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Ground motion selection for performance-based engineering, and the Conditional Mean Spectrum as a selection tool

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ABSTRACT: This paper provides a review of current thinking regarding selection of ground motions for the purpose of predicting the response of a structure subjected to high amplitude ground motions. The distinction between selecting ground motions with appropriate seismological versus time-series properties is discussed, providing motivation for focusing on time-series properties. With this in mind, the Conditional Mean Spectrum (CMS) is described as a tool to facilitate this selection. The CMS provides the expected (i.e., mean) response spectrum, conditioned on occurrence of a target spectral acceleration value at a conditioning period of interest. Following a basic discussion of this target spectrum, a number of topics are briefly discussed, including the potential impact of performing ground motion selection using the CMS, factors to consider in choosing a conditioning period for computing the CMS, and available tools to automate CMS calculations. References are provided to aid interested readers interested in learning more about this topic.

1 INTRODUCTION

Ground motion selection is known to be a critical step in dynamic analysis of structures, as decision-making regarding ground motion selection can have as large of an impact on estimated building performance as decisions made when modelling the structure (e.g., Haselton et al. 2009). There remains a great diversity in methods used by practitioners to select ground motions, and a diversity in requirements of various code documents (e.g., Katsanos et al. 2010; NIST 2011). This paper provides a discussion of current thinking in best practices for ground motion selection, with an emphasis on the Conditional Mean Spectrum (CMS) as a tool for computing target response spectra (e.g., Baker 2011).

When selecting ground motions, the assumption here is that the goal is to obtain time series that are consistent with ground motion amplitudes and other properties computed from seismic hazard analysis. Speaking more loosely, we aim to obtain time series that are representative of the strong shaking that a particular location may experience in the future during an earthquake. Implicit in this assumption is that a particular location of interest, and its potential nearby earthquake sources, is specified. This assumption is valid for most projects to design a new structure or assess an existing one. Additionally, we focus primarily on selecting ground motions from a database of previously recorded motions, though some of the concepts are also relevant when using simulated ground motions.

A key tool for all of the following ground motion selection approaches discussed below is a seismic hazard deaggregation calculation (Bazzurro and Cornell 1999; McGuire 1995), as illustrated in Figure 1. This figure illustrates the properties of ground motions that meet or exceed a given intensity at a particular location (mathematically, the probability distribution of properties such as earthquake magnitude and distance, conditional on exceedance of some ground motion intensity level). In Figure 1, the height of the bars indicates the percentage contribution to exceedance of a given intensity level from of earthquakes from a particular magnitude and distance (indicated by the coordinates of the horizontal axes) and ε (indicated by the colour of the bar)—a parameter that will be discussed below.

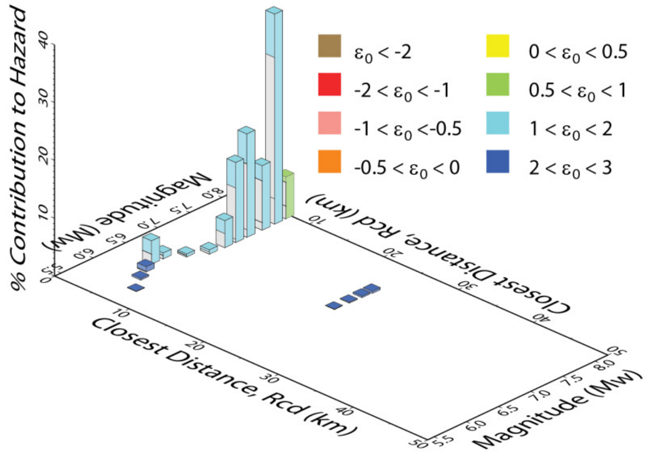
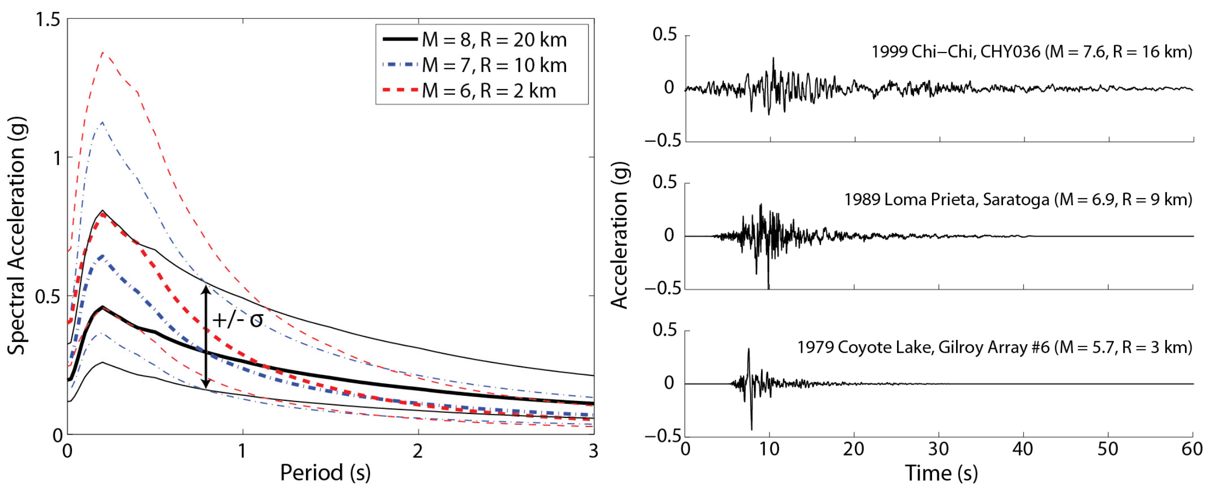


Figure 1: Seismic hazard deaggregation plot for one-second spectral acceleration exceeded with 2% probability in 50 years at Stanford, California (adapted from USGS, http://geohazards.usgs.gov/deaggint/2008/).

2 TRADITIONAL APPROACH FOR SELECTING GROUND MOTIONS—CONSIDER SEISMOLOGICAL PROPERTIES

Traditionally, the primary considerations in selecting ground motions have been on finding recordings with appropriate seismological properties, such as the earthquake magnitude and source-to-site distance indicated in the deaggregation result above, and the tectonic environment and earthquake rupture mechanism. These considerations are evident, for example in the language of ASCE/SEI 7-10 (2010) and other similar documents: "Appropriate ground motions shall be selected from events having magnitudes, fault distance, and source mechanisms that are consistent with those that control the maximum considered earthquake."



(a) (b)

Figure 2 (a) Median predicted response spectra from vertical strike slip earthquakes of various magnitudes (with the corresponding distance varied so that all three spectra have comparable amplitudes at a period of one second). Median spectral values are shown in heavy lines, and plus/minus one log standard deviation (σ) predictions are shown in thin lines. Spectral predictions are from the model of Campbell and Bozorgnia (2008). (b) Time series recorded from earthquakes with varying magnitudes, indicating the relationship between magnitude and duration.

The reason for these considerations is that these seismological properties are known to be related to ground motion properties that affect resulting structural responses. For example, Figure 2a shows response spectra predictions for earthquakes of varying magnitudes and distances, indicating the differences in relative amplitudes of short-period and long-period spectra among these three cases (though note that the variability in spectra, indicated by the standard deviations of the predictions, is large in relation to these differences). Figure 2b shows acceleration time series from three recordings associated with earthquakes of varying magnitudes. The magnitude of the earthquake is related to the duration of shaking in the associated recording. Given that spectral acceleration and duration of shaking are properties known to influence response of structures, it is rational to select recordings with appropriate seismological properties in order to provide some assurance that the selected ground motions' properties are reasonable.

There are two problems, however, with selection approaches focused on seismological parameters. The first problem is that it restricts the selection to a limited number of available ground motions. For example, Figure 3 shows the magnitudes and distances of shallow crustal earthquakes in the PEER NGA-West 1 database (Chiou et al. 2008). In much of coastal California (and other similar active seismic regions in the world) strong ground motions of interest in earthquake engineering are likely to result from earthquakes of magnitude 7 or greater, observed at distances of 20 km or less. Looking at Figure 3, there are a relatively small number of recordings satisfying that criteria. This is expected, as engineers are by definition interested in performance of buildings under high amplitude ground motions resulting from relatively rare earthquake scenarios, but is nonetheless a challenge.

The second problem with this approach is that seismological parameters are imperfect proxies for the ground motion properties of interest (such as response spectra and duration) and those properties are only indirect indicators of the demands that a ground motion will place on a structure. As such, seismological parameters tend to be fairly poor predictors of resulting structural demands (e.g., Haselton et al. 2009; Shome et al. 1998). This raises the question as to whether the strict restrictions on available ground motions that result from seismological constraints are productive when selecting ground motions.

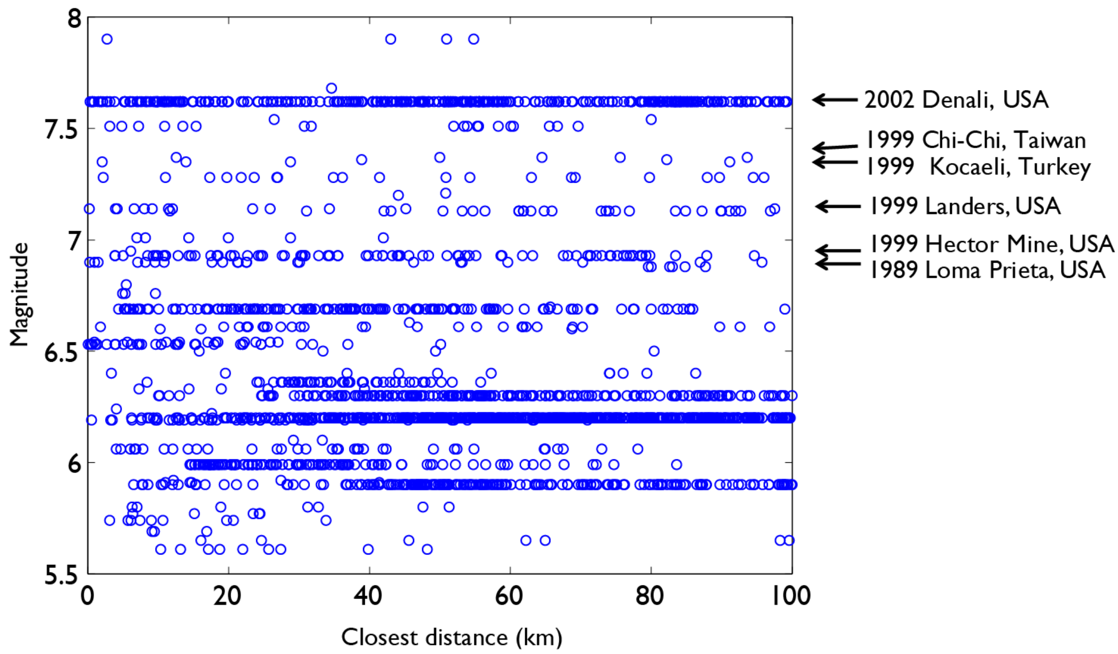


Figure 3: Magnitudes and distances of recordings of active crustal earthquake in the PEER NGA-West 1 ground motion database (Chiou et al. 2008).

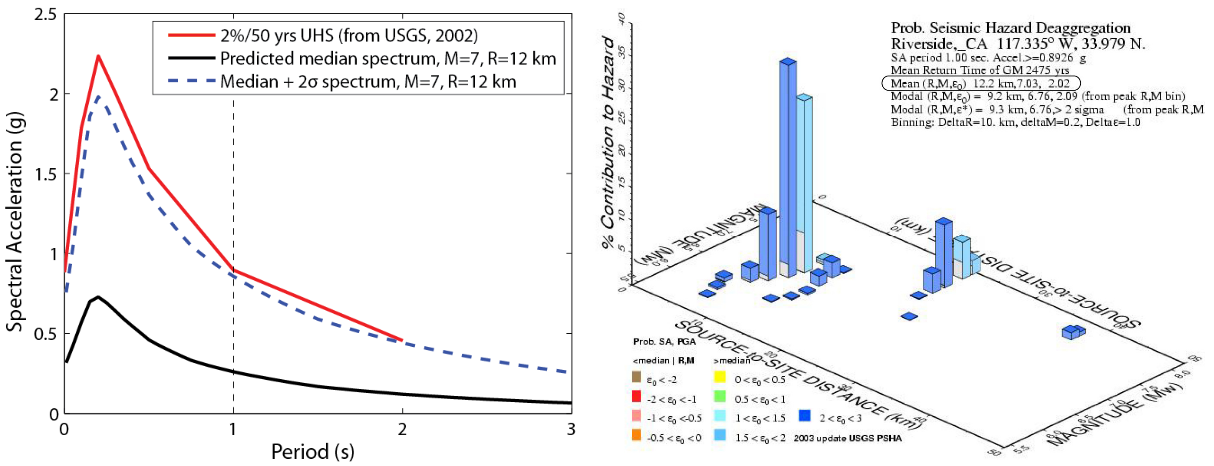
3 CURRENT APPROACH FOR SELECTING GROUND MOTIONS—CONSIDER TIME SERIES PROPERTIES

With the above limitation of traditional approaches in mind, a consensus is emerging that it is more productive to consider time series properties rather than seismological properties when selecting ground motions (e.g., Bommer 2011; NIST 2011). If time series properties are stronger predictors of structural demands, and if seismological properties are relevant primarily in that they indicate properties of time series, then the following is useful strategy: use seismological property information to determine anticipated time series properties, and then select ground motions based on their consistency with those time series properties (even if it means selecting ground motions that are less consistent with the original seismological properties). This paper will discuss primarily the response spectrum as a time series properties of interest, but other measures of shaking duration, energy content, etc., can be considered using the same general approach.

This approach has the benefits of broadening the pool of potential ground motions, and the selected motions have better ability to predict structural response robustly, as well as better robustness to amplitude scaling (Watson-Lamprey and Abrahamson 2006; Baker 2007). Adopting this approach does require the analyst to compute target values for time series parameters. This is not as trivial as with the previous approach, where the seismological parameters are directly produced by standard PSHA deaggregation calculations, but it is still quite straightforward as will be seen below.

4 THE CONDITIONAL MEAN SPECTRUM

In this section, we briefly discuss computation of an appropriate target response spectrum for use in selecting ground motions. This approach has been extended to consider other time series metrics by Bradley (2010, 2012), but for simplicity we will focus on response spectra here. First, we consider hazard calculations for spectral acceleration at a period of 1 second, *Sa*(1s), and consider the hazard data computed in Figure 4a. The uniform hazard spectrum is much larger in amplitude than the median spectrum associated with the dominant magnitude=7 and distance=12 km combination from the deaggregation information in Figure 4b. The difference is due to the ε parameter in Figure 4b, which indicates how many standard deviations larger than the median spectrum the target amplitude is. In this case it is approximate two standard deviations larger, which is why the median-plus-two-standard-deviation spectrum in Figure 4a is comparable to the uniform hazard spectrum.



(a) (b)

Figure 4: Seismic hazard data for an example site in southern California. (a) Uniform hazard spectrum, and median and median-plus-two-standard-deviation spectrum from deaggregation information at Sa(1s) (from Baker 2011). (b) Deaggregation information for Sa(1s) exceeded with 2% probability in 50 years (from USGS interactive deaggregation tools).

But probabilistic seismic hazard analysis is only performed for one period at a time (e.g., for a period of 1s in the calculations that produced Figure 4b). The uniform hazard spectrum summarizes results from a number of such calculations by plotting a set of points that all have equal exceedance probabilities, but it does *not* tell us the probability that any single ground motion would equal or exceed all of those spectral amplitudes.

To get more realistic information about the likely response spectrum of any single ground motion, we need to ask, what is the expected (i.e., mean) response spectrum, conditioned on occurrence of a target spectral acceleration value at the period of interest? Taking the above case as an example, we know that

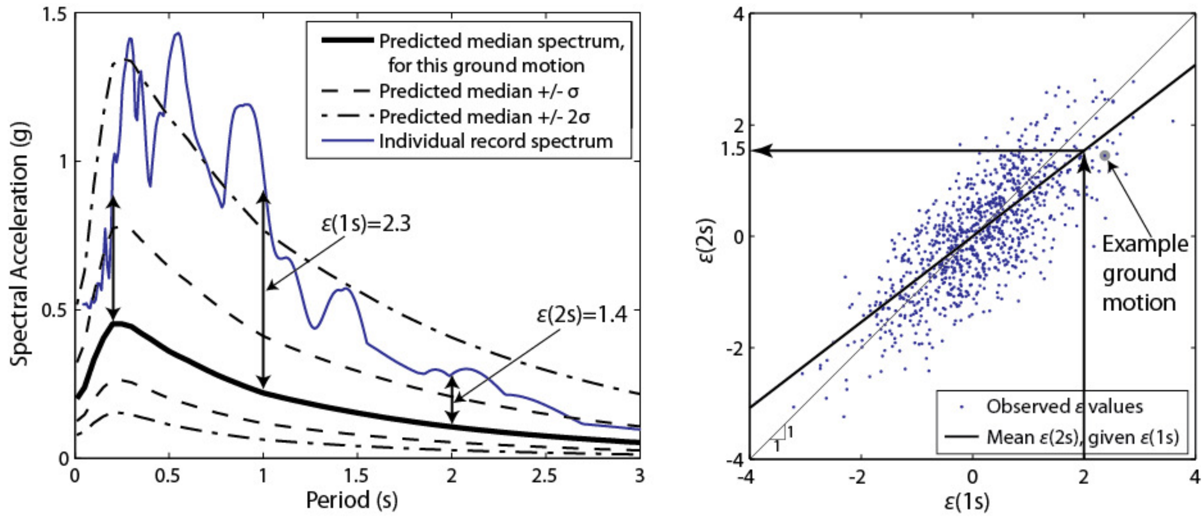
that exceedance of the target $Sa(1\text{s})$ is likely to be caused by an earthquake of magnitude=7 at a distance of 12 km, and that the expected ε value at a period of 1s is 2. The magnitude and distance value give us the median spectrum illustrated in Figure 4a, but we still need to find the ε values associated with other periods.

Figure 5a illustrates ε values at periods of 1s and 2s from an example ground motion. Mathematically, these are residuals of log standard deviations:

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

where $\mu_{\ln Sa}(M,R,T)$ and $\sigma_{\ln Sa}(T)$ are the predicted mean and standard deviation, respectively, of lnSa at a given period, and $\ln Sa(T)$ is the log of the spectral acceleration of interest (e.g., the spectral acceleration amplitude from a hazard calculation, or from an observed ground motion). We can observe that the ε values vary with period, which is associated with the "bumpy" shape of real response spectra. If we perform these calculations for a large suite of ground motions, we can start to understand the statistics of these ε values.

Figure 5b shows a scatter plot of ε(1s) values versus ε(2s) values for a suite of several hundred ground motions. We see a strong correlation between the ε values at these two periods, but not a perfect correlation. In the example of this section, we know the ε(1s) value is 2, and want the mean values of ε(2s) conditional on this knowledge. Some statistical analysis reveals that the mean is the conditioning value (2 in this case) multiplied by the correlation coefficient between the ε's (0.75 in this case), or 1.5 (Baker and Cornell 2005). The correlation values among all combinations of period pairs can be pre-computed and used for this purpose (e.g., Baker and Jayaram 2008). Figure 6 shows a spectrum computed using these conditional mean ε values (note the ε(2s)=1.5 value discussed in this paragraph). This spectrum is termed a "conditional mean spectrum," indicating the objective that led to its calculation. While the brief discussion presented here relied on using mean values of magnitudes, distances and ε values from deaggregation, the calculation procedure can be extended to treat these parameters in a less approximate manner, and to incorporate multiple ground motion prediction models as is usually done in modern seismic hazard analysis (Lin et al. 2013a).



(a) (b)

Figure 5: (a) ε values at two periods for an example ground motion's response spectrum, graphically illustrated with reference to the median predicted spectra for a ground motion with the given magnitude, distance and site conditions. (b) Scatter plot of ε(1s) versus ε(2s) values from a large set of ground motions, illustrating the partial correlation of ε values at differing periods. The example ground motion from (a) is highlighted for reference. Figures adapted from Baker (2011).

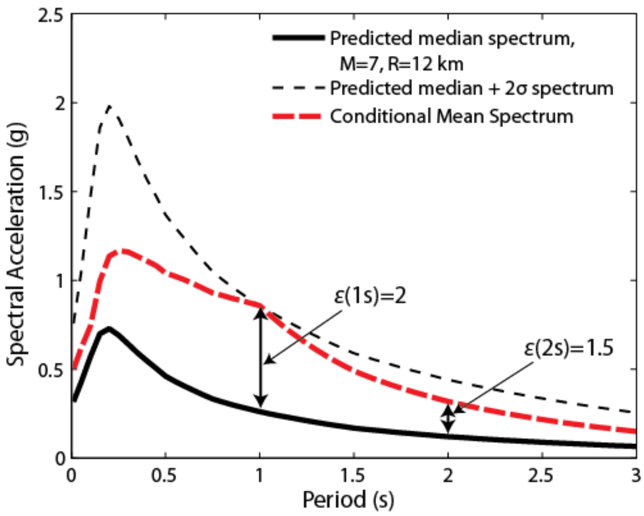


Figure 6: Conditional mean spectrum for the example site.

To recap, this conditional mean spectrum has utilized our knowledge of the seismological properties identified from a hazard analysis, in order to compute the expected time series properties (i.e., response spectra) associated with those seismological properties. We note again that this same procedure can be utilized to find target values of time series properties other than response spectra, as detailed, for example by Bradley (2010, 2012). Returning to our record selection objective, we can now search for ground motions having response spectra close to this target, and select those ground motions for our engineering analysis.

5 DISCUSSION

5.1 Impact of selection approach

This calculation procedure would be of little practical interest if ground motions selected in this manner did not produce substantially different structural responses than ground motions selected using other approaches (such as selecting motions with spectra matching a uniform hazard spectra). A number of studies have found substantial increases, however, in the ability of buildings to resist collapse when conditional mean spectrum concepts are used to select ground motions (e.g., Federal Emergency Management Agency 2009; Goulet et al. 2007; Haselton et al. 2008; Haselton and Baker 2006; Liel 2008; Zareian 2006).

5.2 Choice of conditioning period

The above calculations all used a conditioning period of 1 second, but this was a user choice, and obviously it is undesirable if the results of an engineering analysis depend strongly on an arbitrary choice such as this. The treatment of conditioning period in a procedure like this depends upon the larger analysis procedure for which the ground motions are being selected. If the structural will be analysed at multiple intensity levels, such as what FEMA P-58 (2012) calls a “time-based” assessment, then Lin et al. (2013b) showed that the results are relatively insensitive to conditioning period, as the collective set of motions over all intensity levels will have appropriate probability distributions of spectral amplitudes at all periods.

If, on the other hand, only a single intensity level or ground motion exceedance probability is being considered (such as in a building code check), then the choice of conditioning period is important. This is because, if a structural response parameter is sensitive to excitation at a particular period, and the conditional mean spectrum’s amplitude at that period varies depending upon the conditioning period, then the estimated response value is sensitive to that conditioning period. In these cases, multiple conditioning periods should be considered (such that the envelope of the resulting conditional spectra is sufficiently large) and the structure should be assessed to ensure satisfactory performance under each of the conditioning periods (Carlton and Abrahamson 2014; Loth and Baker 2015).

5.3 Tools for calculation of the Conditional Mean Spectrum

In the United States, automated conditional mean spectrum calculations are now available from the U.S. Geological Survey national hazard maps products (https://geohazards.usgs.gov/deaggint/2008/). They are also available in some commercial seismic hazard analysis software such as EZ-FRISK (http://www.ez-frisk.com/). Professor Bradley provides a number of tools to select ground motions based on the general principles described above but extended to consider ground motion intensity measures other than response spectra (https://sites.google.com/site/brendonabradley/software/), based on his generalized conditional intensity measure approach to this same issue (Bradley 2010, 2012). Additionally, relatively simple tools to compute the CMS based on seismological inputs (e.g., magnitude, distance, ε) are available from PEER (http://ngawest2.berkeley.edu/) and the author's website (http://web.stanford.edu/~bakerjw/gm_selection.html, based on the algorithm in Jayaram et al. 2011). With these various tools, it is now easy for an analyst to utilize the conditional mean spectrum concept without having to perform the intermediate calculations of Section 4 by hand.

6 CONCLUSIONS

Efficient ground motion selection relies on finding recordings with appropriate time history properties (not seismological properties) for a given analysis condition. This strategy allows a user to maximize the value of a catalogue of recorded ground motions when selecting ground motions for analysis. To facilitate this goal, the conditional mean spectrum (CMS) was discussed. The CMS describes the mean response spectrum of a ground motion having the magnitude, distance and ε value that caused occurrence of a target spectral acceleration at some conditioning period. The CMS differs from the Uniform Hazard Spectrum, which envelopes response spectra from multiple magnitudes, distances, and ε values, and thus does not represent the spectrum of any one ground motion. The general concept discussed here can also be easily extended to incorporate other ground motion parameters such as duration, and to address spectrum calculations at sites with complex seismicity.

Because utilization of the procedure to select ground motions has been shown to have a significant impact on resulting structural demands (and pragmatically, because its utilization typically results in reduced structural demands), this approach has been adopted in a number of performance assessment procedures, and will be adopted in the forthcoming ASCE/SEI 7-16 standard in the United States.

This paper has provided a basic review of general concepts and procedures that were developed, and are more completely documented, in the references cited above. The interested reader is referred to those documents for more information on this topic.

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