REVIEW OF RECENT GROUND MOTION STUDIES FOR PERFORMANCE-BASED ENGINEERING

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1 INTRODUCTION

Structural analyses falling under the name Performance-Based Earthquake Engineering (PBEE) often involve dynamic analysis of a structure or system subjected to a recorded or simulated ground motions. Experience has shown that the procedure used to obtain the input ground motions can have a significant impact on the resulting structural response results. Further, if Performance Based Engineering aims to obtain precise estimates of structural response (as opposed to conservative estimates), then it is important to understand and properly account for the ground motion properties that affect these response estimates. This paper aims to summarise recent efforts by the author's research group related to improved use of ground motion selection. Three topics are briefly discussed: choice of the target response spectrum to be considered when selecting ground motions, incorporation of near-fault directivity effects in hazard analysis and ground motion selection, and characterization of ground motions at a regional scale for performance-based assessment of critical infrastructure systems. References are provided to work by the author and his students where these results were first published. (There are many other relevant references to work on these topics, but for brevity the references here are focused primarily on the author's work. This is not intended to imply that the author is the sole investigator of these topics, and references to related work are found extensively in the documents cited below.)

2 CONDITIONAL MEAN SPECTRUM

Response spectra are known to be valuable predictors of structural response, as they indicate the peak response of elastic oscillators (which can behave in a similar manner to the more complex structure being studied). For this reason, many building codes throughout the world specify that ground motions used for structural analysis that have response spectra equal to or larger than some target spectrum (e.g., American Society of Civil Engineers 2005; CEN 2005). For Performance-Based Engineering, the question is what form should the response spectrum take? The author has argued that the Uniform Hazard Spectrum, which serves as the target spectrum in many building codes, is not appropriate for PBEE as it conservatively assumes that a single ground motion may have extremely large amplitudes at all frequencies (Baker 2009).

In PBEE, it is preferable to define ground motion intensity using spectral acceleration (*Sa*) at only one period, because probabilistic assessments benefit greatly from having a direct link to Probabilistic Seismic Hazard Analysis (PSHA) that quantifies the rates of exceedance of that single *Sa* parameter (e.g., Bazzurro and C. A. Cornell 1994; C. Allin Cornell et al. 2002).

PSHA can be extended to a vector format that overcomes this limitation (Baker and C Allin Cornell 2008; Bazzurro and C Allin Cornell 2002), but the added complexity of that procedure means that it has not become widely adopted. Assuming the use of PSHA at a single period, the question is then, what values of *Sa* at other periods are to be expected, given some value of *Sa* at the primary period of interest? This question can be answered, given knowledge of the magnitude, distance and the *Sa* amplitude of interest. The author has termed the resulting spectrum a "conditional mean spectrum," as provides the *mean* values of the response *spectrum* at all periods, *conditional* on an *Sa* value at a single period.

Computation of the Conditional Mean Spectrum is not difficult. The following step-by-step calculation procedure is a straightforward method for obtaining this spectrum. This description is taken from Baker (2009), where it is presented in more detail.

Determine the target Sa at a given period, and the associated M, R and ε

To begin the computation, we identify a target *Sa* value at a period of interest denoted T^* (often, but not neccessarily, equal to the first-mode period of the structure of interest). It is also necessary to determine the magnitude, distance and $\varepsilon(T^*)$ values associated with the target $Sa(T^*)$. If the target $Sa(T^*)$ is obtained from PSHA, then the *M*, *R* and $\varepsilon(T^*)$ values can be taken as the mean *M, R* and $\varepsilon(T^*)$ from deaggregation (this information is provided by, e.g., the U.S. Geological Survey). This ε parameter is defined as the number of standard deviations by which a given ln*Sa* value differs from the mean predicted ln*Sa* value for a given magnitude and distance. Mathematically, this is written

$$\varepsilon(T) = \frac{\ln Sa(T) - \mu_{\ln Sa}(M, R, T)}{\sigma_{\ln Sa}(T)} \tag{1}$$

where $\mu_{\ln Sa}(M, R, T)$ and $\sigma_{\ln Sa}(T)$ are the predicted mean and standard deviation, respectively, of ln*Sa* at a given period, and $\ln Sa(T)$ is the log of the spectral acceleration of interest.

Compute the mean and standard deviation of the response spectrum, given M and R

Next, we compute the mean and standard deviation of log spectral acceleration values at all periods, for the target *M*, *R*, etc. That is, we evaluate $\mu_{\ln Sa}(M, R, T)$ and $\sigma_{\ln Sa}(T)$ from equation 1. These terms can be computed using existing ground motion models (e.g., Boore and Atkinson 2008), and several online calculation tools exist to aid in obtaining these values (e.g., *http://www.opensha.org*).

Compute ε at other periods, given $\varepsilon(T^*)$

Next we compute the "conditional mean" ε. The conditional mean ε at other periods can be shown to equal $\varepsilon(T^*)$, multiplied by the correlation coefficient between the ε values at the two periods

$$\mu_{\varepsilon(T_i)|\varepsilon(T^*)} = \rho(T_i, T^*)\varepsilon(T^*) \tag{2}$$

where $\mu_{\varepsilon(T_i)|\varepsilon(T^*)}$ denotes the mean value of $\varepsilon(T_i)$, given $\varepsilon(T^*)$. Predictions of the required correlation coefficient, $\rho(T_i, T^*)$, have been pre-calculated in previous studies, so users of this procedure can obtain the needed correlations using a simple predictive equation. One prediction, valid for periods between 0.05 and 5 seconds, is

$$\rho(T_{min}, T_{max}) = 1 - \cos\left(\frac{\pi}{2} - \left(0.359 + 0.163 I_{(T_{min<0.189})} \ln\frac{T_{min}}{0.189}\right)\ln\frac{T_{max}}{T_{min}}\right) \quad (3)$$

where $I_{(T_{min<0.189})}$ is an indicator function equal to 1 if $T_{min} < 0.189$ s and equal to 0 otherwise, and where T_{min} and T_{max} denote the smaller and larger of the two periods of interest, respectively (Baker and C Allin Cornell 2006). A more refined (but more complicated) correlation model, valid over the wider period range of 0.01 to 10 seconds, is also available (Baker and Jayaram 2008a), but equation 3 is nearly equivalent if only periods between 0.05 and 5 seconds are of interest (equation 3 is reproduced here because of its greater simplicity).

Compute the Conditional Mean Spectrum

Substituting the mean value of $\varepsilon(T_i)$ from equation 2 into equation 1 and solving for $\ln Sa(T)$ produces the corresponding conditional mean value of $\ln Sa(T_i)$, given $\ln Sa(T^*)$

$$\mu_{\ln Sa(T_i)|\ln Sa(T^*)} = \mu_{\ln Sa}(M, R, T_i) + \rho(T_i, T^*)\varepsilon(T^*)\sigma_{\ln Sa}(T_i) \quad (4)$$

The exponential of these $\mu_{\ln Sa(T_i)|\ln Sa(T^*)}$ values gives the CMS, as plotted in Figure 1.

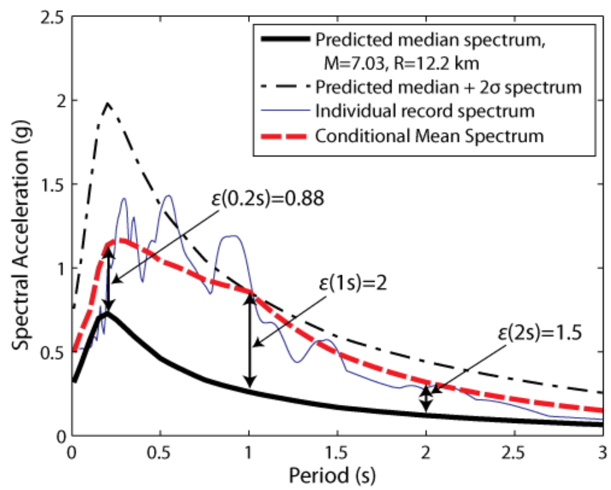


Figure 1. Example Conditional mean spectrum calculations for M = 7, R = 12 km, ε(1s) = 2, compared to recorded ground motion having those same properties (from Baker 2009).

We see from the above steps that computation of the Conditional Mean Spectrum requires only existing ground motion models and PSHA results, plus two additional simple formulas (equations 3 and 4). These calculations can easily be performed using a simple computer program. While this procedure is not as widely implemented as UHS calculations, it is arguably simpler to compute a CMS than a UHS.

2.1 Impact of ground motion scaling

Findings from the Conditional Mean Spectrum approach have also suggested that potential problems caused by ground motion scaling are due primarily to discrepancies in the shape of elastic response spectra between the ground motion to be scaled and the 'target' ground motion desired. These discrepancies may result in the scaled ground motions causing different levels of structural response than the response that would be caused by (unscaled) ground motions naturally at the intensity level of interest. Such a bias can be detected by selecting a suite of ground motion records that have been scaled to all have the same intensity level (where here intensity is measured by spectral acceleration at the structure's first-mode period). The structural responses associated with the records are plotted versus the records' scale factors. Statistical trends between the scale factor and the level of structural response quantify the extent to which record scaling is biasing the structural response. Results obtained using this approach indicate that records selected to match an appropriate CMS (or that otherwise account for this spectral shape) can be scaled without introducing such a bias, whereas the records selected using other methods often have biased structural responses when scaled (Baker 2007a).

3 TREATMENT OF NEAR-FAULT DIRECTIVITY

A common worry in ground motion selection for near-fault sites is how to appropriately incorporate the effects of near-fault directivity into ground motion selection. Forward directivity results when the fault rupture propagates towards the site at a velocity nearly equal to the propagation velocity of the shear waves and the direction of fault slip is aligned with the site. This causes the wave front to arrive as a single large pulse. A more detailed description of this phenomenon is given by, e.g., Somerville et al. (1997). Several researchers have developed detailed analytical models describing the shapes of velocity pulses resulting from directivity (Bray and Rodríguez-Marek 2004; Fu and Menun 2004; Makris and Black 2004). These models are useful when determining loading functions for parametric studies of structural response, but they are not able to determine whether an arbitrary ground motion contains a pulse.

The author has previously developed a signal processing technique to identify whether an arbitrary ground motion contains a strong velocity pulse (Baker 2007b). The proposed pulse extration technique is illustrated in Figure 3, and the extracted pulse can then be evaluated to determine whether it is "large" (based on its peak velocity and energy content). By classifying a large catalog of previously recorded ground motions in this manner, it was then possible to do statistical studies to identify the conditions under which pulses are likely to occur, and the probability of occurence of a pulse for a given set of earthquake and location conditions (Iervolino and C. Allin Cornell 2008). Additionally, these classified ground motions can be used to quanitify the amount by which the presence of a pulse amplifies the ground motion's response spectrum (Baker 2008; Shahi and Baker 2009). Finally, the pulse probabilities and resulting ground motion predictions can be incorporated into a generalization of traditional probabilistic seismic hazard analysis (Shahi and Baker 2009; Tothong et al. 2007). Software for performing this analysis, and example data produced by this work, is available on the author's website at *http://www.stanford.edu/~bakerjw*.

While a modified ground motion prediction model has previously been used in PSHA to account for directivity (Somerville et al. 1997), that general modification did not explicitly distinguish between pulse-like and non-pulse-like ground motions, which means that the resulting hazard analysis output can provide little guidance as to what extent directivity has impact the hazard analysis results, or how directivity should play a role in the ground motions selected to represent the ground motion hazard. In contrast, deaggregation calculations from the newly-proposed approach provide the probability that a given spectral acceleration level (at a given period) will be caused by a ground motion containing a velocity pulse. A distribution of pulse periods will also be provided. This will facilitate the selection of appropriate ground motions, in the same way that magnitude, distance and epsilon deaggregation guides ground motion selection today. This new ground motion selection will also be facilitated by tools such as the Design Ground Motion Library (Youngs et al. 2006), which have included the author's pulse classifications as a parameter by which ground motions can be chosen.

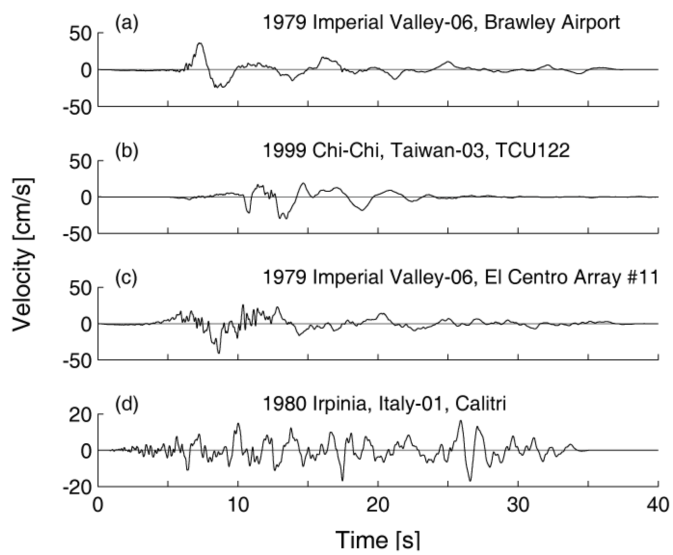


Figure 2. Example near-fault ground motions (from Baker 2007b).

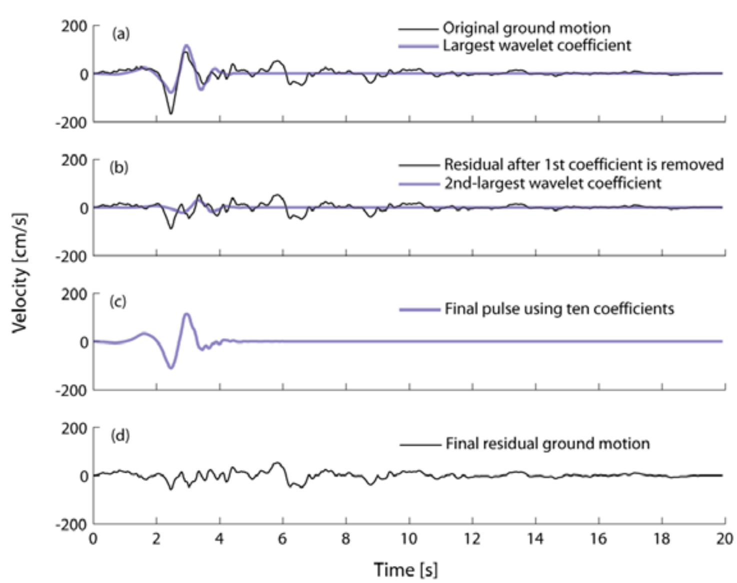


Figure 3. Illustration of the wavelet decomposition procedure used to extract the pulse from the 1994 Northridge, Rinaldi ground motion recording. (from Baker 2007b).

4 REGIONAL SCALE GROUND MOTIONS

A separate but tangentially related topic to the above results is characterization of ground motions for risk analysis of distributed systems such as highway networks or portfolios of buildings owned or insured by a single entity. These systems are difficult to analyze, due to their large spatial extent, the potential proximity to many faults, and (in the case of lifelines) the interaction of lifeline components with each other (see, e.g., Figure 4). There are two big changes in this type of analysis relative to the topics discussed above. First, effects on individual components of these systems will likely be quantified through a fragility curve rather than repeated dynamic analyses, because the system complexity will likely preclude a more detailed analysis (although the fragility curves may have been calibrated ahead of time using dynamic analyses). Second, a probabilistic characterization of ground motion hazard can no longer be obtained using classic Probabilistic Seismic Hazard Analysis, because of the need to quantify the probability of simultaneously observing ground motions at many sites with specified levels of intensity. Quantification can realistically only be obtained using Monte Carlo approaches, where one simulates earthquake events and then simulates resulting ground motion intensities at all locations of interest, taking care to maintain proper correlation among intensities at all locations (Jayaram and Baker 2009a). These simulations can then be combined with fragility functions to simulate damage to system components, and then calculate resulting impacts on the system (e.g., transportation system delays, or losses to an insured portfolio of buildings).

To illustrate, Figure 5a shows one simulation of ground motion intensity for an earthquake in the San Francisco Bay Area, and Figure 5b shows one simulation of the highway network disruption that might result from the ground motion in Figure 5a. These and the following results were obtained using a model for the Bay Area transportation network consisting of a 29,804 links (roads), 10,647 nodes connecting these links, 1,125 bridges, and origin-destination data for 1,120 transportation analysis zones. The bridges have been classified into HAZUS categories (National Institute of Building Sciences (NIBS) 1999; Porter 2009) for the purposes of damage estimation (Stergiou and Kiremidjian 2006). The origin-destination data come from the 1990 MTC household survey (Purvis and Donnelly 1999; Stergiou and Kiremidjian 2006). To facilitate faster distruption analysis, this detailed model was then aggregated into a coarse scale model consisting of 586 links, 310 nodes, and 46 centroidal nodes that act as origins and destinations for the traffic (Jayaram and Baker 2009a). Ground motion maps were obtained using the USGS Hazard Mapping quantification of earthquake sources (Frankel et al. 2000), the Boore and Atkinson ground motion model (2008), and the Jayaram and Baker correlation model (2009b). To verify the ground motion simulation approach, we have also verified that logarithms of spectral accelerations at multiple locations have a multivariate normal distribution (Jayaram and Baker 2008). (Multivariate normality greatly simplifies later simulation steps.)

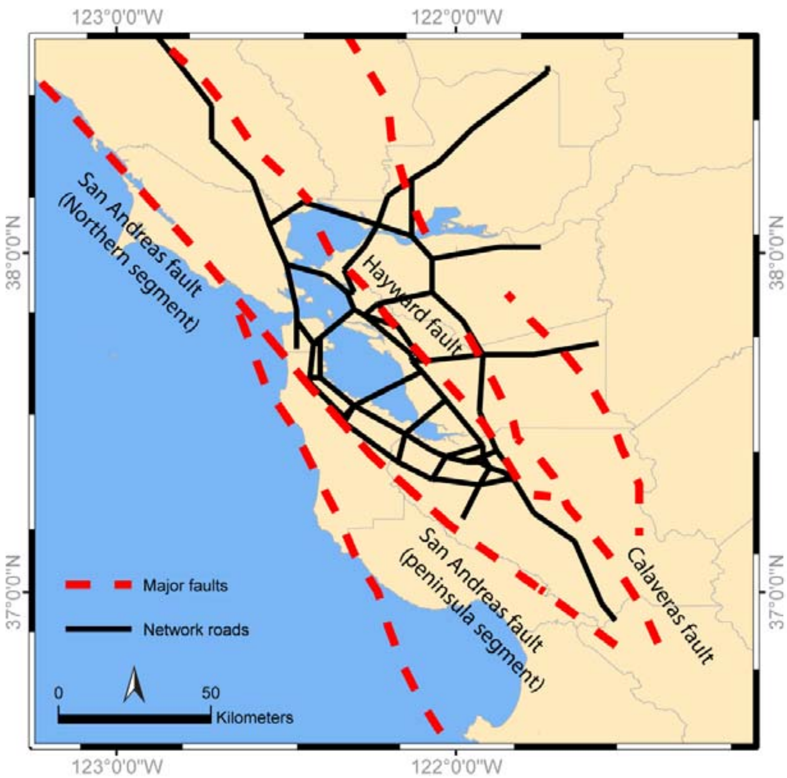
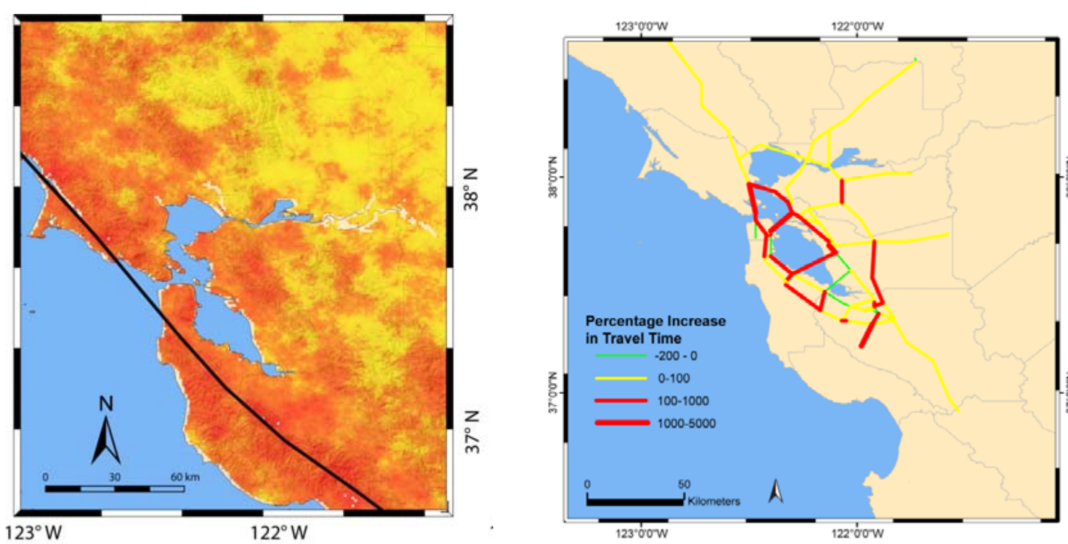


Figure 4. Major faults and highways in the San Francisco bay area (from Jayaram and Baker 2009a).



(a) (b)

Figure 5. (a) One simulation of spatially correlated ground motions from one possible earthquake event. (b) One simulation of resulting transportation system disruption due to bridge damage.

With the above model, Jayaram and Baker have studied disruption to an aggregated model of the San Francisco Bay Area transportation network (Jayaram and Baker 2009a), as well as portfolios of insured buildings (Park et al. 2007; Baker and Jayaram 2008b). That work has also focused on more efficient methods of simulating and identifying ground motion intensity maps of most interest, while still maintaining a proper probabilistic representation of the ground motions that might occur in the region (Jayaram and Baker 2009a); this work has shown that it is possible to reasonably represent the full distribution of ground shaking that can occur in a region using on the order of 100 ground motion maps (as opposed to the approximately 1 million maps that might be needed for the same assessment if basic Monte Carlo simulation is used). This relatively small number means that one can still do a small number of scenario-type analyses of infrastructure disruption (as is preferred for complex infrastructure analyses) while still maintaining the probabilistic rigor of PSHA-type ground motion characterizations). Figure 6 shows loss exceedance rates for various levels of travel time delays in the above-described network, illustrating that accurate estimates can in fact be obtained using very few simulations, if those simulations are obtained using the above approach. Theoretical evidence for the unbiasedness of this approach is also provided elsewhere (Jayaram and Baker 2009a).

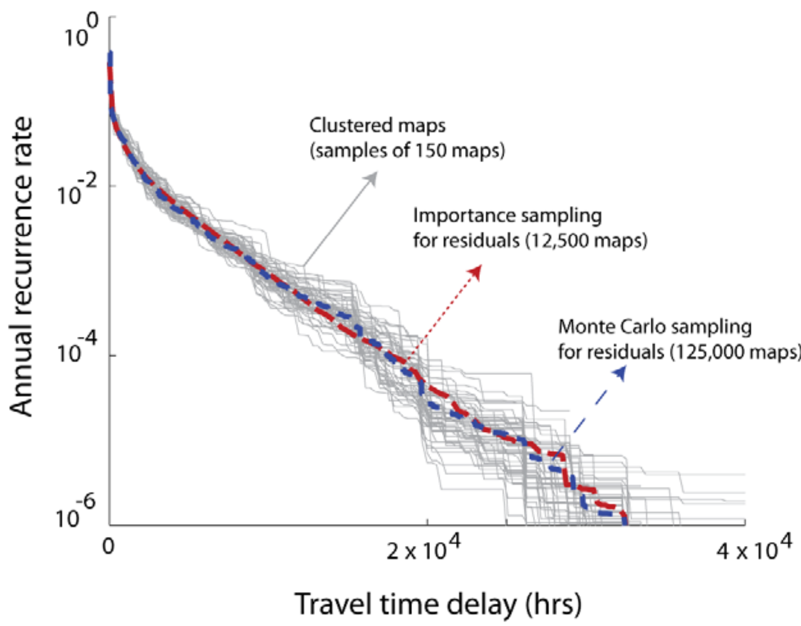


Figure 6. Travel time delay exceedance curves for the Bay Area transportation network shown in Figure 4, illustrating the ability of proposed efficient simulation approaches to accurately reproduce results from more computationally expensive simulation techniques (from Jayaram and Baker 2009a).

5 CONCLUSIONS

Consideration of realistic ground motion spectra, near-fault directivity, and spatial correlation of ground motions are three areas in which new insights can be provided to guide performance-based earthquake engineering. All three topics of inquiry are greatly facilitated by the recent progress in producing large high quality catalogs of strong ground motion data that have been used to calibrate emperical models. Given the great variability in observed ground motion intensities, all three topics are neccessarily treated using the tools of probabilistic modeling in order to quantify this variability. Fortunately, probabilistic descriptions of ground motion characteristics are naturally consistent with many Performance-Based Assessment approaches.

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