

It is important to mention that the comparison between CAV=0.16g-s and I_a=0.06m/s as threshold values below which damage would not be expected to occur is just for one six-building and may not hold in other cases. The threshold values for both CAV and I_a, or any other parameter of interest, can be set to any value at which undesired behaviour of natural or engineered structures initiates. For instance, Harp & Wilson (1995) found a minimum threshold of I_a=0.08m/s to observe rock falls and landslides in Tertiary and younger deposits. Thus, a filtering of the PGA hazard curve obtained using this I_a threshold in the hazard calculations could be useful to assess the hazard of a landslide in this type of geological structures.

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