Ground Motion Selection Criteria: CMS Approach

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***Abstract*—Conditional-Mean-Spectrum (CMS) approach is elaborated & defined as a tool for the ground motion selection with contrast to structural engineers. Earlier traditional approaches for selecting ground motion criteria and their evolution, have set a platform to generate 'Conditional Mean Spectrum (CMS)' approach, proposed by Jack W. Baker[1]. Uniform-Hazard spectrum based on 'PSHA' determines various numbers of deterministic response spectra while CMS deals the mean value of response spectra, which is conditioned on a single target spectral acceleration of the structure's fundamental period (T*). In this technical note, a brief discussion on, 'Why adopt CMS over UHS' is answered. Also steps to apply CMS approach is discussed with examples based on Indian site conditions.**

***Index Terms*—Conditional Mean Spectrum (CMS), Uniform Hazard Spectrum (UHS), Predicted Median Spectrum (PMS), Probabilistic Seismic Hazard Analysis (PSHA), Design hazard level, Design response spectra (DRS).**

I. INTRODUCTION

A Ground motion selection is always a tough task for a structural engineer. Although there are various ways to select the 'Ground Motion' including uniform-hazard-spectrum, but no method gives an accurate way, with respect to structural demand. Usually, structural engineers are interested to find structural demands parameters from an earthquake event, & so the basic aim is to obtain time series data of strong shaking (more magnitude; less rupture distance) that a particular location may experience in the future during an earthquake.

Conditional-mean-spectrum (CMS) approach is conditional upon natural period & the specified spectral acceleration at that period defined on the mean spectral value. Here, in this technical note we have discussed 'Conditional Mean Spectrum (CMS)' approach, with its merits, implication of methodology, limitations & future scope.

II. EVOLUTION OF 'CMS' APPROACH

Traditionally, we select ground motion based on seismological parameters such that, recordings with appropriate seismological properties i.e. magnitude & site-to-source distance. As per ASCE/SEI 7-10 (2010), 'Appropriate ground motions shall be selected from events having magnitudes, fault distance & source mechanism that are consistent with those that control the maximum considered earthquake'. Later on, it is realized that there are various problems associated with the selection of ground motion based on seismological parameters: (1) – It restricts the selection to a limited number of available ground motions (Baker 2015); (2) – Seismological parameters are not the key-things, which structural engineers need as these properties are indirect indicators of the demand (Haselton et al. 2009, Shome et al. 1998). After the failure of traditional approach of selecting ground motion selection criteria, several questions arise, i.e. "What structural engineers need?", "What data they want to extract from an earthquake?" and so the answer is 'To study the performance of building under high amplitude ground motion & their properties of interest from a ground motion are response spectra, duration etc. So, that they will acquire structural demand (i.e. spectral acceleration, peak ground acceleration) at fundamental (or dominating) frequency of the structure.

Recent approaches for selecting ground motion are based on 'time-series properties'. It requires seismological property information as their primary tool to determine time-series properties (i.e. response spectra) and then select ground motion based on their consistency with those 'time-series properties'. One of the recent and most popular approach is 'Uniform-Hazard-Spectrum' as a ground motion selection tool which is based on 'Probabilistic seismic hazard analysis'. In "PSHA", we determine a number of deterministic response spectra for a design hazard level. Recent studies show that there are also problems with 'Uniform Hazard Spectrum' as a selection tool for ground motion as it gives higher values of response spectra as compare to natural occurring response spectra (Baker at al. 2011). Also, when a structural engineer designs a structure, they are most likely interested in one single period of structure (usually fundamental period of a SDOF system) but 'UHS' deals with a number of periods of various earthquake events.

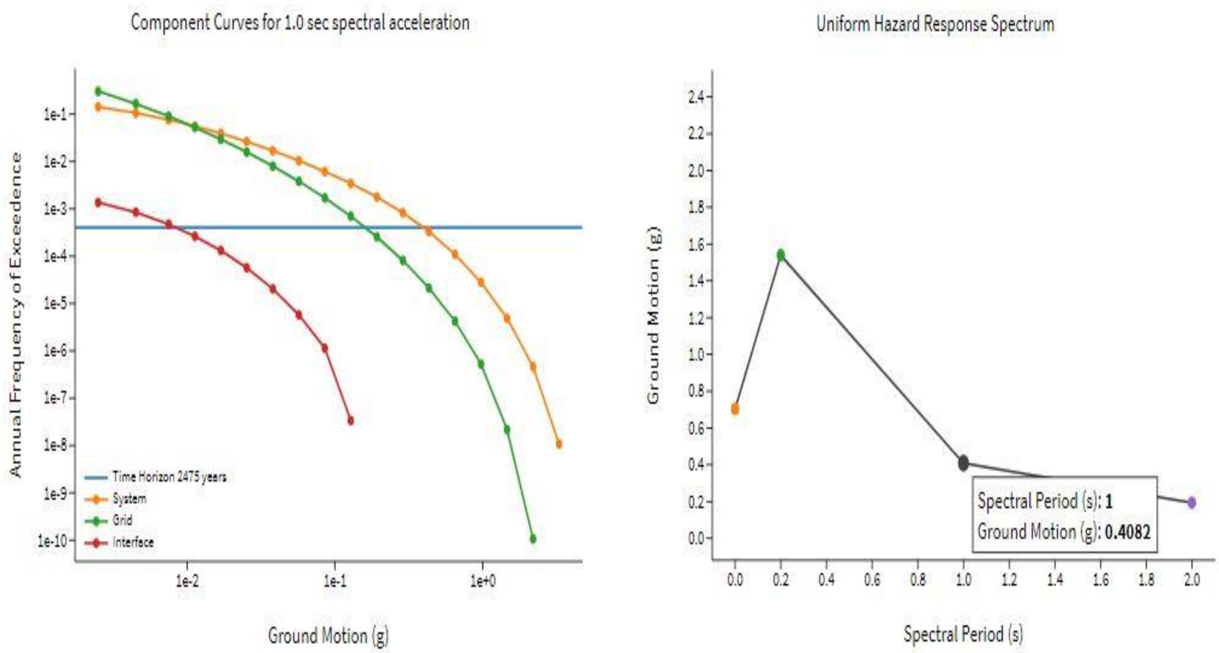

Figure 1: *(a) – Hazard curves* *(b) – Uniform Hazard Response Spectrum*

For a structure having time-period (T) located at 'Los-Angeles' (https://earthquake.usgs.gov).*

To overcome from all these selection tool problems, Baker suggested the approach of 'Conditional Mean Spectrum (CMS)', which is elaborated in next section.

III. GENERAL PROCEEDINGS OF CMS

The general steps for the construction of a 'Conditional Mean Spectrum (CMS)' are given as:

1. Find fundamental period of structure (T*) and corresponding spectral acceleration value. From 'PSHA' results, find the hazard level (design), that closely corresponds to the structure's target spectral acceleration at time period (T*). In the absence of uniform hazard spectrum (UHS), one can use the design spectra in building codes (as per Jack W. Baker). Usually this UHS or the design spectra given in building codes must represent the maximum considered earthquake (i.e. having 2% probability of exceedance in 50 years or a return period of 2475 years). In this technical note for demonstration, design spectra for response spectrum method is adopted from IS1893 (part-1):2016[6] as mentioned in figure (2).
2. Obtain Mean (M, R, ε) from a 'Probabilistic seismic hazard deaggregation' analysis, at that period and hazard level. In order to obtain the deaggregation analysis value, one can use "Uniform hazard tool, USGS" for the site located within the U.S. For sites located outside the region of U.S.A., one can use the scenario earthquake data[1] (M, R, ε) where ε is defined as the number of standard deviations by which spectral acceleration (SA) is larger or smaller than the predicted median spectrum[#].
3. Using Mean (M, R, ε) deterministically, one can use one or more attenuation relationships. In the present study, attenuation relationship based on "Abrahamson, Silva & Kamai (2014)". These attenuation relationships are used to develop a deterministic response spectrum that matches with the target spectral acceleration at time-period (T*).

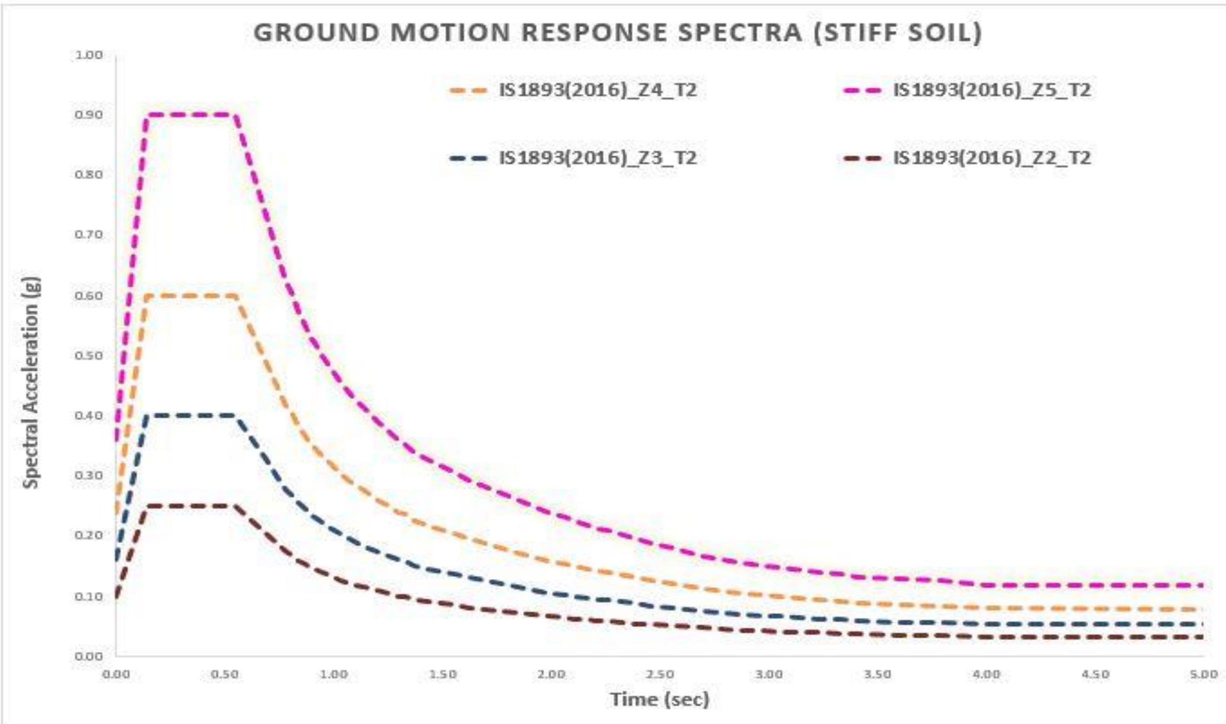

Figure 2: Design response spectra for stiff-soil site condition for all the four seismic zones as per IS1893(part-1):2016

4. Compute ln(SA) and corresponding $\sigma_{ln(SA)}$ for periods between 0.05 to 5 seconds. Also compute the mean correlated residual $\varepsilon(T_i)$ for all other periods, with the help of correlation factors. Such that:

→Conditional Mean → με[(Ti)/ε(T*)] = ρ(Ti, T*).ε(T*) ....…..…. (1)

where ρ (Ti, T*) is correlation coefficient and is given by -

- $\rho_{(Ti,\,T^*)} = \left[1 - \left[\cos\{\left(\frac{\pi}{2}\right) - (0.359 + \left(0.163 * I * ln\left(\frac{Tmin}{0.189}\right)\right\} * ln\left(\frac{Tmax}{Tmin}\right)\right]\right]$

Here, T_{min} is minimum value from T_i & T* (T_i – all time-period of structure except fundamental period of structure).

I = 1 (if T_{min}<0.189sec) else 0 (zero).

5. Compute the CMS: spectral-acceleration (SACMS) for all periods (Ti) between 0.05 to 5 seconds. Such as:

→ SA(CMS)(Ti) = exp [ln(SA)Ti + {με(Ti)/ε(T*)}* σln(SA)Ti}] ……..…. (2)

Furthermore, the 'ε-effect' is a real phenomenon where 'ε0' is defined as the number of standard-deviation above median of spectral acceleration for the fundamental period of structure & 'ε(Ti)' is defined for all other time period as:

→ε(Ti) = [ln(SA)Ti – μln SA (M, R, Ti)] / σln SA(Ti) ……….. (3)

6. After generating conditional mean spectrum along with its +/- spectrums, ground motions need to be filtered by using sum of squared error (SSE) concept as:

→ε(Ti) = [$ln(SA)_{Ti} - \mu_{ln\ SA\ (M,\ R,\ Ti)}$] / $\sigma_{ln\ SA(Ti)}$ ………… (4)

7. Next and final step is to select ground motion that will fit in between the curves of (CMS + σ) and (CMS – σ) by scaling the selected ground motions with least value of SSE, as:

→ Scale factor = $\sum_{n=1}^{\infty}(ln\ Sa(T_n) - \ln\ Sa_{CMS}(T_n))^2$ ………….. (5)

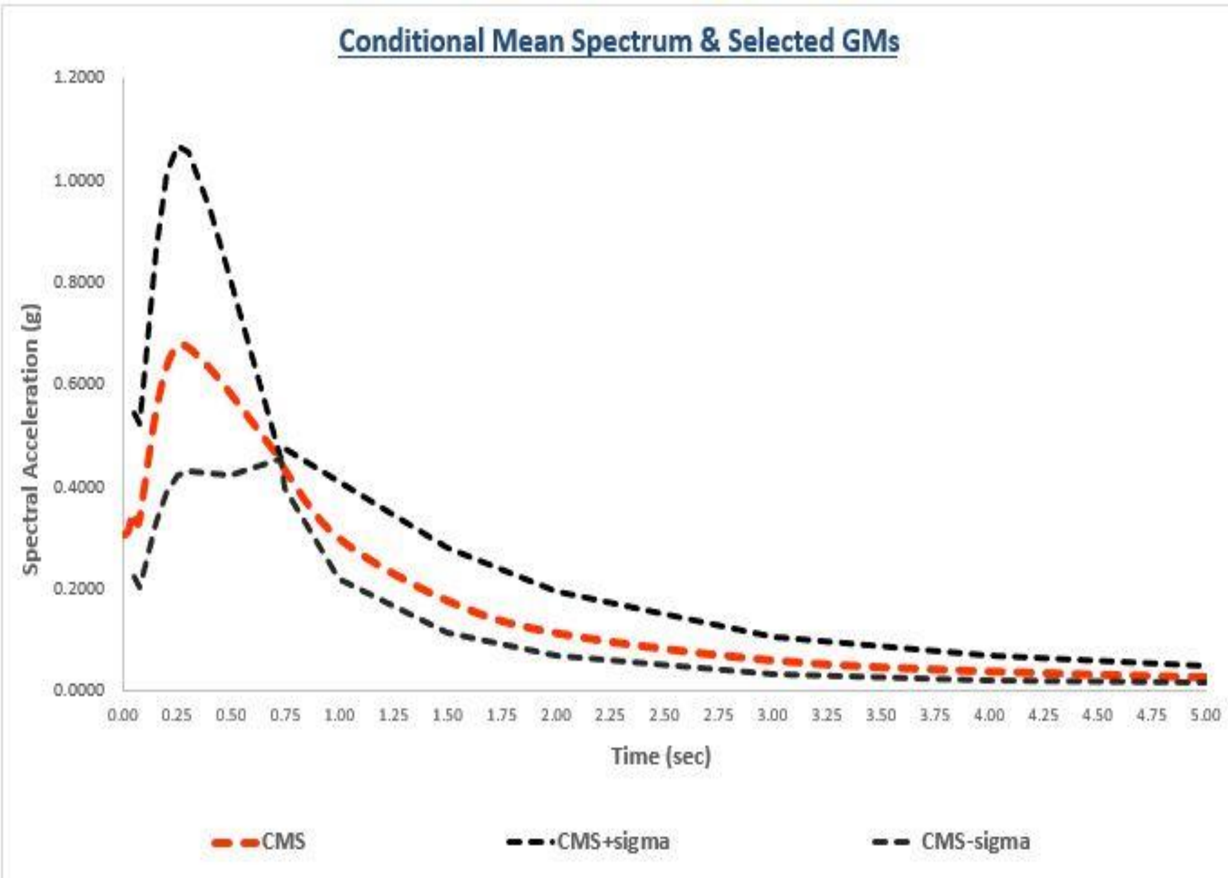

Figure 3: Typical 'Conditional-Mean-Spectrum' (red colour curve) with +/- standard deviation

IV. CONDITIONAL MEAN SPECTRUM v/s UNIFORM HAZARD SPECTRUM

The conditional mean spectrum is derived for a specific time-period of structure (T*) whereas uniform hazard spectrum is made from multiple magnitude/distance bins contributing to hazard for a particular geological site. The uniform hazard spectrum, as made from multiple hazards contributing data gives higher value of intensity measure (i.e. spectral acceleration), when compared to median spectra. This is the reason, the amplitudes obtained from conditional mean spectrum gives fewer conservative spectra when compared to uniform hazard spectra.

The 'CMS' approach was developed basically for site-specific structures and deals with the help of deaggregation and hazard spectrum data. The design spectra from a building code gives a representation of uniform hazard spectra (Baker et al. 2011). In the present study, a design spectra of building code (i.e. IS1893-part1:2016) is used at the place of uniform hazard spectra of a site having probability of exceedance of an earthquake event is 2% in 50 years (or return period of 2575 years). A conditional mean spectrum is drawn for a structure having conditional (i.e. fundamental period of structure) time-period of 0.73 seconds by following procedures discussed in previous section[#].

It can be evidently seen that conditional mean spectrum obtained for a structure (located at seismic zone 4 and founded on stiff-soil as per IS 1893-1:2016) at conditional time-period of 0.73 seconds gives much lower value of amplitudes, when compared to uniform hazard spectrum (or the design spectrum of a building code). The design spectrum for a building code, obtained from a uniform hazard spectrum is smoothened and modified curve at some instances. This is the reason, the conditional-mean-spectrum represented here is giving some higher values at time-period less than 0.5 seconds.

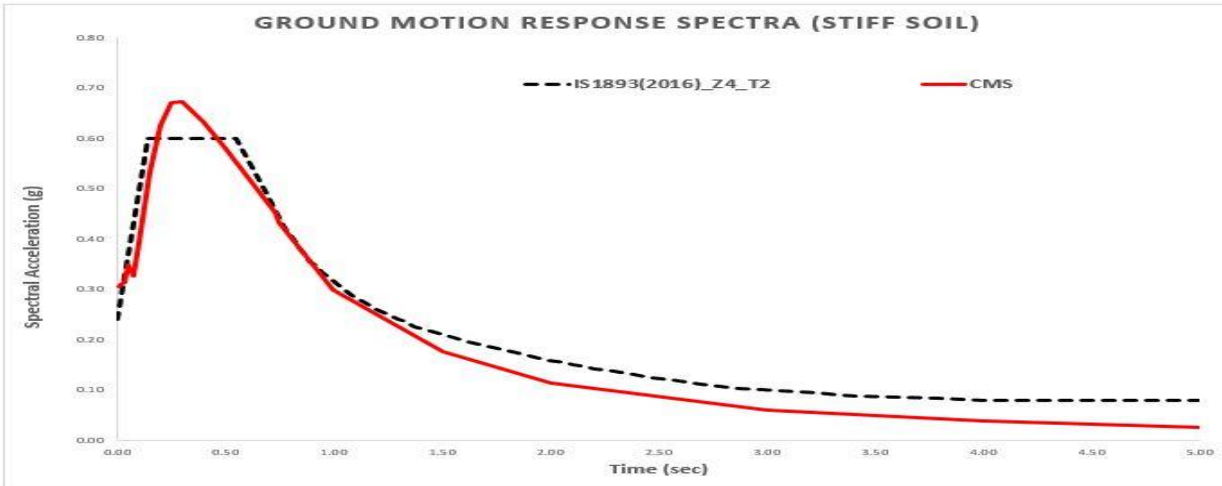

Figure 4: Conditional-mean-spectrum with v/s uniform hazard spectrum

Appendix#: HOW TO PLOT PREDICTED MEDIAN SPECTRUM

Although, the concept used in the present study to compare the uniform hazard spectrum with conditional-mean-spectrum is based on scenario earthquake data (M, R, ε) but here in this section it is demonstrated using both deaggregation map data and scenario earthquake data.

Using Deaggregation Map Data

Let us assume a structure, located in 'Los-Angeles (U.S.)', having fundamental time-period(T*) of 1 second. With the help of a site specific 'Uniform hazard response spectrum', one can determine it's spectral acceleration (Sa) value as 0.4082g. This spectral acceleration value comes from 'Uniform Hazard Spectrum Curve' which is obtained with the help of https://earthquake.usgs.gov. The corresponding hazard curves are given in figure (1). Now, with the same source, "https://earthquake.usgs.gov" values of Mean (M, R, ε) is obtained from a deaggregation plot. The values obtained are as: moment-magnitude (M) = 7.29; rupture-distance (R) = 15.30km; Residual (ε) = 1.48σ. These Mean values are deterministic attenuation relationships.

From these mean (M, R, ε) obtained from deaggregation details, one can plot 'Predicted Median Spectrum". Here, in this technical note, PMS is plotted with the help of "Abrahamson, Silva & Kamai (2014)" attenuation relationship. The PMS plotted is then compared to site-specific 'design response spectrum'. Here, one more plot is introduced which is the base step for CMS approach i.e. median values obtained from PMS plot is added to a multiple of standard deviation (in this case, that multiple, which is represented by N is equals to 1.48.

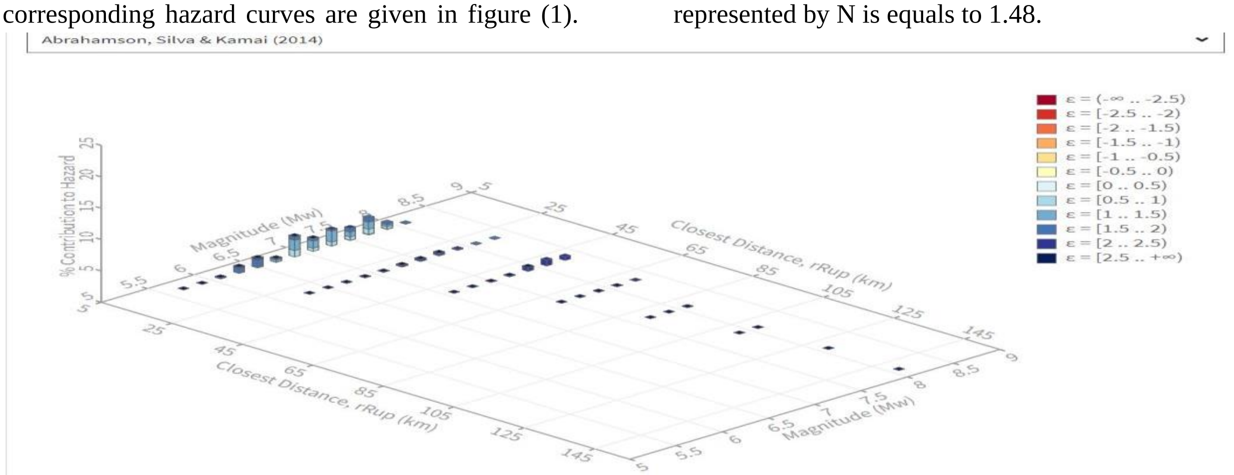

Figure 5: Probability Hazard Deaggregation map for the structure having (T*=1sec) at Los-Angeles (Courtesy: - https://earthquake.usgs.gov)

Deaggregation targets	Recovered targets	Totals
Return period: 2475 yrs **Exceedance rate:** 0.0004040404 yr^{-1} **1.0 s SA ground motion:** 0.40822285 g	**Return period:** 2708.18 yrs **Exceedance rate:** 0.00036925168 yr^{-1}	**Binned:** 20.24 % **Residual:** 0 % **Trace:** 0.07 %
Mean (for all sources)	**Mode (largest r-m bin)**	**Mode (largest ε_0 bin)**
r: 15.3 km **m:** 7.29 **ε_0:** 1.48 σ	**r:** 6.9 km **m:** 6.91 **ε_0:** 1.24 σ **Contribution:** 3.21 %	**r:** 9.57 km **m:** 7.28 **ε_0:** 1.14 σ **Contribution:** 1.74 %

Figure 6: Deaggregation data for the structure having (T*=1sec) at Los-Angeles (Courtesy: -https://earthquake.usgs.gov)

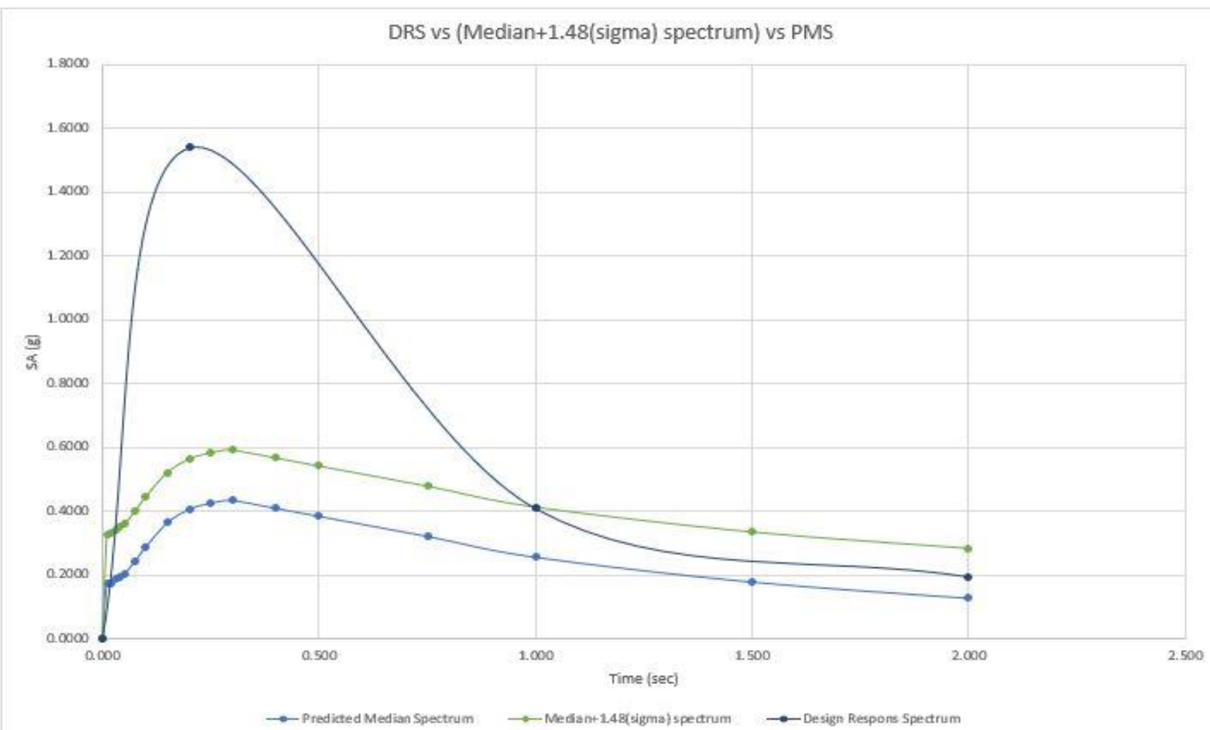

Figure 7: PMS v/s DRS v/s "Median + N.σ'' Plot

Using Scenario Earthquake Data

In this approach a set of ground motions are selected from "PEER ground motion database" to match the design spectra of a building code (Baker et al. 2015), which is the IS1893(part-1):2016 in the present study case. Considering structure is located at New-Delhi (seismic zone-4) and founded on stiff soil base. The fundamental time-period of the selected structure is 0.73 seconds, which is also its conditional time-period. Now, the ground motion record which matches exactly to the design spectra as per IS1893(part-1):2016 at the conditional period of structure is chosen here. It helps to get the scenario earthquake database in form of (M, R, ε). Then by the application of attenuation relationship given by Abrahamson, Silva & Kamai (2014), predicted median spectrum is obtained. The same concept is used in the present study to get the conditional mean spectrum.

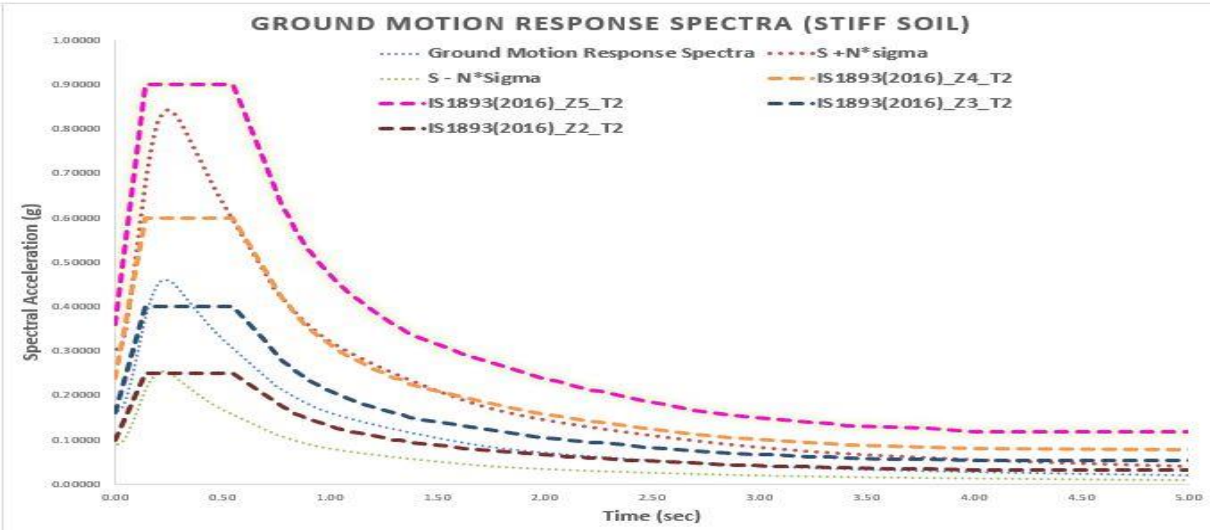

Figure 8: Predicted median spectrum with (+/-) standard deviation PMS curves v/s Design spectra of stiff-soil site condition for all seismic zones in India (IS 1893-1:2016)

V. CONCLUSION

The concept of CMS is quite new but in a less time it gains a lot of positive attention because it represents more accurate match with the corresponding real ground motion spectra. Although, there are some questions which are associated with that, i.e. "What to do if a structure has more than 1 dominating time period?". A specific solution to this problem is to CMS analysis at each time-period. There are certain limits associated with this ground motion selection tool, like:

- This tool is site-specific (& structure) and hence requires re-selection of ground motion with every change in structure or site-details.
- It is comparatively less conservative than its predecessor tools (i.e. UHS).
- It is based on "Probabilistic seismic hazard deaggregation' & availability of this factor marks question on CMS approach (especially in the case of developing countries i.e. India).

So, overall CMS is very useful & trendy tool in order to select more accurate ground motion for a structure. The CMS based on the mean response spectrum of a ground motion having the magnitude(M), rupture-distance (R) and residual-value (ε) that causes occurrence of a target spectral acceleration at a conditioning time-period.

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