Comparing E-CMS and CMS for Nuclear Design Spectra

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Received: 08/12/2011
Accepted: 19/06/2012

ABSTRACT

The target spectrum, which has been used most frequently for the seismic analysis of structures, is the Uniform Hazard Spectrum (UHS). The joint occurrence of the spectral values in different periods, in the development of UHS, is a key assumption that remains questionable. Baker et al [3-4] have recently developed the Conditional Mean Spectrum (CMS) as an alternative for UHS. The CMS provides the expected response spectrum, conditioned on the occurrence of the target spectral acceleration value in the period of interest. It is shown that CMS can be accounted as an improvement of UHS. The correlation between the Peak Ground Velocity (PGV) and the spectral acceleration values is investigated in the current study and a newer form of the target spectrum has been proposed. It is shown that the emerged new spectrum, named Eta-based Conditional Mean Spectrum (E-CMS), is more efficient than the conventional CMS in order to modify the UHS. The nuclear industry design guidelines (i.e. Nuclear Regulatory Commission Guide 1.165) provide an alternative procedure for defining the design spectrum, which has been compared with using the proposed E-CMS. The results show that the alternative procedure may not be conservative for stiff structures such as nuclear facilities.

Keywords:
Uniform Hazard Spectrum (UHS); Conditional Mean Spectrum (CMS); Epsilon indicator; Eta indicator; Record selection

1. Introduction

One of the most important challenges in the structural response assessment is the careful Ground Motion Record (GMR) selection before performing nonlinear dynamic analyses. Ground motion records should represent the properties of a given hazard level. Design codes use a suitable target spectrum to facilitate the ground motion record selection approach and finally use those GMRs as input to the dynamic analysis [1]. The commonly used Uniform Hazard Spectrum (UHS) is considered the target spectrum in most design codes and guidelines. However, most of the recent research results have shown that the UHS is not a good representative of a suitable target [2]. The UHS is an elastic spectrum at a site with a given hazard level which the structure is supposed to be located. The spectral acceleration amplitudes in UHS would be more than the median predicted spectrum in all periods within a single ground motion. This fact is highlighted when the UHS is compared with the spectral shape records in higher hazard levels. Figure (1) shows the UHS given exceedance of the spectral acceleration (Sa) values with 2475 years return period considering a structure with the first period of one second. Only one rare record is found to have Sa values equal to UHS in the target period indicating that this record has an epsilon value in target period of approximately two. However, it is obvious that there is a clear observed difference for the other periods between the selected record and the UHS. In other words, this fact illustrates why the

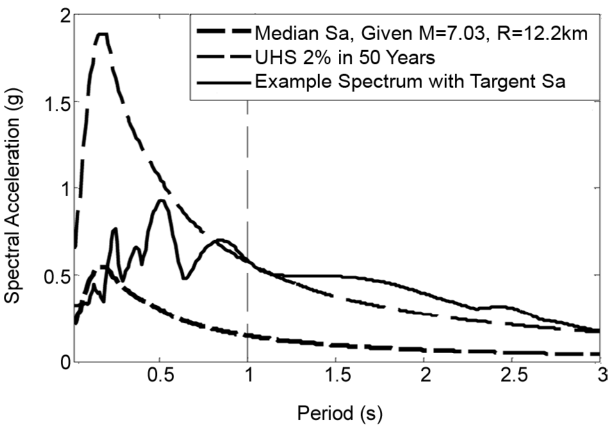

Figure 1. Median predicted spectrum having M = 7.03 and R = 12.2 km. UHS for 2 % probability of exceedance in 50 years. The example spectrum is the Newhall-W Pico Canyon Rd with M = 6.7 recorded from Northridge event.

UHS is not representative of individual ground motion spectrum. As UHS, in the lower period range, is affected by strong ground motions and weak earthquakes have the most contribution in the UHS values in lower frequencies, UHS has not satisfied users to be a suitable target spectrum for the ground motion record selection purposes and considered as a conservative target by researchers [2]. The CMS has been introduced by Baker et al. in recent years to decrease the UHS disadvantages [3-4]. The epsilon as a spectral shape indicator is employed in CMS [4]. The CMS is a method that accounts for magnitude, distance and epsilon values likely to cause a given target ground motion intensity at a given site for a specified hazard level. The main assumption in CMS is that the only value that would be exactly equal to the target value (Sa in UHS) is located at the target period. In fact, CMS usually has a peak at target period and decays towards the median spectrum in other periods. The decreasing process is based on a correlation model.

The spectral acceleration is the only Intensity Measure (IM) that is employed in the spectral shape indicator. An alternative indicator, as a more robust predictor of the non-linear response of structures, was recently proposed by Mousavi et al named eta [5]. It has been shown that a simple linear combination of IM epsilons can result in more robust predictor of the non-linear structural response. In addition to the spectral acceleration, the peak ground acceleration, the peak ground velocity and the peak ground displacement were also assumed as IMs in the prediction of the new spectral shape indicator. A new target CMS is presented here which uses the eta advantages instead of the conventional epsilon. The Eta-based Conditional Mean Spectrum (E-CMS) provides the mean response spectrum conditioned on occurrence of a target spectral acceleration value in the period of interest with consideration of a new correlation model that is based on a new spectral shape indicator.

The Nuclear Regulatory Commission (NRC) guidelines suggest a simple approach for identification and characterization of the seismic sources and determination of the safe shutdown ground motions [6]. The Safe Shutdown Earthquake (SSE) is the ground motion for which certain structures, systems, and components are designed. The SSE for the site is characterized by both horizontal and vertical free-field ground motion response spectra at the free ground surface. Based on NRC assumptions after completing the Probabilistic Seismic Hazard Analysis (PSHA) and determining the controlling earthquakes, a simple scaling should be done. Controlling earthquakes are the earthquakes used to determine the spectral shapes or to estimate ground motions at the given site. Several controlling earthquakes may be applicable for a given site. As a result of the probabilistic seismic hazard analysis, the controlling earthquakes are characterized by means of the magnitudes and the distances, which are derived from a standard disaggregation analysis. Sa5-10 is used to scale the response spectrum shape corresponding to the controlling earthquake, which is the average Sa value at 5 Hz and 10 Hz frequencies obtained from PSHA for a given probability of exceedance. Then, the response spectrum shape needs to be scaled at 7.5 Hz by this factor.

The CMS was introduced as a suitable alternative because of its reliability and robustness. One of the disadvantages of NRC target is that the supposed spectrum is independent of the target period, which is usually considered to be the first period of structural vibration, while in the case of CMS, the target period is a key parameter. Replacing eta indicator instead of the conventional epsilon in conditional computations leads to introduction of a new target response spectrum that shows more similarity to NRC target in comparison with the conventional CMS as discussed in the following sections.

2. A Brief History on Epsilon and Eta Indicators

Recent studies have shown that for ground motion records with the same spectrum value in a given period, the spectral shape has an important influence on the response of higher modes of structures as well as on its non-linear behaviour [7]. It was shown that the epsilon indicator, as expressed in Eq. (1), could be a robust predictor of the spectral shape [4], which has also high correlation with structural collapse capacity values [7]. Therefore, these summarized advantages are enough to identify epsilon as an applicable indicator in structural analysis and design. The spectral acceleration value is the most important intensity measure against other ground motion intensity parameters. It has been widely employed in the common non-linear dynamic analysis procedure that is termed Incremental Dynamic Analysis (IDA) [8]. The discussed epsilon uses Sa as IM, which means that the current epsilon is based on an intensity measure only. However, Mousavi et al [5] have recently shown that a simple combination of IM epsilons can result in more robust prediction of the spectral shape. In other words, the peak ground velocity epsilon associated with the conventional Sa epsilon is more effective than other IM epsilons. A linear combination of these two important IM epsilons was introduced as a new indicator of elastic spectral shape, and this new indicator, named eta, has shown more correlation with non-linear response. In fact, the eta indicator has improved the correlation with the collapse capacity by approximately 50 percent. The eta indicator can be defined as written in Eq. (2) [5].

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

$$\eta = 0.472 + 2.730\varepsilon_{Sa} - 2.247\varepsilon_{PGV} \tag{2}$$

where ε_{Sa} and ε_{PGV} are the observed spectral acceleration epsilon and the peak ground velocity epsilon, respectively.

3. The Eta-Based Conditional Mean Spectrum

The aim of the current research is to introduce the eta-based CMS as a new target spectrum for the record selection purposes. First, it is needed to define a target spectral acceleration value at a period of interest. The period of interest can be computed by modal analysis for a particular structure. Usually, the target period is chosen equal to the first mode period of vibration. The mean causal magnitude (M), the mean causal distance (R) and the mean causal epsilon can be obtained by disaggregation analysis based on the probabilistic seismic hazard analysis (PSHA) [9]. The mean predicted spectral acceleration and the corresponding standard deviation of logarithmic spectral acceleration can be computed using the existing ground motion prediction models e.g. CB08, used in Figure (1) [10]. Now, the CMS value in the target period can be calculated easily. The probability calculation shows that the epsilons in other periods are equal to the original epsilon value multiplied by the correlation coefficient between the two epsilons. The correlation coefficient can be obtained either by the Baker's prediction equation as a closed-form solution [11] or using the correlation based on a suitable subset of GMRs (e.g. from NGA database). GMRs used in this study are given in reference [12].

The target epsilon is needed for the conditional computation as well as the target eta, but the disaggregation analysis only provides the target epsilon. For this purpose, the target eta value had been normalized to the target epsilon value in Eq. (2). The target eta can now be considered to be equal to the target epsilon, which is one of the disaggregation results. The target peak ground velocity epsilon (ε_{PGV}) can be obtained as written in Eq. (3) by using Eq. (2). Substituting Eq. (1) and (3) into Eq. (2) can produce the conditional mean spectrum based on the eta indicator given in Eq. (4).

$$\varepsilon_{PGV}^{target} = \frac{1}{2.247}(1.730\varepsilon_{Sa}^{target} + 0.472) \tag{3}$$

$$Sa(T) = \exp\left(\mu_{\ln Sa} + \eta^{*}\sigma_{\ln Sa}\rho'_{\eta,\eta^{*}}\right) \tag{4}$$

A correlation model can be employed in order to find the ρ′ values in the above equation. Baker and Jayaram proposed a model for the correlation coefficients calculation between the two epsilon values [13] based on the Chiou and Youngs model [14]. This method is consistent enough with other ground motion prediction models with high level of accuracy. In the current study, all parameters including the epsilon values, the eta values and the correlation coefficients are computed based on the considered GMR database without using any closed-form solution. Figure (2) shows a contour of the correlation coefficient between each two arbitrary epsilons or eta values, respectively. The period range is taken from 0.01 to 5 sec. The epsilon and the eta values at other periods can be calculated easily by multiplying the target value by the corresponding correlation coefficient value, which can be summarized in Eqs. (5) and (6). For comparison of the two correlation coefficients obtained by eta and epsilon values, a new correlation equation is defined in Eq. (7). This correlation equation expresses the only difference between CMS and E-CMS equations. In fact, the parameter ρ′ plays the same role as ρ in CMS equation, which makes the E-CMS easy to be implemented.

$$\varepsilon(T) = \varepsilon^{target} \times \rho(\varepsilon(T), \varepsilon(T^*)) \tag{5}$$

$$\eta(T) = \eta^{target} \times \rho(\eta(T), \eta(T^*)) \tag{6}$$

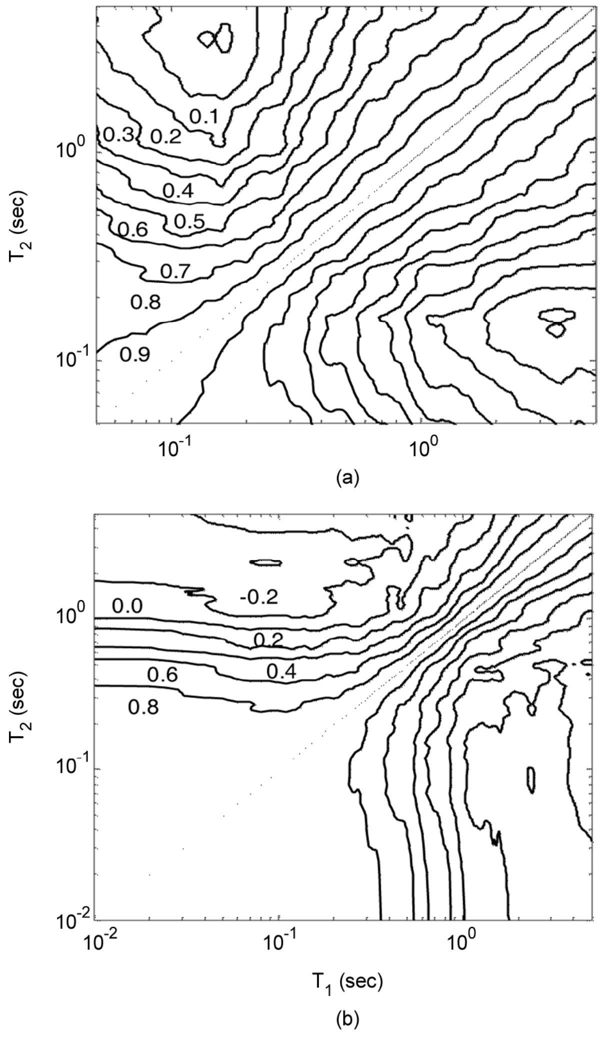

Figure 2. Empirical correlation coefficients: (a) for epsilon (b) for eta (T_1: Period of interest, T_2: Target period).

$$\rho'_{(\eta(T),\eta(T^*))} = \frac{\rho_{(\eta(T),\eta(T^*))} + 1.73}{2.730} \tag{7}$$

Finally, the epsilon-based CMS can be computed based on [3] and the eta-based CMS can be obtained by using Eq. (4). It is worth to emphasis that the peak ground velocity epsilon (ε_{PGV}) is a period independent parameter; hence, ε_{PGV} would be a constant value during a period range for a single record. This fact helps obtaining a simple predicting equation as expressed in Eq. (4).

In the current study, both CMS and E-CMS are calculated and the effect of the new eta indicator is investigated in the following simple example.

4. Comparing CMS and E-CMS Spectra by a Simple Example

A simple structure located in Riverside with a first-mode period of 0.1 second was assumed, and 1% probability in 100 years was considered as a given hazard level, corresponding to 1E-04 annual probability of exceedance. The Abrahamson-Silva 1997 attenuation model [15] is employed to calculate the median predicted spectral acceleration. The mean casual magnitude, the mean casual distance and the mean casual epsilon are needed to calculate the target design spectra, which can be obtained by using standard disaggregation analysis. For this purpose, the U.S. Geological Survey (USGS) tool (interactive disaggregation updated in 2009) is employed to explore real values instead of a simple assumption [16]. Figure (3) shows the disaggregation distribution of magnitudes, distances and epsilons that will cause the occurrence of Sa(0.1 sec) = 2.04 g at this site. The obtained epsilon from disaggregation is assumed equal to the target epsilon and the other epsilon values at other periods can be determined as well. The uniform hazard spectrum is calculated by using the predicted median added by the standard deviation that is multiplied by the target epsilon. CMS and E-CMS can be derived similarly by consideration of the correlation term in Eq. (1) and Eq. (4). The NRC spectrum is obtained by scaling the median response spectrum shape at 7.5 Hz using Sa5-10 scale factor. The calculation of UHS by using the AS97 attenuation relationship results in the occurrence of Sa(0.1 sec) = 1.7 g at this site in which it is the case for the CMS and E-CMS spectra as seen in Figure (4).

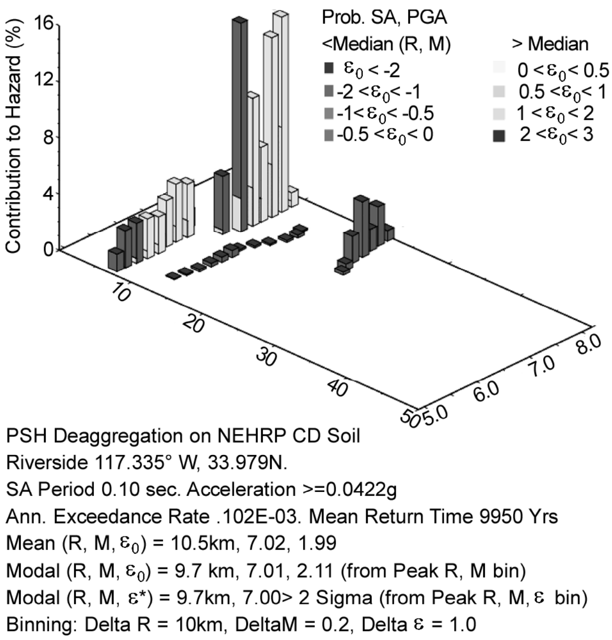

Figure 3. The PSHA disaggregation, obtained by USGS.

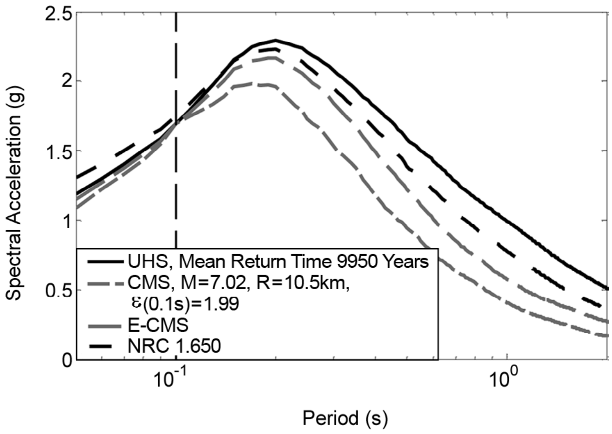

Figure 4. Comparison of the UHS, CMS, E-CMS, and NRC 1-165 standard spectra.

Figure (4) compares UHS with CMS, E-CMS, and NRC 1-165 standard spectra for the given site. As it was expected, the NRC procedure leads to a lower spectrum level compared with the conventional UHS. The most interesting finding is that both CMS and E-CMS show a significant reduction in comparison with NRC. It can be concluded that the current NRC is a conservative spectrum compared with the reasonable spectra e.g. CMS and E-CMS. Note that the same results can be achieved for different hazard levels since the observed difference is independent of the given Sa. In other words, the difference is sourced by the correlation term in Eqs. (1) and (4) and is not affected by spectral acceleration or a design factor.

Another arising issue is the significant difference between CMS and E-CMS as seen in Figure (4). Both CMS and E-CMS have a peak value at period of 0.1 second since the correlation coefficient is high near the target period. The correlation coefficients decrease in large and small periods but the reduction process is more significant in CMS from the target period in comparison with the E-CMS. This fact is also shown in Figure (5) where the parameter ρ' for eta and ρ for both epsilon and eta are compared. Note that Figure (5) is explaining the correlation values, and does not reflect the spectral acceleration terms, but this figure can justify the differences between CMS and E-CMS since CMS is based on ρ and E-CMS is based on ρ'.

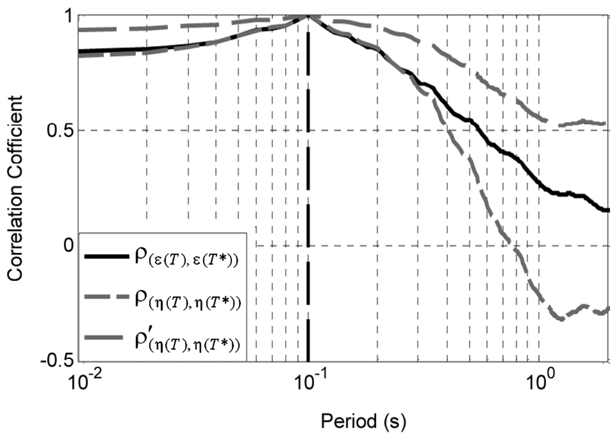

Figure 5. The correlation coefficients over a period range.

The correlation between the Eta indicator and the structural response is remarkable, which is a key logic for the robustness of E-CMS. This correlation is also observed in the conventional CMS [5]; however, it is less significant in the case of CMS compared with the case of E-CMS.

However, it is worth exploring this issue from different viewpoints in a more detailed study. As a concluding statement, authors emphasize that using E-CMS as an alternative to the current nuclear standard spectrum e.g. NRC-165, leads to a more realistic assessment of the structural response.

5. Conclusion

For the GMRs selection in non-linear dynamic analysis, different target spectra have been introduced by researchers. The UHS was shown to be a conservative target. A new target spectrum, named E-CMS, has been introduced in this paper that uses the eta indicator advantages. The E-CMS seems leading to reduction of the bias in the estimation of the structural seismic response since the correlation of eta and the structural response is greater than the correlation between the conventional epsilon and the structural response. It is shown that the E-CMS amplitude is greater than the CMS, in short or long periods depends on the considered structure, which means that the conventional CMS can underestimate the structural response. Based on the obtained results, the authors believe that the eta-based CMS can be a more realistic alternative for the nuclear standard spectrum e.g. NRC 1.165.

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