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Development of Site Specific Seismic Inputs for Structures

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Abstract - *A probabilistic method to simulate the seismic ground motion parameters specific to sites located in earthquake prone region with a limited or scanty earthquake records for developing site specific seismic inputs for structures in the form of power spectral density functions or response spectra is presented. Generation of site-dependent earthquake ground motions is the best alternative in the absence of enough earthquake records for a site. Risk consistent spectral shapes and corresponding power spectral density functions are obtained using empirical relationships. Modification of soil is done using frequency domain spectral analysis to develop free field inputs considering linear soil overlying the bedrock. The method is applied to generate site dependent response spectrum and power spectral density function for a region surrounded by three point sources. A parametric study is carried out to show the effect of sensitivity of the constants of empirical equations and soil condition on the risk consistent response spectrum. It is found from the study that the shape of the response spectrum remains nearly the same for different PGA intervals considered in the study. It is seen that the PGA amplification is more for the stiffer soil (i.e. for Vs =250 m/sec) for linear soil conditions.*

Keywords- *Risk consistent response spectrum, power spectral density function, soil amplification, probability density function, bedrock and free field.*

I. INTRODUCTION

Amongst the natural hazards, earthquakes have the potential for causing the greatest damages. Since earthquake forces are random in nature & unpredictable, therefore disastrous damage and life losses incurred by earthquakes in the last decade around the world have increased public attention and concern of how to reduce potential seismic risk. The occurrence of earthquakes poses a hazard to structures that can lead to disaster unless appropriate engineering counter measures are employed. When a site is surrounded by a number of earthquake sources, the frequency composition of the ground motion or the shape of the input response spectrum should include the elements of seismic risk associated with the sources of earthquake. There have been several studies to relate the response spectrum ordinate with the magnitude and epicentral distance related to earthquake sources. The idea behind this is to associate a risk to the response spectrum ordinate by considering the probability of exceedance of a certain magnitude of earthquake. For the seismic risk analysis of structure especially for Probabilistic risk analysis procedure, the use of such risk consistent response spectrum has been favoured. However, there have been a number of studies on the seismic risk of many cities of the world and on the risk consistent response spectra. [1] carried out seismic risk at a site in a probabilistic format in terms of PGA and return period. [2] proposed a fault rupture model for risk analysis. [3] developed a new attenuation relation for PGA applicable to the near source region in Japan. Here-in a simplified method for obtaining the site specific seismic response spectrum and power spectral density function is presented. The risk consistent spectral shapes at the bedrock level is obtained by assuming certain existing empirical relationship which expresses the ordinates of the normalized acceleration response spectrum in terms of magnitude and epicentral distance of earthquake. Mean and standard deviation of spectral ordinates are then made risk consistent by weighing them with the conditional probability of occurrence of different levels of PGA given certain magnitude of earthquake ordinates. The risk consistent response spectrum thus obtained is valid for bedrock level. Modification of the risk consistent response spectrum for the soil effect is carried out by frequency domain spectral analysis for linear uniform soil. The method is applied to a site surrounded by three earthquake sources. A probabilistic method to simulate the seismic ground motion parameters specific to sites located in earthquake prone region with a limited or scanty earthquake records for developing site specific seismic inputs for structures in the form of power spectral density functions or response spectra is presented. The modification of the risk consistent response spectrum obtained at the bedrock level because of the soil conditions. Also, the characteristics of free field absolute acceleration for different soil conditions, sensitivity of the constants of empirical equations and the shear wave velocity of the soil are examined.

II. ASSUMPTIONS

The following assumptions are made in the study

(i) No or little earthquake data is available for the region under study, except for the recurrence interval of earthquakes and some indirectly evaluated magnitudes of earthquakes.
(ii) The region is having a constant thickness of soil layer over the bedrock.
(iii) The region is surrounded by multiple sources (point sources) of earthquake.
(iv) Cornell attenuation law is valid for the region.

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(v) It is assumed that normalized response spectrum ordinates, [SN(T)] normalized by the peak ground acceleration (PGA) is an empirically determined function of magnitude M and epicentral distance R.

(vi) It is assumed that they are lognormally distributed.

III. METHODOLOGY

The three earthquake point sources are assumed to be located around the site. The annual occurrence of earthquake is modelled as a poisson process and the probability density function of earthquake magnitude is assumed to be of the following form.

$$F(m) = \text{Exp}[-\exp - \alpha (m - u)] \quad (1)$$

where α and u are parameters for Gumbel Type-1 distribution given by

$$\overline{m} = u + 0.5772/\alpha \quad (2a)$$

$$\sigma_m^2 = \Pi^2/6\alpha^2 \quad (2b)$$

in which $\overline{m}$ and σ_m are the mean and standard deviation of the magnitudes of earthquake respectively.
For the development of the risk consistent response spectrum at the bedrock level, the following empirical relationship is used to describe the normalized response spectrum ordinate [4]

$$S_N^* = \ln S_N(T) = \ln S_N(M,R,T) = a(T)M - b(T)\ln R + c(T) \quad (3)$$

in which a(T), b(T) and c(T) are constants for a particular value of the period (T). These constants depend upon the seismicity of the region. In the absence of any recorded data of earthquake in a region to obtain the values of these constants, it may be useful to adopt some reported values of these constants from the literature and then, perform a sensitivity analysis i.e. to find out the effect of the variation of these constants on the shape of the response spectrum. Since the normalized response spectrum ordinate is expressed in terms of M and R, risk associated with the response spectrum is included, for a given R, by weighting the response spectrum ordinates with the probability of occurrence of a magnitude of earthquake conditional upon a PGA value occurring within two bounds. This conditional probability of a magnitude of earthquake, given that the PGA value is between a1 and a2 due to an earthquake event in the k-th zone is obtained from the conditional probability. It can be shown that the conditional probability function of the magnitude of earthquake P_k (mi | a1 < A ≤ a2) can be written as

$$P_k(m_i \mid a_1 < A \le a_2) = \frac{P(a_1 < A \le a_2 \mid m_i) P_k(m_i)}{P_k(a_1 < A \le a_2)} \quad (4)$$

in which P_k (mi) is the probability density function of the magnitude of earthquake for the kth zone and P(a1 < A ≤ a2 | mi) is the conditional probability matrix and P_k (a1 < A ≤ a2) is obtained by

$$P_K(a_1 < A \le a_2) = \sum_{i=1}^{n} P_k(a_1 < A \le a_2 \mid m_i) P_k(m_i) \quad (5)$$

The conditional mean value of the natural logarithm of response spectrum for the kth source is therefore,

$$\bar{S}_{N_k}^*(T) = \sum_i S_N^*(m_i, T) P_k(m_i \mid a_1 < A \le a_2) \quad (6)$$

Considering all seismic sources, the conditional mean value of $S_N^*(T)$ is represented by

$$\bar{S}_N^*(T) = \frac{\sum_k \bar{S}_{N_k}^*(T) \nu_k P_k(a_1 < A \le a_2)}{\sum_k \nu_k P_k(a_1 < A \le a_2)} \quad (7)$$

In a similar way, the conditional mean square value of the $S_N^*(T)$ can be obtained by replacing the $S_{N_K}^*(T)$ by $S_{N_K}^2(T)$ in Eq. 7 and is given by

$$S_N^{*2}(T) = \frac{\sum_k S_{N_k}^{*2}(T) \nu_k P_k(a_1 < A \le a_2)}{\sum_k \nu_k P_k(a_1 < A \le a_2)} \quad (8)$$

Then, the conditional standard deviation is given by

$$\sigma\{S_N^*(T)\} = \sqrt{\{S_N^*(T)\}^2 - \bar{S}_N^{*2}(T)} \quad (9)$$

The plot of Eq. (7) with the time period provides the normalized risk consistent acceleration response spectrum for the PGA interval between a1 to a2. This response spectrum is called 50th percentile response spectrum. The plot of mean plus one standard deviation response spectrum ordinate by using Eqs. (7) and (9) with time period (T) provides the 84th percentile response spectrum for the same PGA interval. It is to be noted that the response spectrum ordinates at two successive values of time period are mutually independent. In reality, there exists a correlation between response spectrum ordinates at two time periods. The response spectrum, as obtained from Eqs. (7) and (9), can be modified to include the correlation effect between two ordinates if sufficient number of recorded earthquakes are available for the site. With the help of such earthquake records, a correlation matrix of the response spectrum ordinates can be generated, and the response spectrum obtained from Eq. (7) can be modified to include this correlation effect. The procedure is given by [4]. Since it is assumed that there is no or little earthquake data available, the shape of the risk consistent spectrum as obtained from Eqns. (7) and (9) cannot be modified to include correlation between response spectrum ordinates at any two time periods. Therefore, the shape of the risk consistent response spectrum is directly used here as seismic input for the PRA procedure. Use of the shape of the risk consistent response spectrum, as obtained above, has been made by previously by other group for the PRA of structures [5]. The conditional probability of any value, A exceeding any particular level, say a1, for a given mi, is obtained using the Cornell attenuation law [1] for PGA (cm/sec^2).

$$\ln A(gal)=6.74+0.859M-1.8\ln(R+25);\ \ \sigma \ln A = 0.57 \qquad (10)$$

The attenuation law used for obtaining the PGA at the site and the normalised spectrum as obtained from Eq. (7) are valid for the bed rock level. In order to obtain the risk consistent spectrum for the free field ground motion, from that for the bedrock the effect of soil amplification is to be considered as the local soil characteristics can significantly change the characteristics of the risk consistent response spectrum of ground motion [6 and 7].

For obtaining the former, a wave propagation analysis, is performed with bedrock response spectrum as input. Two types of analysis are carried out for this purpose. First one is the frequency domain spectral analysis and second one is a simulation analysis .As stated before, the normalized response spectrum is obtained at the bedrock level. The direct input to the structure is the response spectrum of the free field absolute acceleration. Because of the soil condition, the response spectrum for the free field absolute acceleration is a modified form of the risk consistent normalized response spectrum at the bedrock.

Frequency domain spectral analysis is carried out for linear soil condition. In this analysis, a power spectral density function (PSDF) is obtained from the response spectrum using the empirical relationship derived by [8]. In the present analysis, the relationship given by [8] is used i.e.,

$$S_b(\omega) = \frac{\omega^{\theta+2}}{\omega^{\theta}+\omega_{ff}^{\theta}}[2\xi\omega/\pi+4/\pi\tau][D_j(\omega,\xi)/p_f]^2 \qquad (11)$$

where ω is frequency in radians per second; τ is the duration of earthquake shaking and is taken as 15sec; p_f is the peak factor of white noise; ωff and θ are two constants which can be obtained by iteration procedure; however, values of ωff and θ are taken as 0.705 and 3.0 as suggested by [8]; $D_j(\omega,\xi)$ is the ordinate of the risk consistent response spectrum for displacement and $S_b(\omega)$ is the PSDF of acceleration. Once the PSDF at the bedrock level is obtained, the PSDF of free field absolute acceleration is obtained by

$$S_g(\omega) = |A(\omega)|^2 \times S_b(\omega) \qquad (12)$$

in which $S_g(\omega)$ is the PSDF of free field absolute acceleration; $A(\omega)$ is the transfer function for uniform soil. The transfer function in the closed form for uniform soil layer of thickness H; shear wave velocity Vs and percentage critical damping of soil is given by [9].

$$A(\omega) = \frac{1}{\sqrt{\cos^2(\omega H/V_s)+[(\xi\omega H/V_s)]^2}} \qquad (13)$$

Once the PSDF of free field absolute acceleration is obtained, the corresponding response spectrum may be derived using inverse of the relationship represented by Eq. (11). If the process is relatively broad banded the relationship given by Eq. (11) is ideally suited.

PGA of the free field absolute accelerations for different types of soil are obtained from the respective response spectrum ordinates at zero time period. PGA amplifications are obtained from the ratios between PGA values of free field acceleration and the bedrock accelerations.

IV. NUMERICAL STUDY

It is assumed that the site is surrounded by three point sources which are at distances of 72.8 km; 92 km and 111.03 km respectively from the site. The values of the probability of occurrence of earthquakes for the three sources (vi , i = A, B, C) and the parameters of the probability density function of the magnitude of earthquake are assumed to be known and given in Table 1.

Depth of overlying soil is assumed to be 20m. Different types of soil condition have been considered namely, (i) uniform soil with Vs = 80 m/sec and 250 m/sec; The variations of the constants a(T), b(T) and c(T) with time period (T) are taken as those shown in Figure 1 given by [4].These constants are obtained from a regression analysis for a damping of 2%.

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Note that in the absence of much earthquake data, it is difficult to assume appropriate values for a(T), b(T) and c(T). Therefore, the values given in Figure 1 are adopted and then, a sensitivity analysis is performed to show the influence of the variation of these constants on the response spectrum. The normalized response spectrum of acceleration at bedrock level is obtained by attenuation law given by Eq. (10).

Table1. Seismological Characteristics of Earthquake Sources

Sources	$\bar{m}$	σ_m	α
1	5	2.5	0.5127
2	4.4	1.0	1.281
3	3.5	0.8	1.602

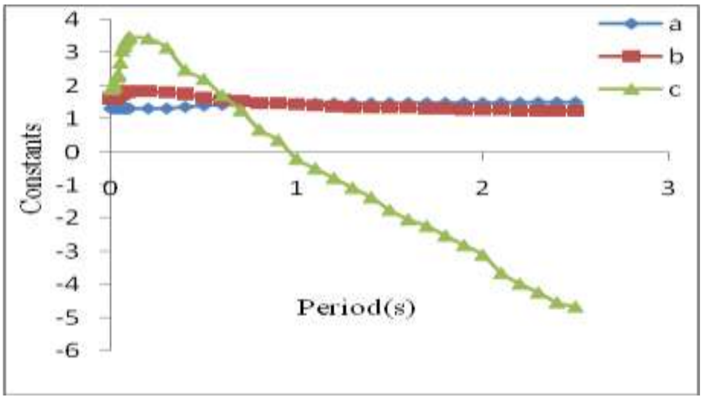

Figure 1. Variation of Constants with Time Period

4.1 Response Spectrum at the Bedrock Level:

Figure 2 shows the normalized acceleration response spectrum at the bedrock level for different PGA intervals. It is seen from to the figure that the shape of the acceleration response spectrum is not very sensitive to the PGA intervals. Figure 2 shows both 50th percentile and 84th percentile normalized response spectrums. It is seen from the figure that the peak values for both spectrums occur at the same time period and therefore, the difference between the two spectrums is maximum at this periods. In order to study the effect of different parameters on the normalized response spectrum or the spectral shape, the following studies are made.

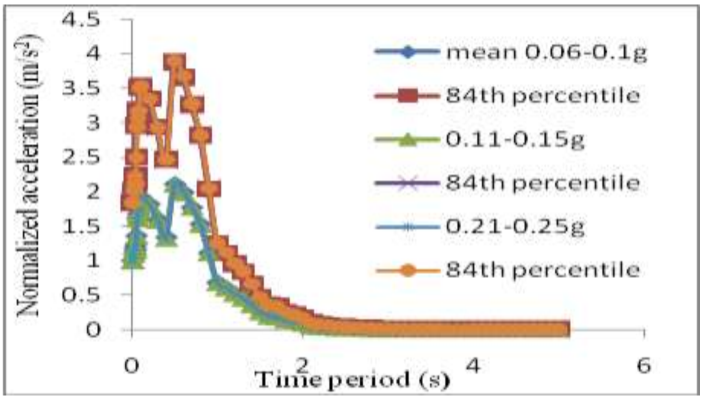

Figure 2. Norm. Response Spectrum at Bedrock (50th Percentile and 84th Percentile)

4.2 Effect of the Constant a(T), b(T), c(T):

Figures 3 to 5 show the effect of the variation of these constants on the spectral shape when they are varied one at a time. In Figure 3, the sensitivity of a(T) is shown. It is seen from the figure that 15% variation of a(T) significantly influences the shape of the spectrum near the peak. From Figure 4, it is observed that the variation of b(T) does not significantly effect the spectral shape. A moderate effect on the spectral shape near the peak is observed when c(T) is varied by about 15% as shown in Figure 5. Therefore, the constants a(T) and c(T) must be very carefully selected when much earthquake data is not available.

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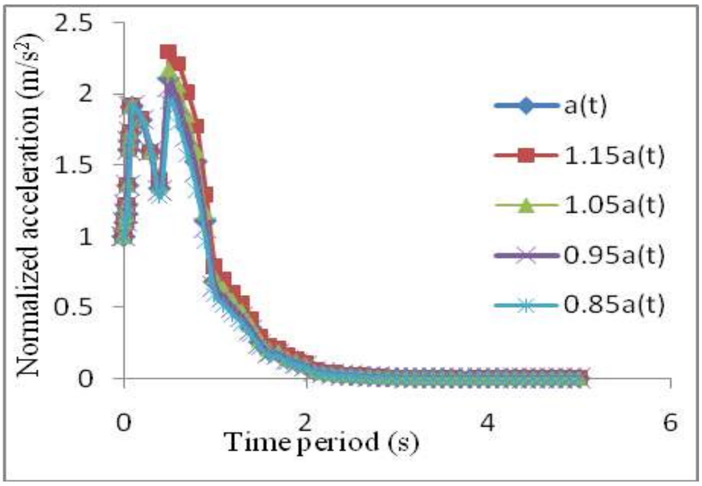

Figure 3. Effect of the Variation of a(T) on Spectral Shape

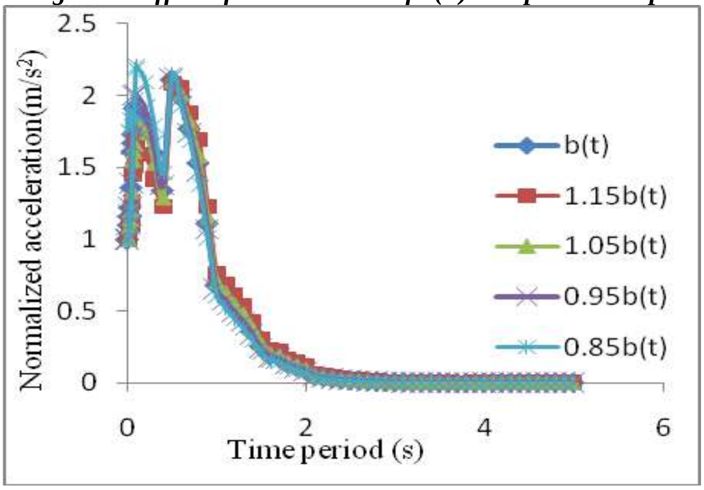

Figure 4. Effect of the Variation of b(T) on Spectral Shape

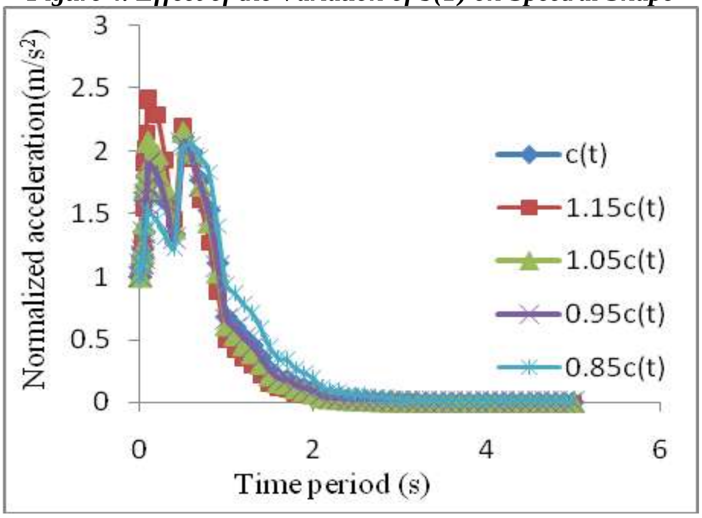

Figure 5. Effect of the Variation of c(T) on Spectral Shape

4.3 Effect of Soil Condition on Free Field Absolute Acceleration:

Figure 6 compares the free field response spectrums for the PGA bedrock of 0.13g for Vs = 80 m/sec and for Vs = 250 m/sec. It is seen from the figure that for Vs = 80 m/sec, the free field absolute acceleration is a broad band process with most of the frequency contents centered around a frequency of 6.28 rad/sec (fundamental frequency of soil for Vs=80m/sec) whereas for Vs = 250 m/sec the free field absolute acceleration is relatively a narrow banded.

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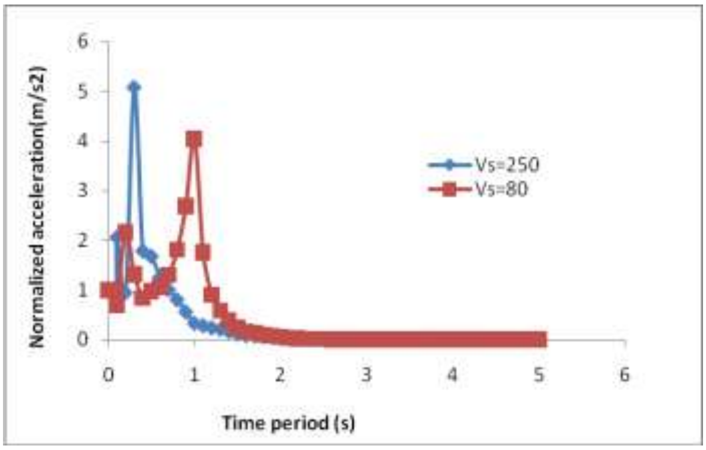

Figure 6. Normalised Risk Consistent Response Spectrum for Free Field Absolute Acceleration (Linear Soil; PGA at Bed=0.13g)

4.4 Frequency Characteristics of the Risk Consistent Input and PGA Amplification:

Figure 7 shows the PSDF obtained from the risk consistent response spectrum for a PGA value of 0.13g. It is seen from the figure that the PSDF at bedrock is not a narrow banded. This shows that the empirical relationship used for obtaining normalized spectral ordinate is quite applicable. It is seen from the Table 2 that the PGA amplification is more for the stiffer soil (i.e. for Vs =250 m/sec) for linear soil conditions.

Table 2. PGA Amplification for different types of Soil

Soil type	PGA Amplification (linear 0.13g)
Vs=80m/s	2.15
Vs=250m/s	2.35

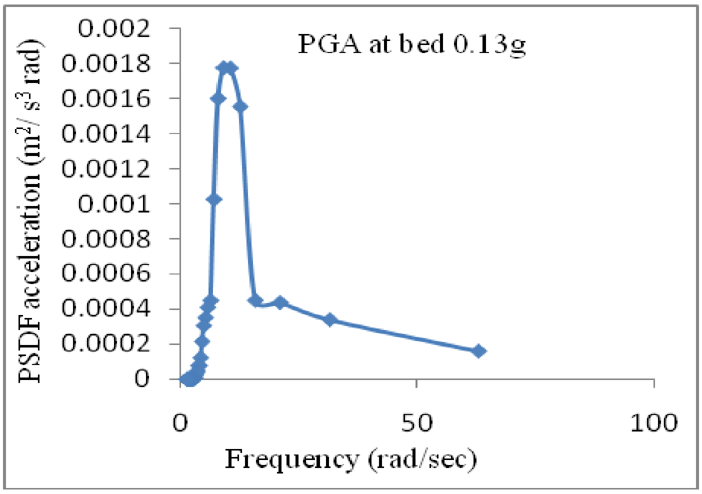

Figure7. Risk consistent PSDF at bedrock

V. CONCLUSIONS

A methodology is presented for obtaining the risk consistent acceleration response spectrum for a site, which does not have much recorded earthquake data. The risk consistent response spectrum is obtained using an empirical formula which relates the response spectrum ordinates with the magnitude of earthquake and epicentral distance. Seismic risk factor is incorporated in the response spectrum by using conditional probability, which describes the probability of occurrence of certain magnitude of earthquake given that the PGA lies between two bounds. This conditional probability matrix is derived from Cornell attenuation law. The risk consistent spectrum thus obtained is for the bedrock level. Response spectrum for the free field absolute acceleration is obtained by modifying the response spectrum at the bedrock by incorporating the soil effect. This is achieved by a random vibration analysis. All parametric studies relate to the response spectrums for the bedrock. The following conclusions can be drawn from the numerical study:

1. For the example problem, risk consistent normalized acceleration response spectrum (spectral shape) at the bedrock is quite broad banded.
2. Shape of the response spectrum remains nearly the same for different PGA intervals considered in the study. Therefore, only a very few (two or three) spectral shapes may be required to describe the ground motions at the bedrock for the region.
3. Spectral shape is sensitive to the variation of the constants b(T) and c(T) near the peaks; variation of the other constant has insignificant influence on the spectral shape.
4. Response spectrum for the free field absolute acceleration for uniform soil with Vs = 80 m/sec, is broad banded for linear soil condition. Maximum spectral ordinate is significantly greater than that of the bedrock response spectrum.
5. For soil with Vs = 250 m/sec, shape of the free field absolute acceleration is relatively a narrow banded. The maximum spectral ordinate occurs at the first natural frequency of the soil layer and its peak ordinate is more than that for the soil with Vs=80m/sec.
6. PGA amplification increases with the increase in shear wave velocity for linear soil conditions.

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