New Earthquake Classification Scheme for Mainshocks and Aftershocks in the NGA-West2 Ground Motion Prediction Equations (GMPEs)

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SUMMARY:
Previous studies have shown that median ground motions from aftershocks are systematically lower than median ground motions from mainshocks by about 20 - 40% at short spectral periods. Given these observations, the Next Generation Attenuation (NGA) developers accounted for this difference either by removing aftershocks from the dataset (Boore and Atkinson, 2008) (Campbell and Bozorgnia, 2008), or by including a term to account for a constant scale factor between mainshocks and aftershocks (Abrahamson and Silva, 2008) (Chiou and Youngs, 2008). In the first NGA project, each developer team made an independent classification of the earthquakes in their dataset. In this paper, we develop a definition of mainshocks (Class 1 earthquakes) and aftershocks (Class 2 earthquakes) for use in ground motion prediction equations based on the distance of the aftershock from the mainshock rupture plane and propose a functional form for ground motion scaling between Class 1 and Class 2 earthquakes.

Keywords: Aftershocks, Mainshocks, Attenuation, Ground Motion, Declustering

1. BACKGROUND

Over the past 20 years, it has been observed that median ground motions from aftershocks are systematically lower than median ground motions from mainshocks by about 20 - 40% at short spectral periods (Boore and Atkinson, 1989; Boore and Atkinson, 1992; Abrahamson and Silva, 2008); however, classifying an earthquake as a mainshock or aftershock is not a straightforward problem. At best, aftershock is a loosely defined term because there is no clear distinction between aftershocks, triggered events, clusters, etc., all of which are presumably responding to different physical processes following the mainshock. In terms of ground motion, not all of these aftershock types systematically produce the same median ground motions. For example, the February 22, 2011 Christchurch earthquake is related to the September 3, 2010 Darfield earthquake, but it ruptured a separate fault. Is it an aftershock or a triggered event? Figure 1.1 compares the peak accelerations from the Christchurch earthquake, adjusted to a VS30=500 m/s site condition, to the Abrahamson and Silva (2008) median Peak Ground Acceleration (PGA) for mainshocks and for aftershocks. The PGA values from the Christchurch earthquake are more typical of a mainshock type earthquake of than an aftershock type earthquake. Similarly, the 1992 June 28, Big Bear earthquake is related to the 1992 June 28 Landers earthquake, but it ruptured a separate fault. Figure 1.2 compares the PGA values from the Big Bear earthquake with the Abrahamson and Silva (2008) median PGAs. As with Christchurch, the Big Bear PGAs are more consistent with the mainshock median than with the aftershock median. There is large variability in ground motions, so the comparisons for these two earthquakes are, by themselves, not conclusive, but they serve to demonstrate the issue.

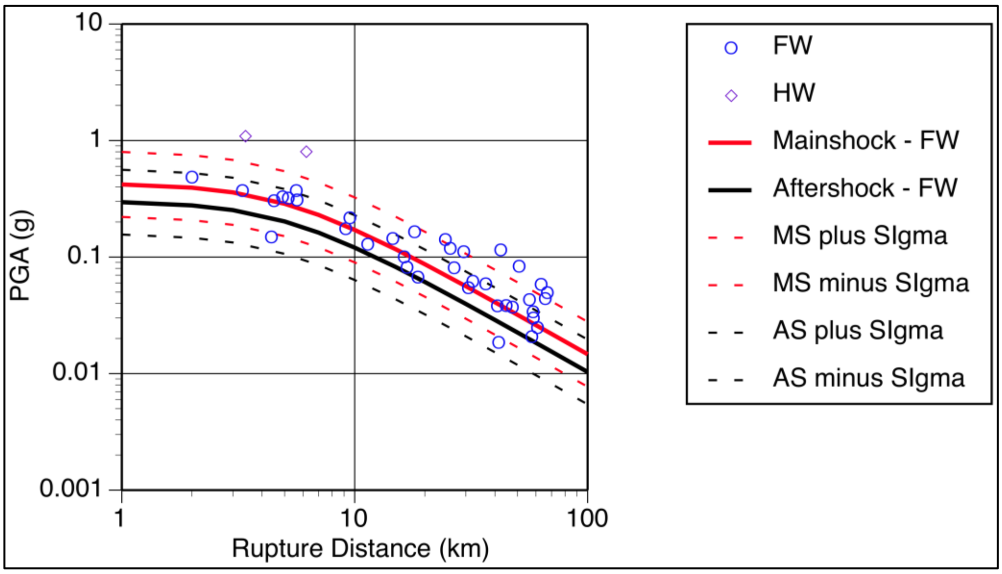

Figure 1.1. Peak Ground Accelerations normalized to a reference Vs30 of 500 m/s for the 2001 Christchurch earthquake compared with the A&S 2008 GMPE for mainshocks and aftershocks.

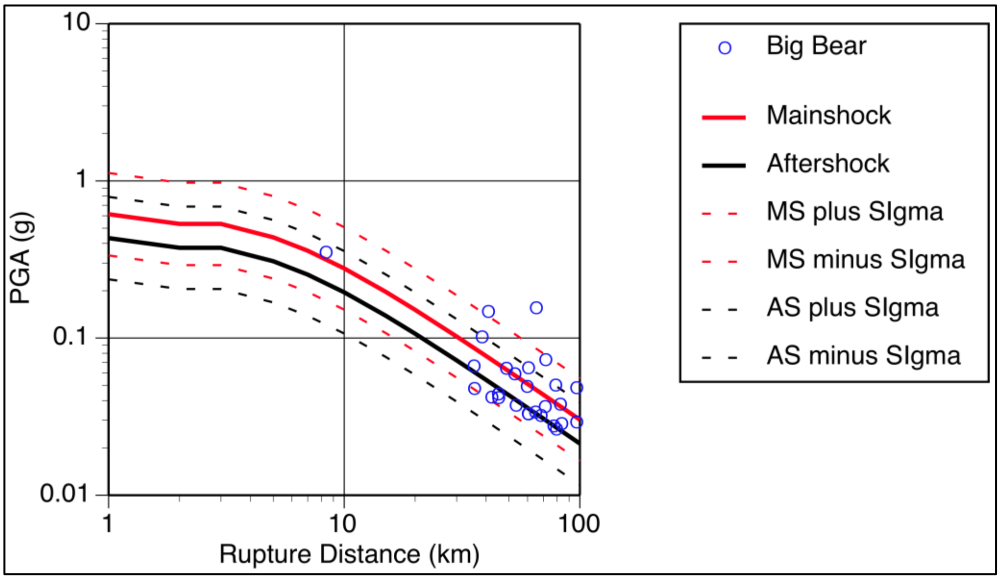

Figure 1.2. Peak Ground Accelerations normalized to a reference Vs30 of 500 m/s for the 1992 Big Bear earthquake compared with the A&S 2008 GMPE for mainshocks and aftershocks.

Based on observations such as these, triggered events that occur off the mainshock rupture plane, which are often called aftershocks, may have median ground motions more similar to mainshocks. Therefore, we group the earthquakes in the NGA-West2 database into two classes based on their distance to the rupture plane of the main event. Our hypothesis is that the earthquakes occurring within the fault plane of the main event have a systematic bias toward lower median ground motion due to the lower stress drops from these earthquakes that re-rupture the fault plane. This is consistent with the results of Baltay et al (2012) which showed that, on average, the stress drops for the mainshocks (Class 1 earthquakes) in the NGA-West2 dataset are about 1.6 times higher than the stress drops for the aftershocks (Class 2 earthquakes). In this paper, we develop a definition of Class 1 and Class 2 for use in ground motion models that will account for the lower stress-drops observed in aftershocks as compared to mainshocks but also account for triggered events that are off of the mainshock rupture plane. As described below, we define Class 1 earthquakes as mainshocks, triggered events, or foreshocks that occur off the surface projection of the mainshock rupture plane and we define Class 2 earthquakes as the earthquakes that occur within or near the surface projection of the mainshock rupture plane and within a time window for aftershocks.

2. APPROACH

2.1. Time and Distance Windows for Aftershocks

The Gardner and Knopoff (1974) algorithm provides a simple approach for identifying aftershocks based on magnitude-dependent time and distance windows from the mainshock. Earthquakes that fall within both the time and distance windows, defined by the magnitude of the mainshock, are classified as aftershocks, and earthquakes that fall outside of one or both of the magnitude and distance windows are classified as mainshocks. The Gardner and Knopoff time and distance windows are shown in Figure 2.1. We parameterized these values using a linear model for the distance window and a bi-linear model for the time window, as shown in Figure 2.1.

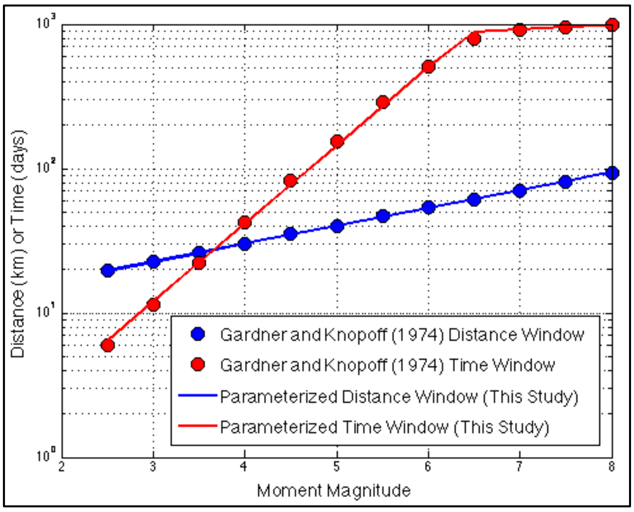

Figure 2.1. Gardner and Knopoff time and distance windows.

Figure 2.2 below shows an example of applying the Gardner and Knopoff algorithm directly to the NGA-West2 dataset for the Mw7.9 2008 May 12, Wenchuan, China earthquake. In the NGA-West2 database, the Wenchuan, China earthquake has 65 aftershock records associated with it, with dates ranging from May 12 to August, 5 2008. The right panel shows the earthquake sequence, and the left panel shows the events identified as aftershocks by the Gardner and Knopoff algorithm. The algorithm identifies only 39 of the 65 aftershocks because it searches over a radial distance from the epicenter of about 90 kilometers for a Mw7.9 earthquake. The rupture plane for the Wenchuan, China earthquake spanned a length of approximately 300 kilometers. By using the mainshock epicenter for measuring the separation distances between earthquakes, many of the earthquakes that are clearly related to the mainshock are not associated with the mainshock by the Gardner and Knopoff algorithm.

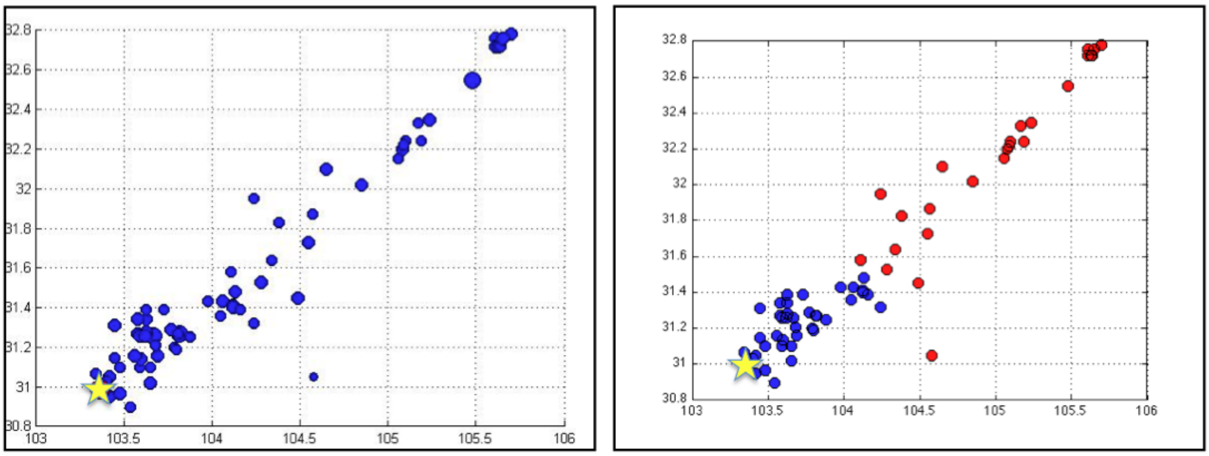

Figure 2.2. Left Panal: 2008 Wenchuan, China Earthquake (yellow star) and aftershock sequence (blue dots); Right Panal: 2008 Wenchuan, China earthquake (yellow star), aftershocks as defined by the Gardner-Knopoff algorithm (blue dots) and events not associated with the event sequence (red dots).

This example demonstrates the obvious shortcoming of adopting the Gardner and Knopoff approach for classifying earthquake sequences on long rupture planes. When the rupture plane is long, many of the dependent events, located along the rupture plane but far from the hypocenter, are either misclassified as Class 1 earthquakes or associated with the wrong sequence. Another disadvantage of defining the distance window radially from the mainshock epicenter is that Class 1 earthquakes (off-rupture plane earthquakes) can be misclassified as Class 2 earthquakes (along-rupture plane earthquakes).

2.2. Modifications to the Distance Window

To address the shortcomings of using the epicentral distance to classify earthquakes, we introduce a new metric called $\Delta R_{JB.}$ It is related to the well-known Joyner-Boore distance metric, Rjb, used in ground motion models. The Joyner-Boore distance metric is defined as the shortest horizontal distance from a site to the vertical projection of the rupture plane. We extend this concept to use the shortest separation distance between the Joyner-Boore rupture surface of the mainshock and Joyner-Boore rupture of the potential Class 2 earthquakes, hence the term ΔR_{JB}. An example of this metric is shown in the left panel of Figure 2.3, where the red lines are the surface projections of the top of the rupture planes, the dashed lines are the surface projections of the rupture planes, the yellow star is the epicenter of the Class 1 mainshock, and the orange stars are the epicenters of the aftershocks (potential Class 2 earthquakes). By definition, aftershocks inside the surface projection of the Class 1 mainshock rupture plane have a ΔR_{JB} distance equal to zero and are Class 2 earthquakes.

One short-coming of this approach is that an earthquake may rupture a segment of the fault adjacent to the segment that ruptured in the mainshock, leading to a small (or zero) ΔR_{JB} while the majority of the rupture plane is located on a separate segment and may be much further from the mainshock rupture. In Figure 2.3, this is demonstrated by the relationship between the mainshock rupture plane and the rupture plane of aftershock #3. Therefore, we modified the definition to use the shortest distance between the centroid of Joyner-Boore rupture surface of the potential Class 2 earthquakes (shown with the open circles in the right panel of Figure 2.3) and the closest point on the edge of the Joyner-Boore rupture surface of the mainshock as shown in the right panel of Figure 2.3. We call this the centroid Joyner-Boore distance CR_{JB}.

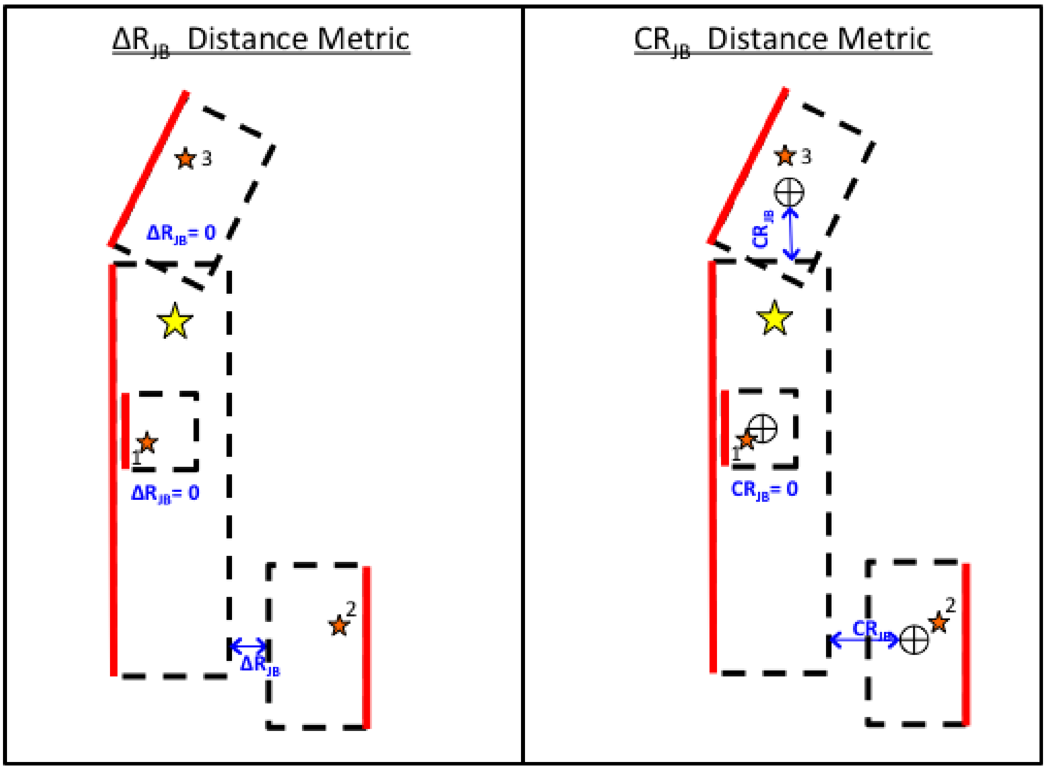

Figure 2.3. Definitions of the ΔR_{JB} and CR_{JB} distance metrics.

This classification scheme, using the CR_{JB} distance metric and the Gardner and Knopoff time window, was used to classify the earthquakes in the NGA-West2 database. Rupture geometries are associated with all earthquakes in the NGA-West2 large magnitude database; however, rupture geometries are not yet available for the NGA-West2 small magnitude database, containing earthquakes with moment magnitudes less than approximately Mw5. Due to this limitation, we use the potential Class 2 earthquake epicenter as an approximation of the centroid of the rupture plane to calculate the CR_{JB} distance. This is a reasonable assumption considering that the rupture plane for a small magnitude earthquake is commonly approximated with a point source.

Figure 2.4 shows an example of using the proposed classification scheme to classify the earthquakes associated with the Mw7.9 2008 Wenchuan, China Class 1 mainshock using a maximum CR_{JB} of five kilometers for Class 2 earthquakes. In each of the figures, the red stars are the Class 1 earthquakes, and the blue circles are the Class 2 earthquakes. The yellow rectangles show the surface projections of the fault planes. Events within the surface projection of the Class 1 mainshock rupture plane have a CR_{JB} of zero. The simple modification of adding the rupture plane geometry and basing the separation distance calculation on the surface projection of the rupture plane results in a more appropriate classification of earthquakes for the purposes of ground motion estimation. From this example, however, it is unclear what maximum value of CR_{JB} should be used to define Class 2 earthquakes.

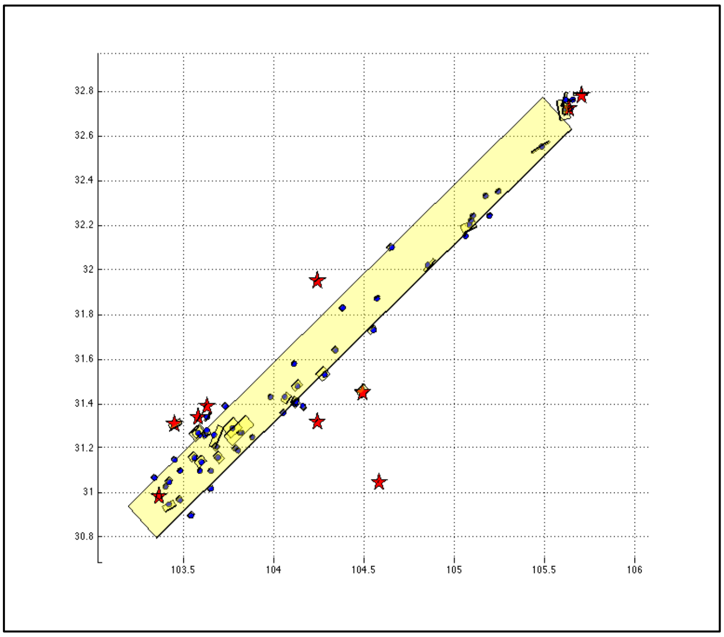

Figure 2.4. Example of identification of Class 1 and Class 2 earthquakes for the 2008 Wenchuan, China Class 1 mainshock using a maximum CR_{JB} of 5 kilometers for defining Class 2 earthquakes. The red stars are the Class 1 earthquakes, and the blue circles show the centers of the Joyner-Boore rupture surfaces for the potential Class 2 earthquakes. The yellow rectangles are the surface projections of the rupture planes.

Our hypothesis is that the stress drops are lower for earthquakes that re-rupture the Class 1 mainshock rupture plane. Therefore, as the centroid of a Class 2 earthquake moves further away from the surface projection of the Class 1 rupture plane (CR_{JB} increases), we expect the median ground motion to increase back to the median ground motion level characteristic of Class 1 earthquakes because the earthquakes are no longer re-rupturing the Class 1 rupture plane and the stress drops should increase accordingly. We evaluate the cutoff CR_{JB} distance using the inter-event residuals from the ground motion regression on a preliminary version of the NGA-West2 database. A preliminary regression is conducted following the random effects methodology described in Abrahamson and Youngs (1992). The event terms represent the average factor between median ground motion as given by the GMPE and the ground motion observed in individual earthquakes.

As an example, the PGA event terms for the potential Class 2 earthquakes (those that occur within the Gardner-Knopoff time window) are plotted as a function of the CR_{JB} for PGA in Figure 2.5. The zero line (dashed black line) shows the median event term for Class 1 earthquakes. As with all ground motion data, there is significant variability of the event terms, but Figure 2.5 shows that for short CR_{JB} distances (less than about 5 km), the medians of the event terms for Class 2 earthquakes are lower than for Class 1 mainshocks, but at larger CR_{JB} distances, the medians of the event terms for the potential Class 2 earthquakes become similar to the medians for Class 1 earthquakes.

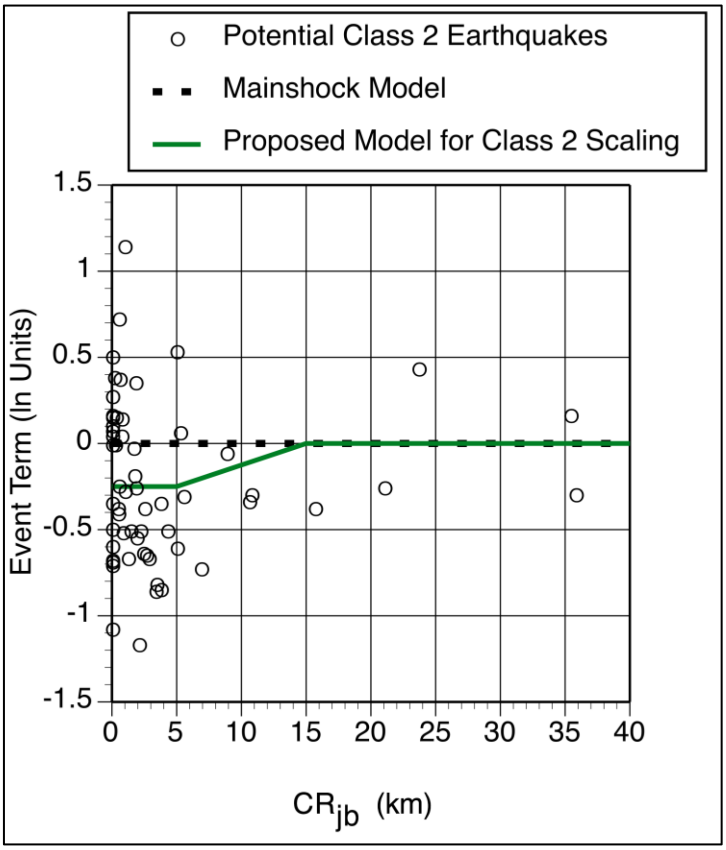

Figure 2.5. Event terms plotted against CR_{JB} for earthquakes in the NGA-West2 database (PGA).

2.3. Modifications to the Time Window

We have not evaluated the dependence of the median ground motions for Class 1 and Class 2 earthquakes on the time window. However, the idea has been proposed that faults may begin to heal over time following an earthquake (NGA-West2 and UCERF3 Workshop Coordination Meeting, October 24-25, 2011). As the fault is re-sutured, we would expect the ground motions from future earthquakes rupturing along the previously ruptured fault plane to increase as the stress drops increase to the previous levels dictated by the regional stress field. Future work will include evaluation of the stress-drop dependence on the time window.

3. RESULTS

Based on this initial evaluation, we propose to identify Class 2 earthquakes using the Gardner and Knopoff (1974) time window and a distance window with CR_{JB} < 15 kilometers. The effect on the median ground motion is tapered for CR_{JB} at distances from 5 to 15 kilometers, as shown in equation 3.1 below.

$$T(CR_{JB}) = \begin{cases} c_1 & for\, CR_{JB} \leq 5\, km \\ c_1 \left[\dfrac{CR_{JB} - 5}{10} \right] & for\, 5 < CR_{JB} < 15\, km \\ 0 & for\, CR_{JB} > 15\, km \end{cases} \tag{3.1}$$

This proposed functional form of the Class 2 earthquake scaling will be further evaluated as part of the

NGA-West2 project. As previously mentioned, the idea of fault healing has not yet been evaluated for classifying Class 1 and Class 2 earthquakes, and no modifications have yet been made to the Gardner and Knopoff (1974) time window. Also, the distance taper is likely dependent on a number of factors that have not yet been analysed, such as magnitude and style of faulting. Once the NGA-West2 database is finalized, the larger dataset will allow an evaluation of magnitude and style-of-faulting dependencies.

The decision was made to base our distance metric on the Joyner-Boore distance. In doing this, we make the assumption that the crust immediately above as well as below the rupture plane is sufficiently damaged in an earthquake to result in lower stress drop aftershocks causing systematically lower ground motions. However, it is possible that earthquakes occurring much deeper than the Class 1 mainshock rupture plane are still occurring in crust that was undamaged by the Class 1 mainshock. If this is true, there may be a depth dependence relative to the Class 1 mainshock to consider.

The length of the distance taper may also depend on how well integrated, or old, the fault system is on which the earthquake occurred. Old, well integrated fault systems may not cause as much off-fault damage as the younger, poorly integrated fault systems. The use of slip rate as a proxy for the degree of fault system integration will be pursued in future studies.

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REFERENCES

Abrahamson, N.A. and Silva, W.J. (2008). Summary of the Abrahamson & Silva NGA ground-motion relations. *Earthquake Spectra* **24:1**,67-97.

Abrahamson, N.A. and Youngs, R.R. (1992). A stable algorithm for regression analyses using the random effects model. *Bulletin of the Seismological Society of America* **82**, 505-510.

Baltay,A.S., Hanks,T.C. and Beroza,G.C. (2012). Understanding the NGA-West ground motion prediction equations for PGA and PGV. *Seismological Society of America Annual Meeting 2012.* **SRL 83:2**,354.

Boore, D.M. and Atkinson, G.M. (2008). Ground -motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. *Earthquake Spectra* **24:1**,99-138.

Boore, D.M. and Atkinson, G.M. (1992). Source spectra for the 1988 Saguenay, Quebec earthquakes. *Bulletin of the Seismological Society of America* **82**,683-719.

Boore, D.M. and Atkinson, G.M. (1989). Spectral scaling of the 1985-1988 Nahanni, Northwest Territories, earthquakes. *Bulletin of the Seismological Society of America* **79**,1736-1761.Campbell, K.W. and Bozorgnia, Y. (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 10s. *Earthquake Spectra* **24:1**,139-171.

Chiou, B.S.-J. and Youngs, R.R. (2008). An NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra* **24:1**,173-215.

Gardner, J.K. and Knopoff, L. (1974). Is the sequence of earthquakes in southern California with aftershocks removed, poissonian? *Bulletin of the Seismological Society of America* **64:5**,1363-1367.