Design Ground Motion Time Histories using the Conditional Mean Spectrum

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Abstract

Engineers need ground motion time histories for the analysis of the response of structures to earthquake ground shaking. In current practice, these time histories are usually spectrally matched to a uniform hazard response spectrum. At low probabilities, this spectrum is too “broadband” (i.e. large over an unrealistically broad range of periods), and envelopes a set of more appropriate design response spectra, termed conditional mean spectra. These concepts are illustrated using a site-specific probabilistic seismic hazard analysis of ground shaking in which ground motion time histories are spectrally matched to conditional mean spectra that were derived from the uniform hazard spectrum.

Keywords: Ground motion time histories, Conditional mean spectrum.

1. INTRODUCTION

The response spectrum used for design is sometimes defined as a specific scenario earthquake, but in most seismic codes the design response spectrum is defined probabilistically. The probabilistic uniform hazard response spectrum (UHS) obtained through probabilistic seismic hazard analysis (PSHA) takes account of all of the earthquake scenarios that could affect the site, and describes the ground motion level that corresponds to a specified return period or annual probability of exceedance. The probabilistic response spectrum represents the contributions from many different earthquakes, perhaps including small nearby earthquakes and more distant larger earthquakes, and may not be a realistic representation of the response spectrum of any individual scenario earthquake.

For this reason, if it is desired to use ground motion time histories to represent the response spectrum, it is then necessary to identify one or more scenario earthquakes that dominate the hazard for that return period in the period range of importance for the structure. This process, termed deaggregation of the probabilistic response spectrum, results in one or more earthquake scenarios, each having a specified magnitude, distance, and severity (described by the parameter epsilon). The deaggregation of the hazard varies with the return period and the ground motion period of interest. Selection of time histories therefore needs to take account of the return period and ground motion period of interest. Ideally, it should also consider site-specific conditions such as rupture directivity, topographic amplification, and basin response that may be important features of the ground motion environment at the site (and contribute to large values of epsilon), even if these conditions were not explicitly considered in the development of the probabilistic response spectrum, but these considerations lie outside the scope of this paper.

Once the time histories have been selected based on the deaggregation of the seismic hazard, they need to be scaled or spectrally matched to a target spectrum. Currently, the probabilistic uniform hazard response spectrum (UHS) is usually used as the target spectrum. However, at low probabilities, this response spectrum is too "broadband" (i.e. large over a range of periods that is unrealistically broad), and envelopes a more appropriate response spectrum, called the conditional mean spectrum. The purpose of this paper is to describe the current state-of-the-art in the development of ground motion time histories that avoids this conservatism, using a suite of conditional mean response spectra.

2. CONDITIONAL MEAN SPECTRUM

A common goal of dynamic structural analysis is to predict the response of a structure subjected to ground motions having a specified spectral acceleration at a given period. The prediction is often obtained by selecting ground motions that match a target response spectrum, and using those ground motions as input to dynamic analysis. The commonly used uniform hazard spectrum (UHS) obtained by probabilistic seismic hazard analysis (PSHA) is shown by Baker (2011) to be an unsuitable target for this purpose, because it conservatively implies that large-amplitude spectral values will occur at all periods within a single ground motion time history. An alternative, termed a Conditional Mean Spectrum (CMS), provides the expected (i.e., mean) response spectrum, conditioned on occurrence of a target spectral acceleration value at the period of interest (Baker and Cornell, 2006; Baker, 2011). Baker (2011) shows this spectrum to be the appropriate target response spectrum for the goal described above, and it is thus a useful tool for selecting ground motions as input to dynamic analysis. He further demonstrates that the CMS spectrum maintains the probabilistic rigor of PSHA, so that consistency is achieved between the PSHA and the ground motion selection. This enables quantitative statements to be made about the probability of observing the structural response levels obtained from dynamic analyses that utilize this spectrum; in contrast, the UHS does not allow for such statements (Baker, 2011).

Figure 1 shows the hypothetical case in which it is desired to design a structure with a first mode period of 1 second for an earthquake of magnitude 7 at a closest distance of 10 km, and the design criteria specify the use of a response spectrum that is two standard deviations above the median value for that combination of magnitude and distance (epsilon value of 2). In addition to the median response spectrum and the response spectrum that is two standard deviations above the median, the left side of Figure 1 shows recorded response spectra for earthquakes of magnitude about 7 and closest distance of about 10 km. Unlike the smooth target spectrum, the individual recorded response spectra have peaks and troughs. Most of these spectra, those shown in green, are much lower than the target spectrum (median plus 2 sigma) at a period of 1 second. One record that is at about the target spectrum level at 1 second period, shown in black, is much lower than the target spectrum at other periods. This illustrates the fact that, unlike the smooth target spectrum, the individual recorded response spectra have peaks and troughs, so it is very unlikely that a time history whose response spectrum is two standard deviations above the median at 1 second period will also be two standard deviations above the median at other periods.

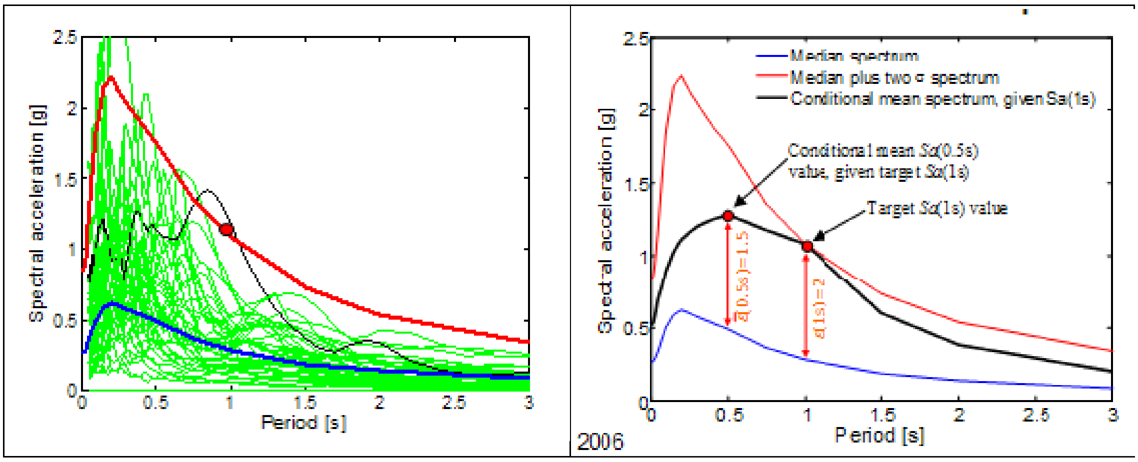

Figure 1. Left: Median (blue) and median plus two standard deviations (red) design spectrum for a magnitude 7 earthquake at a closest distance of 10 km, shown with recorded response spectra (green), one of which (black) is close to the design spectrum at a period of 1 second. Right: Derivation of the conditional mean spectrum for a period of 1 second from a scenario spectrum, which in this case is the median plus two standard deviations spectrum. The conditional mean is derived from the correlation between response spectral values at adjacent periods. Source: Baker, 2006.

The left side of Figure 1 demonstrates the lack of correlation between the response spectral amplitudes at different periods in a given ground motion time history. The correlation generally decreases with increasing separation between periods, as quantified by Baker and Jayaram (2008). The right side of Figure 1 shows the conditional mean spectrum constructed using these correlation values for a magnitude 7 earthquake recorded at a distance of 10km. When the epsilon of the design response spectrum is greater than zero, which is usually the case for design spectra at long return periods, then the level of the conditional response spectrum at adjacent periods is lower than that of the scenario spectrum. This reflects the fact that is very unlikely that the response spectrum of a time history will match the scenario spectrum at all periods, due to the lack of correlation of amplitudes between periods. The conditional mean response spectrum is less broadband than the scenario spectrum, which envelopes it. This CMS spectrum may be a useful target spectrum for ground motion selection in many applications, because the alternative UHS is conservative relative to this target. Structural responses from ground motions matching the CMS may be significantly smaller than the responses from ground motions matching the UHS..

Most structures are designed to be ductile, and their first mode period tends to progressively lengthen as they yield to ground motions whose levels exceed their elastic limit. Consequently, they may experience larger displacement demands than those that are indicated from their response at their first mode elastic period. Similarly, the response of some structures may have significant contributions from higher modes, which are prominent at periods that are shorter than the first mode period. Therefore, to appropriately represent the response of the structure across the full period range to which it is sensitive, it is usually necessary to develop a suite of CMS at different periods, and to match time histories to each of the CMS. In this case it is not necessary that any of the selected periods represent the first mode period of the structure. For some structures, there may not be any clearly defined first mode period, but this does not preclude the use of CMS to develop target spectra for the development of time histories.

3. TARGET SPECTRA FOR GROUND MOTION TIME HISTORIES

The uniform hazard response spectrum (UHS) and the deaggregation of the hazard form the starting point for the preparation of target spectra for the development of ground motion time histories. The earthquake events that dominate the hazard in the period range of importance for the structure for the specified annual probability are identified through the process of deaggregation of the probabilistic response spectrum. This results in one or more earthquake scenarios, each having a specified magnitude, distance, and epsilon. Epsilon is the number of logarithmic standard deviations by which the probabilistic response spectrum in the period range of importance differs from that of the median response spectrum for that magnitude and distance as predicted by the ground motion model used in generating the probabilistic response spectrum. There are two sources of conservatism in using the uniform hazard spectrum as the target for the spectral matching of time histories for use in analysis. First, when a ground motion time history is used in analysis, it is a scenario earthquake, just one of the many earthquakes that contribute to the uniform hazard spectrum and are enveloped by it. The time history is therefore matched not to the UHS but to the response spectrum of the scenario earthquake, derived from the magnitude, distance and epsilon obtained through deaggregation, scaled to match the UHS at the natural period of the structure. This response spectrum is generally less "broadband" than the uniform hazard spectrum, which usually envelopes it. Second, the scenario spectrum is modified to represent the conditional mean response spectrum described above. For low probabilities, this response spectrum is less "broadband" than the scenario spectrum, which envelopes it.

We illustrate the development of conditional mean spectra and time histories for a site located in the cratonic region of Australia. The uniform hazard response spectrum (UHS) and the deaggregation of the hazard form the starting point for the preparation of target spectra for the development of ground motion time histories. The earthquake events that dominate the hazard at four different ground motion periods for the specified annual probability are identified through the process of deaggregation of the probabilistic response spectrum. This resulted in four earthquake scenarios, each having a specified magnitude, distance, and epsilon (Table 1). The magnitude and closest distance of the earthquake both increase with increasing ground motion period. Epsilon is the number of logarithmic standard deviations by which the probabilistic response spectrum at a specified period differs from that of the median response spectrum for that magnitude and distance as predicted by the ground motion model used in generating the probabilistic response spectrum.

Table 1. Deaggregation of the Probabilistic Hazard for a Return Period of 10,000 years

	CMS Period (sec)			
	0.0 (PGA)	0.5	1.0	2.0
Magnitude (M_w)	6.0	6.2	6.4	6.8
Distance (km)	10	15	18	30
Epsilon (std)	+0.6	+0.9	+0.9	+0.9

Developing the target spectra involved the following steps:

- Generation of median response spectra for the four scenario earthquakes listed in Table 1

- Scaling of the scenario spectrum to the UHS spectrum at the corresponding period used for the CMS
- Modification of the scaled scenario spectra into the conditional mean spectra (CMS) based on epsilon

The median scenario spectra were derived by averaging the response spectra predicted by the ground motion prediction models used to generate the uniform hazard spectrum (UHS). Each scenario spectrum was then scaled by Epsilon to match the UHS at the period of its CMS.

Four separate conditional mean spectra were then developed to jointly span the entire period range, using the correlation coefficients of Baker and Jayaram (2008). The CMS for 2.0 second is conditional only for periods shorter than 2 seconds, in order to represent the UHS at all periods.

CMS period 0.0 sec: conditional for all periods
CMS period 0.5 sec: conditional for all periods
CMS period 1.0 sec: conditional for all periods
CMS period 2.0 sec: conditional for periods shorter than 2 sec, otherwise the UHS

The CMS together with the probabilistic (UHS) and scenario spectra are shown in Figure 2 for the four spectral periods.

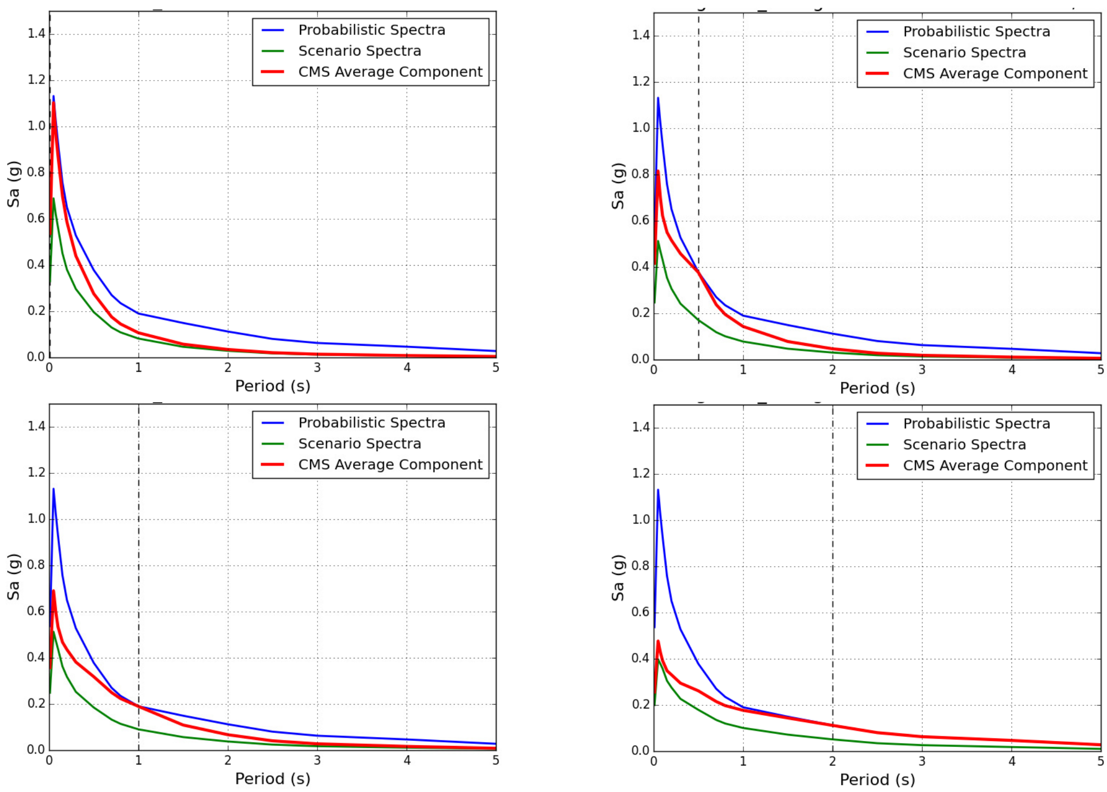

Figure 2. Conditional mean spectra (red) for response spectral periods of 0.0 sec (PGA, top left), 0.5 sec (top right), 1.0 sec (bottom left), and 2 sec (bottom right) used to represent the probabilistic UHS spectrum; the dashed vertical lines indicate the CMS periods. The probabilistic (UHS, blue) and median scenario spectra (green) are also plotted for comparison.

4. GROUND MOTION TIME HISTORIES

The spectral matching of ground motion time histories to the conditional mean spectra is illustrated in Figure 3. This figure shows the acceleration, velocity and displacement time histories before and after spectral matching, the response spectra before and after spectral matching, and the target spectrum to which matching was done.

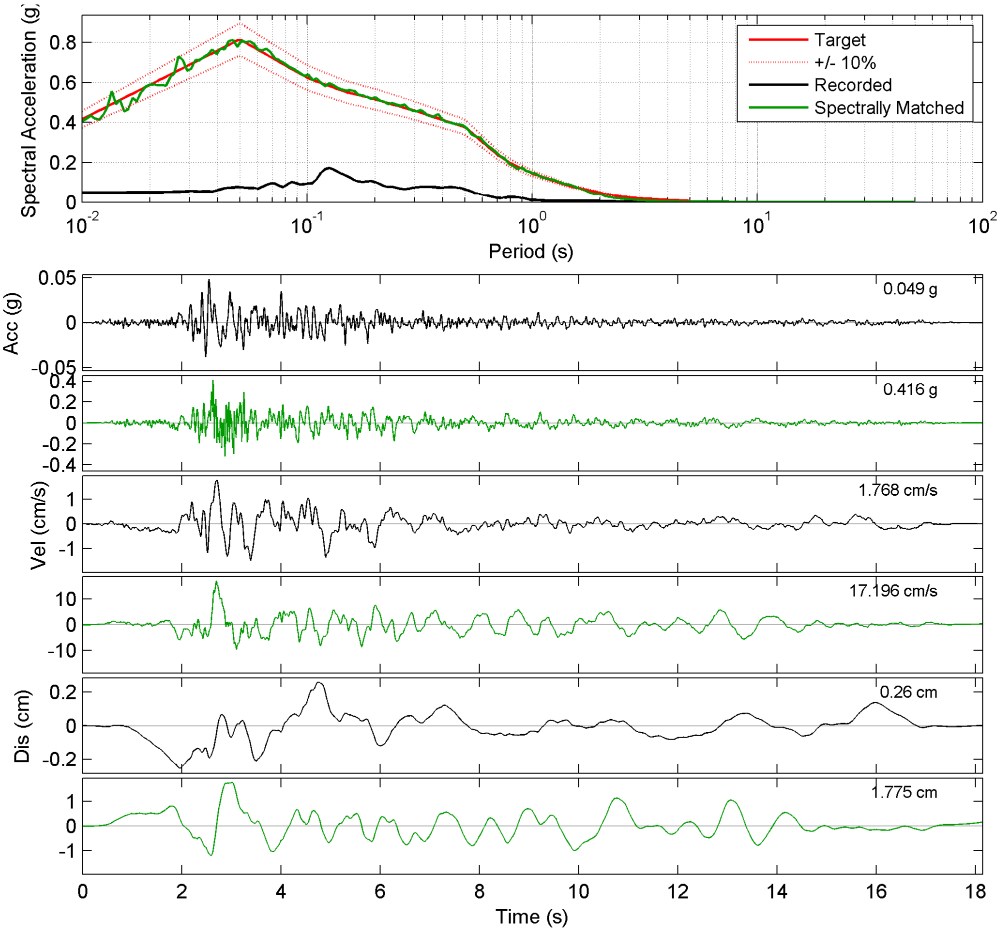

Figure 3. Bottom panel: Acceleration, velocity and displacement time histories before (black traces) and after (green traces) the spectral matching process for CMS period 0.5s. Top panel: Response spectrum of the seed time history before (black line) and after (green line) spectral matching to the target spectrum (solid red line).

5. REDUCTION IN ESTIMATED FRAGILITY USING THE CMS

Structural responses from ground motions matching the CMS may be significantly smaller than the responses from ground motions matching the UHS and having the same spectral acceleration level at the natural period of the structure. An example of a steel frame building with a natural period of 1.5 seconds is shown in Figure 4. The right side compares the fragility curves derived from uniform hazard spectra (black) and the conditional mean spectra (blue). In each case, the ground motion time histories used to represent the response spectra are spectrally matched to progressively stronger spectra in an incremental dynamic analysis (IDA) to develop fragility curves of the structure. For a given value of response spectral acceleration at 1.5 seconds period, the probability of collapse under the CMS (which is a more realistic representation of the hazard) is significantly lower that it is under the UHS (which is an unrealistically conservative representation of the hazard). For example, for a response spectral acceleration of 1.5g at 1.5 sec, the probability of collapse is about 97% for the UHS but only 60% for the CMS.

The example shown in Figure 4 applies to a building, but conditional mean spectra also apply to dams. For example, an embankment may have a natural period of about 1 second, so the time histories developed from the 1.0 second CMS would be of special relevance to the analysis of the embankment. However, because the period of the embankment may lengthen during shaking or because the embankment may have higher modes, it is not sufficient to only use the time histories representing the CMS. The same would apply to the 0.0 second CMS (peak acceleration) if the purpose of the analysis were to evaluate liquefaction. Time histories for all four CMS are required to fully represent the UHS.

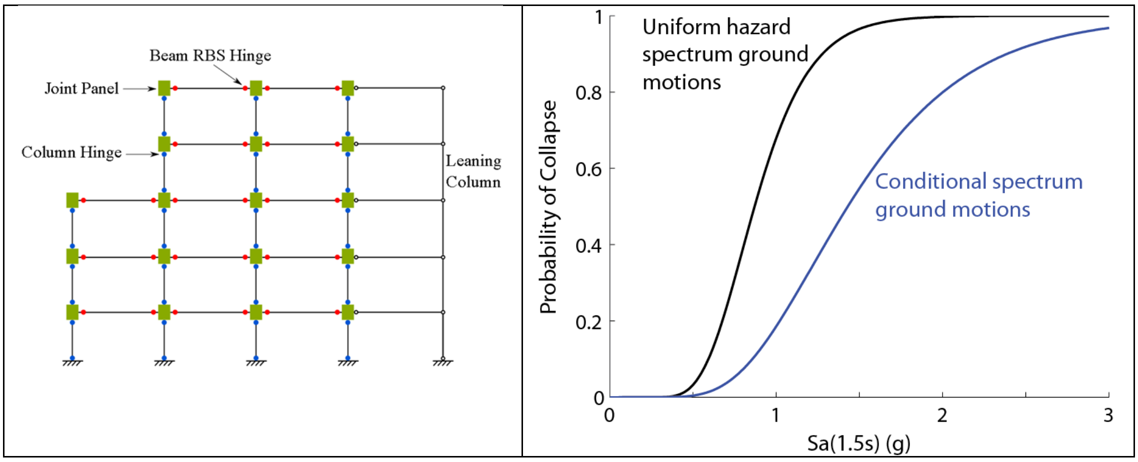

Figure 4. Example of the impact of conditional mean spectra on fragility curves. The left side shows the model of a steel moment frame building with a natural period of 1.5 seconds. The right side compares the fragility curves derived from uniform hazard spectra (black) and conditional mean spectra (blue), in each case progressively scaled up in an incremental dynamic analysis (IDA) to develop fragility curves of the structure. For a given value of response spectral acceleration at 1.5 seconds period, the probability of collapse under the CMS is significantly lower that it is under the UHS. Source: Chandramohan et al., (2016).

4. REFERENCES

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