The Conditional Mean Spectrum Based on Eta Indicator

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SUMMARY:
The Conditional Mean Spectrum (CMS) based on a new spectral shape indicator, named Eta, has been introduced in this paper. The Eta parameter is an indicator which can predict the spectral shape effects as well as the nonlinear structural response. The correlation coefficients between Eta values in different spectral periods have been employed to define the Eta based Conditional Mean Spectrum (E-CMS) and to introduce the corresponding closed-form formula. The formulation format is fully compatible with the existing CMS definition which makes the E-CMS quite easy to be implemented.

Keywords: Uniform Hazard Spectrum, Epsilon indicator, Eta indicator, Conditional Mean Spectrum.

1. INTRODUCTION

The Pacific Earthquake Engineering Research (PEER) centre framework is a popular methodology in order to estimate the Mean Annual Frequency (MAF) of exceedance of a particular Limit State (LS) (e.g. FEMA-350 2000) as expressed mathematically in Equation (1) (Shoma 2000).

$$MAF(LS) = \int_{IM} \int_{EDP} G(LS|EDP).\left|dG(EDP|IM)\right|.\left|d\lambda(IM)\right| \quad (1)$$

where EDP is the engineering demand parameter, e.g. maximum inter story drift ratio; *IM* is the intensity measure e.g. Spectral acceleration (*Sa*) at the first period of structure and a given damping ratio; *G(LS|EDP)* denotes the probability of exceeding LS conditioned on the value of EDP and *G(EDP|IM)* denotes the probability of exceeding EDP conditioned on the value of *IM*. One of the key points in calculation of Equation (1) is the inherent assumption about the dependency of EDP only on the chosen *IM*. If there is dependency of EDP on any other indicator (except the chosen *IM*), then, Equation (1) results in a biased estimate of the MAF. Hence the sufficient *IM* is the *IM* which can represent the EDP without any dependency on other variables e.g. magnitude, distance and etc. On the other hand the spectral acceleration at the first period of structure, $S_a(T_1)$, has been commonly used as *IM* in most of the past researches (Baker and Cornell 2006). Design codes use a suitable *Sa*-based target spectrum to facilitate Ground Motion Record (GMR) selection approach and finally use those GMRs as input to dynamic analysis (ASCE7-5 2005). The Uniform Hazard Spectrum (UHS) is commonly considered to be as a target in the most of design codes and guidelines. This spectrum is developed by performing Probabilistic Seismic Hazard Analysis (PSHA) calculations (Kramer 1996) for spectral accelerations at a range of periods. Then, for a given rate of exceedance (e.g. 2% in 50 years) and for each period, the spectral acceleration amplitude corresponding to that rate is extracted. Those spectral acceleration values are then plotted versus their periods, which results in formation of UHS target spectrum. As every ordinate of the obtained target spectrum has an equal rate of being exceeded, this target is so-called uniform hazard spectrum. Here care should be taken that all ordinates are results of different earthquake events. Comparing UHS to a recorded ground motion shows why UHS is an unrealistic target. By considering the target period equal to one second, this fact is illustrated in Fig. 1 which shows the UHS for 2475 years return period versus an example ground motion (Chalfant Valley event) by using CB08 attenuation prediction model. Significant difference can be observed between the selected record spectrum and the UHS in other periods rather than 1 second. Since UHS in low period range is affected by strong ground motions in large distances and weak earthquakes have most contribution in UHS values in low frequencies, it cannot be a representative of a real single event. Many researchers have demonstrated that using UHS as a target spectrum can lead to highly conservative over-prediction of structural response under extreme ground motions, e.g. (McGuire 1995); hence, obtaining an accurate prediction of structural response has been the main concern in recent years.

Besides using *Sa*-based elastic spectrum, many approaches have been emerged to predict the response of a structure more precisely. It is proved that $S_a(T_1)$ is not sufficient enough specially when applied to the long-period buildings (Shoma 1999), the structures with high levels of nonlinearity (Shoma 1999) or in the near source regions (Luco 2002; Luco 2007). To deal with this problem, some researchers attempted to introduce new *IMs* which are more sufficient than $S_a(T_1)$ (Tothong 2007). Despite of the *IM* sufficiency, the attenuation model availability plays an important role in this subject which makes many of the new proposed *IMs* inapplicable. Another approach is to use the conventional $S_a(T_1)$ as *IM* with additional criteria to avoid bias in calculation of Equation (1). For example it is shown that the records which have approximately the same Epsilon (Baker 2006) can be employed with the conventional $S_a(T_1)$ to increase the *IM* sufficiency (Baker 2005). The Epsilon is defined with details in the next section. This advantage was also employed to propose a new design spectrum which is called Conditional Mean Spectrum (CMS) (Baker 2011). The CMS, which has been recently introduced to increase $S_a(T_1)$ sufficiency and decrease the UHS disadvantages, uses the advantages of the Epsilon as a spectral shape indicator (Baker 2006). 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 which would be exactly equal to the target value (*Sa* in UHS) is located on the target period which is usually the natural period of the considered structure. In fact CMS has a peak at the target period and decays towards the median spectrum in other periods based on a correlation model. In other words the correlation between the spectral acceleration values which does not have any contribution in UHS, is taken here into account and finally CMS has more realistic interpretation against UHS for a real event. The discussed advantages show that CMS can be a suitable tool for GMR selection because the current target provides a wide range of records that do not necessarily have appropriate magnitude, distance and Epsilon.

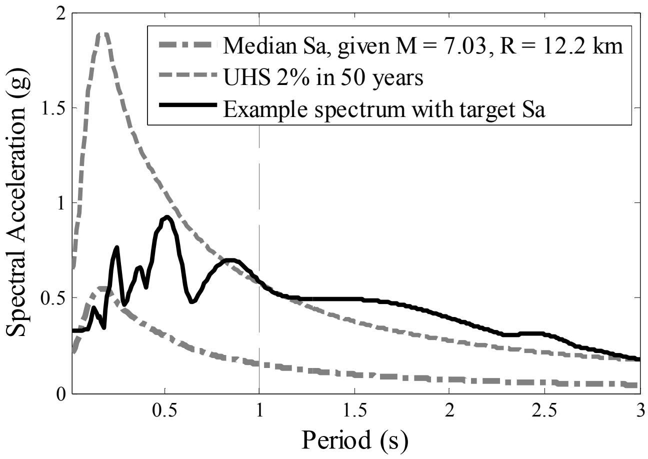

Figure 1. Median predicted spectrum having *M=7.03* and *R=12.2* km. UHS for 2 % probability of exceedance in 50 years. The example spectrum is the Newhall-W Pico Canyon Rd with *M=6.7* recorded from Northridge event (PEER 2010).

The spectral acceleration is the only intensity measure which was employed in the development of CMS. An alternative indicator as a more reliable predictor of non-linear response of structures was proposed by Mousavi et al. which was termed Eta (Mousavi 2011). They have shown that a simple linear combination of intensity measure Epsilons can result in more robust prediction of non-linear structural response as well as the spectral shape effects. In addition to the spectral acceleration, the Peak Ground Velocity (PGV) was also employed as *IMs* in the prediction of new spectral shape indicator.

A new target conditional mean spectrum is presented in this paper which employs 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 at the period of interest with considering new correlation model that is based on new spectral shape indicator. It is worth emphasising that the corresponding developed formulation format is fully compatible with the existing CMS definition which makes the E-CMS quite easy to be implemented.

2. REVIEW ON EPSILON AND ETA AS PREDICTORS OF LINEAR SPECTRAL SHAPE

Recent studies have shown that the spectral shape has an important effect on the response of higher modes of structures as well as on its non-linear behaviour (Baker 2005). The spectral shape was identified by Baker and Cornell (Baker 2006). For a given intensity measure, the Epsilon indicator measures the deviation of a given *IM* for a ground motion as recorded from the geometric mean *IM* computed from a ground motion prediction model. In other words Epsilon is the difference between the natural logarithms of two *IMs* normalized by the standard deviation of *IM* obtained from an attenuation model. This introduction to epsilon indicator results in values having zero mean and unit standard deviation. The epsilon indicator can be formulated in mathematical relationship as written in Equation (2).

$$\varepsilon_{IM} = \frac{\ln(IM) - \mu_{\ln(IM)}}{\sigma_{\ln(IM)}} \tag{2}$$

where *IM* is the intensity measure for a given record; $\sigma_{ln(IM)}$ and $\mu_{ln(IM)}$ are, respectively, the mean and the standard deviation of the intensity measure obtained from a specific ground motion prediction model (e.g. Abrahamson 1997). The discussed intensity measure can be chosen as (pseudo) spectral acceleration at the natural period of structure and a specific damping ratio e.g. $Sa(T_1,5\%)$. $Sa(T_1,5\%)$ is used because majority of hazard curves are available in terms of spectral acceleration as a result of probabilistic seismic hazard analysis from a well-known ground motion database. Ground Motion Prediction Equations (GMPEs), giving ground motion intensity measures such as peak ground acceleration or response spectra as a function of magnitude and distance are essential parts in the analysis of seismic hazard. These equations are typically developed using a regression of recorded GMR amplitude versus magnitude, distance and other seismic parameters.

Baker and Cornell have shown the importance of Epsilon as a spectral shape indicator (Baker 2005). They concluded that selected records with the same *Sa* values at the target period but different Epsilon values can result in different inelastic structural response. This fact is because the Epsilon value works as a proxy over average spectral shape. Therefore the average spectral shape for negative and positive Epsilon values would be different. Thus the Epsilon indicator can be taken as a robust predictor of the spectral shape and not being influenced by record linear scaling procedure (Baker 2005). As a result selection of GMRs, which are compatible with the target Epsilon, is a reasonable approach to increase the sufficiency of spectral acceleration (Baker 2005). The target Epsilon for a given site can be calculated from a standard disaggregation analysis (Bazzurro 1999). The obtained target Epsilon specifies the objective level of hazard and consequently corresponds to a particular spectral shape. Therefore such summarized advantages are enough to identify Epsilon as an applicable indicator in the structural analysis and design.

As the current common predictor of the spectral shape (e.g. Epsilon) uses only one intensity measure, the Epsilon has been investigated more precisely and an alternative indicator of the spectral shape, named Eta, was proposed by Mousavi et al. which leads to better prediction of the linear spectral shape as well as the non-linear structural response (Mousavi 2011). The concept of the new spectral shape indicator is formed based on employing more *IMs* associated with *Sa*. New spectral shape indicator was derived in order to increase the correlation between Eta and non-linear response of single degree of freedom structures. A simple introduction to the Eta can be a linear combination of *IM* Epsilons composed of peak ground motions and spectral ordinates. The coefficients of *IM* epsilons were determined through an optimization problem using Genetic Algorithm (GA) (Goldberg 1989) in such a way that the average correlation between the indicator and the non-linear response of 84 SDOF with different periods and ductility becomes maximum. The Eta indicator improved the average correlation with collapse capacity by approximately 50 percent. Therefore the Eta has shown that it can be a better predictor of structural non-linear response. It was seen that a combination of PGV and *Sa* Epsilons resulted in the same correlation as employing all *IM* Epsilons. The Eta indicator can be expressed as written in Equation (3).

$$\eta = 0.472 + 2.730\varepsilon_{Sa} - 2.247\varepsilon_{PGV} \tag{3}$$

where ε_{Sa} and ε_{PGV} are, respectively, the observed spectral acceleration Epsilon and the peak ground velocity Epsilon which can be obtained using Equation (2) by replacing *IM* by *Sa* and PGV. For clarify of exposition 267 GMR horizontal components were employed as described in (Baker 2005). The mean spectrum based on *N* records which have the highest/lowest Epsilon values and the highest/lowest Eta values are shown in Fig. 2 and compared with the mean spectrum based on all GMRs. Both of Epsilon and Eta are obviously strong spectral shape indicators as seen in Fig. 2. However the difference between the mean spectral shape based on *N=8* and *N=50* is not significant in the case of Eta while it is meaningful for the case of Epsilon. In other words Eta can predict the spectral shape with less numbers of GMRs which means it is a better indicator of spectral shape effects in comparison with the conventional Epsilon in the record selection procedures. In addition, as the Eta indicator has shown greater average correlation with the collapse capacity in comparison with the conventional Epsilon, it is reasonable to claim that the potential of the new proposed Eta is greater than the convenient Epsilon in non-linear response prediction. This issue is more discussed in details in the following section.

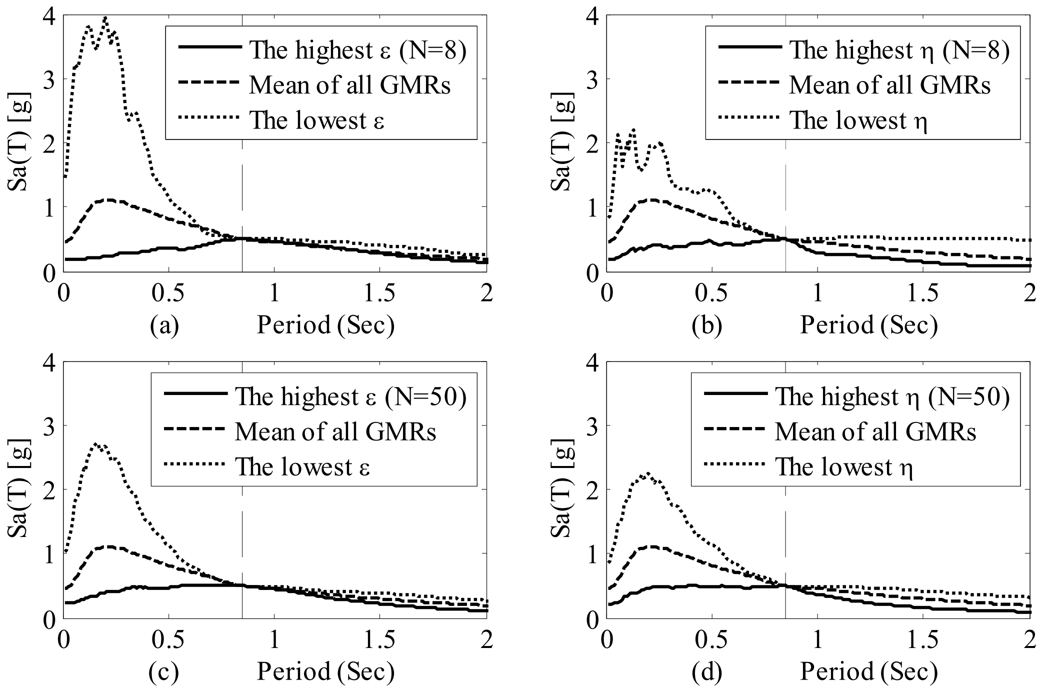

Figure 2. Comparison of the mean spectrum based on 534 GMRs with (a) the mean spectrum based on *N=8* highest/lowest Epsilon, (b) the mean spectrum based on N=8 highest/lowest Eta(PEER), (c) the mean spectrum based on *N=50* highest/lowest Epsilon, (d) the mean spectrum based on *N=50* highest/lowest Eta.

Note that ε_{PGV} is not a function of period and is constant for all spectral values. This characteristic allows us to arrange a closed form formula for the E-CMS in the following sections. Here care should be taken that the older Ground Motion Prediction Models (GMPMs) only provide predicted *Sa* and the corresponding logarithmic standard deviation, e.g. (Abrahamson 1997; Campbell 1997). Therefore employing a suitable GMPM is an essential part in our study. For this purpose CB08 attenuation model (Campbell and Bozorgnia 2008) was used since Eta is originally obtained based on this model in addition to the ability of PGV predictions. Also note that the Eta equation was derived in such a way to have the same value as the target Epsilon that can be achieved by hazard disaggregation analysis. By using Equation (3), to calculate Eta value for each ground motion record, the same target Eta as the target Epsilon can be used in the procedure.

3. ETA-BASED CONDITIONAL MEAN SPECTRUM

The aim of the current research is to introduce the Eta-based conditional mean spectrum as a new target spectrum for the record selection purposes. First it is essential 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 (T^*). 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 ($\varepsilon_{Sa(T^*)}$) can be obtained by disaggregation analysis, e.g. from (USGS) based on the probabilistic seismic hazard analysis. The mean predicted spectral acceleration (μ_{lnSa}) and the corresponding standard deviation of the logarithmic spectral acceleration (σ_{lnSa}) can be computed using existing ground motion prediction models (i.e. CB08 in this paper).The probability calculation shows that the Epsilon values (*Sa*-based) at other periods are equal to the original Epsilon value multiply by the correlation coefficient between two Epsilon values as written in Equation (4). Consequently the CMS value at the target period can be calculated easily by rearranging Equation (2) which is written in Equation (5) (Baker 2011).

$$\varepsilon_{Sa(T)} = \rho_{\varepsilon(T),\varepsilon(T^*)}\varepsilon_{Sa(T^*)} \tag{4}$$

$$Sa(T) = \exp(\mu_{\ln Sa(T)} + \sigma_{\ln Sa(T)}\varepsilon_{Sa(T)}) = \exp(\mu_{\ln Sa(T)} + \sigma_{\ln Sa(T)}\rho_{\varepsilon(T),\varepsilon(T^*)}\varepsilon_{Sa(T^*)}) \tag{5}$$

The correlation coefficient can be obtained by Baker's prediction equation as a close form solution (Baker 2006; Baker 2008), or using the correlation based on a suitable subset of GMRs (e.g. from NGA database). The GMRs which were used in this study can be obtained in (Baker 2005).

For the E-CMS computation, the target Epsilon and the target Eta are needed. However the disaggregation analysis only provides the target Epsilon. This is a reason why the Eta equation had been normalized to the target Epsilon value in Equation (3) (Mousavi 2011). The target Eta can now be considered to be equal to the target Epsilon which is one of the disaggregation results ($\eta^*=\varepsilon_{Sa(T^*)}$). The target peak ground velocity (ε_{PGV}) can be obtained as written in Equation (6) by using Equation (3) and considering the equality of the target Epsilon ($\varepsilon_{Sa(T^*)}$) with the target Eta (η^*).

$$\varepsilon_{PGV} = \frac{1}{2.247}(0.472 + 1.730\varepsilon_{Sa(T^*)}) \tag{6}$$

Again note that the peak ground velocity Epsilon is a period independent parameter and is constant over the whole period range. Substituting Equation (2) and (6) into Equation (3), can produce the conditional mean spectrum based on Eta indicator as written in Equation (7). The Eta at other periods is predicted using correlation approach according to Equation (4) replacing η instead of ε i.e. $\eta(T) = \rho_{\eta(T),\eta(T^*)}\eta(T^*)$.

$$Sa(T) = \exp(\mu_{\ln Sa(T)} + \frac{\eta^* \sigma_{\ln Sa(T)}(\rho_{(\eta(T),\eta(T^*))} + 1.730)}{2.730}) \qquad (7)$$

where $\rho_{(\eta(T),\eta(T^*))}$ is the correlation coefficient between Eta in an arbitrary period (T) and the target period (T^*). It is obvious that Eta in an arbitrary period (T) is equal to Eta in the target period multiply by the correlation coefficient between two corresponding Eta values. It is also clear that the target *Sa* value in E-CMS is equal to CMS value in target period i.e. replacing ρ value by one. In other words both ε and η based spectra are conditioned on T^*. It is worth noting that the general similarity between Equation (5) and Equation (7) allows the final simple formulation for E-CMS which is quite similar to the conventional CMS formulation. This issue is discussed in the following sections. In current study, CMS and E-CMS are calculated in the following sections.

3.1. Example: Deriving the E-CMS Spectrum

A simple structure with a first-mode period of 1 second and 5% critical damping ratio was assumed, and 2% probability in 50 years was considered as a given hazard level. The Shear wave velocity and other seismic parameters are given as:

- Shear wave velocity = 760 (m/s).
- Depth to the top of co-seismic rupture = 0 (km).
- Rake angle = 35 (degree).
- Dip = 90 (degree).
- Depth to the 2.5km/s shear wave velocity horizon = 2.5 (km).

The median predicted spectral acceleration is equal to 0.17g and the standard deviation is equal to 0.66 in the target period (*1sec*) which were obtained by using CB08 attenuation model. The mean causal values from disaggregation analysis are required. Therefore the following mean values were assumed for an ideal site:

- Mean causal magnitude: 7.0
- Mean causal distance: 10 km
- Mean causal Epsilon: 1.4

As the obtained Epsilon from disaggregation is assumed to be equal to the target Epsilon, the other Epsilon values at other periods can be determined as well. For this purpose a linear regression (a correlation model) can be employed. Baker and Jayaram proposed a model for correlation coefficients calculation between two Epsilon values based on the Chiou and Youngs model (Baker and Jayaram 2008). This method is consistent enough with other ground motion prediction models with high level of accuracy. In the current study all parameters including Epsilon values, Eta values and the correlation coefficients were computed based on the considered GMR database without using any close form solution. Figs. 3(a) and 3(b) show contours of the correlation coefficient between each two arbitrary Epsilon and Eta values respectively. The period range is taken from 0.01 to 5 sec.

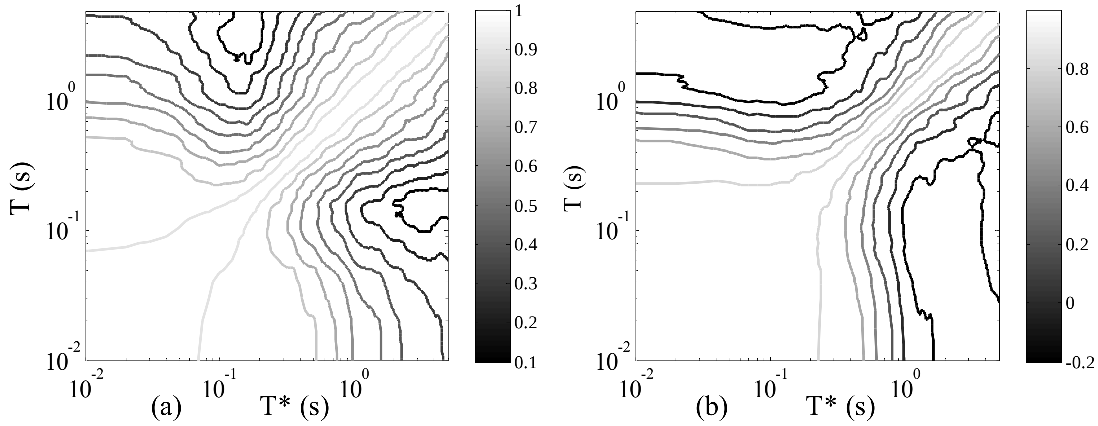

Figure 3. Empirical correlation coefficients based on the considered GMR database. (a) For Epsilon. (b) For Eta. (T: Period of interest, T*: Target period)

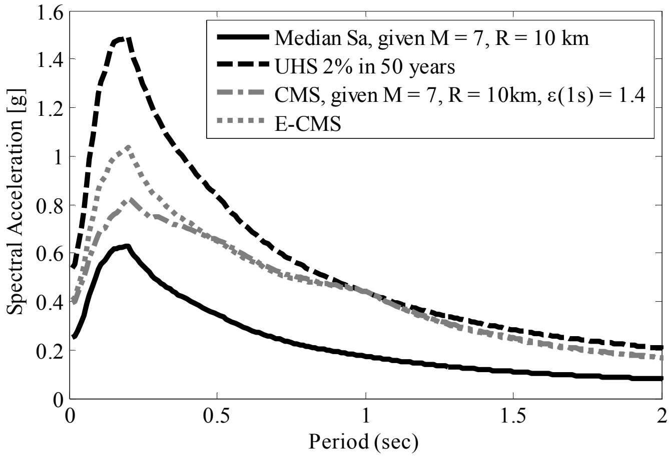

Figure 4. UHS, Epsilon-based and Eta-based conditional mean spectrum for an ideal site, given M=7, R=10 km, ε=1.4.

Finally the Epsilon-based conditional mean spectrum can be computed based on Equation (5) (Baker 2011) and the Eta-based conditional mean spectrum can be obtained by using Equation (7). Fig. 4 compares the CMS, E-CMS, median and the UHS spectra for the given simple example.

In the long period values, which is an essential part in the non-linear response of structure as seen in Fig. 4, CMS and E-CMS are matched well; hence, the non-linear response seems to be as effective as both CMS and E-CMS can produce. A noticeable difference between CMS and E-CMS is apparent in the low period range which can influence the higher modes of structures. In other words the multi degree of freedom structures are good candidates to be employed for investigation of the discussed difference whereas the SDOF structures may not show that effect. Both CMS and E-CMS have a peak at period of 1 second since the correlation coefficient is unit at the target period. The correlation coefficients decrease at large and small periods but the reduction process is more rapid in the CMS case in comparison with the Eta case. In other words, E-CMS values in smaller periods are more than the CMS values. This fact can be more investigated if Equation (7) being rearranged to produce Equation (8) and Equation (9).

$$Sa(T) = \exp(\mu_{\ln Sa(T)} + \eta^* \sigma_{\ln Sa(T)} \rho'_{(\eta(T),\eta(T^*))}) \quad (8)$$

$$\rho'_{(\eta(T),\eta(T^*))} = \frac{\rho_{(\eta(T),\eta(T^*))} + 1.73}{2.730} \quad (9)$$

This fact is shown in Fig. 5 where the parameter ρ′ for Eta and ρ for both Epsilon and Eta are compared. Note that Fig. 5 is explaining the correlation values, and do 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′. Fig. 5 shows that the difference between two important spectra is beginning from approximately period of 0.5 sec to lower periods where this difference is present in Fig. 5 too. It can be seen in Fig. 5 that the Eta correlation values are lower than the Epsilon correlation values. The lower period bound is related to the response of higher modes of vibration. As an important result the CMS is underestimating Sa values against E-CMS for short period structures as well as the medium period structures with strong higher modes effects.

Since the correlation between Eta and the structural response is higher than the corresponding correlation between Epsilon and the structural response [15], it can be tentatively claimed that the E-CMS is more realistic spectrum than the conventional CMS spectrum. The target period is taken to be equal to the first-mode period of vibration which cannot be a reliable target, because the sensitivity of the structure is not discussed. Therefore, an effort should be made to find the critical target period. Accordingly the record selection can be repeated by different CMS or E-CMS. Separate sets of selected records based on different CMS or E-CMS can be used for analysis and the effect of choosing the target period can be investigated more precisely. Finally it can be inferred that which target period is more sensitive, and it can be chosen as an appropriate target period. Fig. 6 shows two E-CMS cases computed by different target periods.

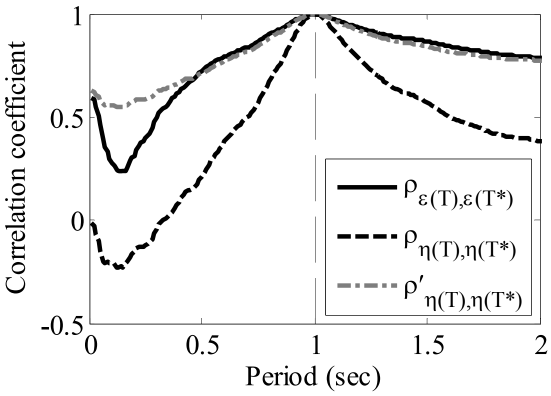

Figure 5. The correlation coefficients over a period range.

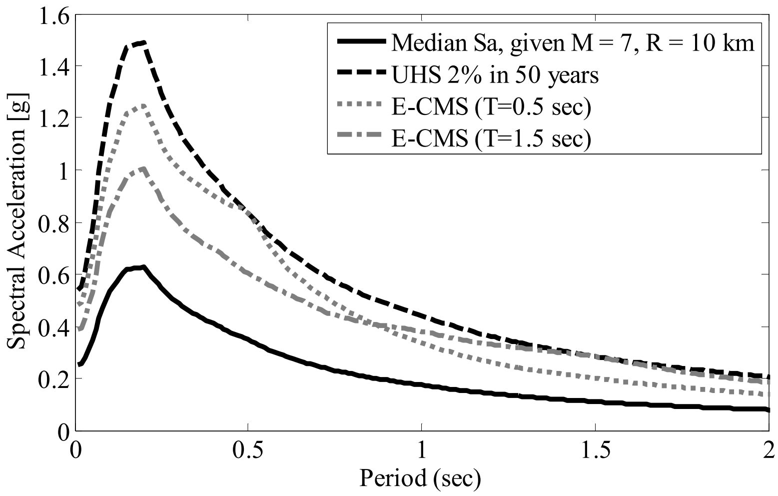

Figure 6. Eta-based conditional mean spectra in different periods for an equal probability of exceedance 2% in 50 years. (T*=0.5 sec & T*=1.5 sec).

4. CONCLUSION

A new target spectrum, named E-CMS, has been introduced in this paper which uses the advantages of a new elastic spectral shape indicator that is termed Eta. Eta indicator has the advantage of having a high level of correlation with the structural nonlinear response as well as the elastic spectral shape. The existing CMS formulation has been modified to produce the E-CMS format. The new proposed formulation is fully compatible with the existing CMS format which makes it easy for implementation in seismic analysis. It was shown that the E-CMS amplitude is usually greater than the CMS, in short period range, which means that the conventional CMS can underestimate the structural response for midrise structures.

REFERENCES

Abrahamson, N. A. and Silva, W.J. (1997). Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismological Research Letters* **68 (1)**: 94-126.

ASCE7-5 (2005). Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers/Structural Engineering Institute, Reston ,VA.

Baker, J. W. (2005). Vector-valued ground motion intensity measures for probabilistic seismic demand analysis. Report #150, John A.Blume Earthquake Engineering Center, Stanford.

Baker, J. W. (2011). Conditional Mean Spectrum: Tool for Ground-Motion Selection. *Journal of Structural Engineering* **137**(3): 322-331.

Baker, J. W. and Cornell C. A. (2006). Which Spectral Acceleration Are You Using? *Earthquake Spectra* **22**(2): 293-312.

Baker, J. W. and Cornell C. A. (2005). A vector-valued ground motion intensity measure consisting of spectral acceleration and epsilon. *Earthquake Engineering & Structural Dynamics* **34**(10): 1193-1217.

Baker, J. W. and Cornell C. A. (2006). Correlation of Response Spectral Values for Multicomponent Ground Motions. *Bulletin of the Seismological Society of America* **96**(1): 215-227.

Baker, J. W. and Cornell C. A. (2006). Spectral shape, epsilon and record selection. *Earthquake Engineering & Structural Dynamics* **35**(9): 1077-1095.

Baker, J. W. and Jayaram, N. (2008). Correlation of spectral acceleration values from NGA ground motion models. *Earthquake Spectra* **24(1)**: 299-317.

Bazzurro, P. and Cornell, C.A. (1999). Disaggregation of seismic hazard. *Bulletin of the Seismological Society of America* **89**(2): 501-520.

Campbell, K. W. (1997). Empirical Near-Source Attenuation Relationships for Horizontal and Vertical Components of Peak Ground Acceleration, Peak Ground Velocity, and Pseudo-Absolute Acceleration Response Spectra. *Seismological Research Letters* **68**(1): 154-179.

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 10 s. *Earthquake Spectra* **24**(1): 139-171.

FEMA-350 (2000). Recommended seismic design criteria for new steel moment-frame buildings. SAC Joint Venture, Federal Emergency Management Agency, Washington, DC.

Goldberg, D. (1989). Genetic Algorithms in Search, Optimization, and Machine Learning, Addison-Wesley: Reading, MA.

Kramer, S. L. (1996). Geotechnical earthquake engineering, Prentice Hall, Upper Saddle River, N.J.

Luco, N. (2002). Probabilistic seismic demand analysis, SMRF connection fractures, and near-source effects. Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA; 260pp. http://www.stanford.edu/group/rms/ (accessed 05/31/2006).

Luco, N. and Cornell, CA. (2007). Structure-specific scalar intensity measures for near-source and ordinary earthquake ground motions. *Earthquake Spectra* **23**(2): 357–392.

McGuire, R. (1995). Probabilistic seismic hazard analysis and design earthquakes: closing the loop. *Bulletin of the Seismological Society of America* **85**(5): 1275-1284.

Mousavi, M., Ghafory-Ashtiany, M. and Azarbakht, A. (2011). A new indicator of elastic spectral shape for the reliable selection of ground motion records. *Earthquake Engineering & Structural Dynamics*.

PEER. Pacific Earthquake Engineering Research Center, NGA Database, University of California, Berkeley, accessed 8/3/2010. from http://peer.berkeley.edu/ngawest/nga.

Shoma, N. (1999). Probabilistic seismic demand analysis of nonlinear structures. Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA; 320. http://www.stanford.edu/group/rms/ (accessed 05/31/2006).

Shoma, N. and Cornell, C.A. (2000). Structural seismic demand analysis: consideration of collapse. *8th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability,* paper **119**, Notre Dame; 1-6.

Tothong, P. and Luco, N. (2007). Probabilistic seismic demand analysis using advanced ground motion intensity measures. *Earthquake Engineering & Structural Dynamics* **36**: 1837-1860.

USGS. PSHA disaggregation. from https://geohazards.usgs.gov/deaggint/2008/.