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A NEW STOCHASTIC APPROACH FOR SEISMIC FLOOR SPECTRA GENERATION

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SUMMARY

A new stochastic approach has been presented here for the estimation of floor response spectra for the seismic hazard characterized in form of a set of design spectra. This approach is based on the direct use of the modal properties of the primary system in calculating the transfer function of the absolute acceleration response of the single-degree-of-freedom secondary system. This thus does not require the computation of the modal properties of the combined system. The proposed approach uses all the design spectra available for various damping ratios. It is quite generalized as it can be used to estimate the floor spectra for higher order response peaks and for any level of confidence. The proposed approach has been illustrated through parametric study on one example shear building and by using two example AERB-specified design motions.

INTRODUCTION

It is common to generate the floor response spectra corresponding to the estimated seismic hazard at a nuclear power plant site, for ensuring the seismic safety of the secondary systems e.g., pumps, compressors, piping systems, in the plant during its lifetime. These spectra describe the maximum (absolute) acceleration responses of a series of different single-degree-of-freedom (SDOF) oscillators supported on the floor under consideration, and are obtained from the design spectra used to characterize the seismic hazard. A typical spectrum of this type is usually developed by i) generating a ground accelerogram consistent with a design spectrum, ii) subjecting the primary structure to the generated accelerogram and obtaining the floor accelerogram by direct time-step integration of the equations of motion, iii) determining the floor response spectrum from this floor accelerogram, and by iv) moderating the peaks in this spectrum to account for the uncertainties associated with the modelling techniques and system properties. To make this approach statistically more meaningful, a large ensemble of the spectrum-consistent ground accelerograms has to be generated. This makes the entire exercise computationally infeasible, particularly when many alternative attachment configurations of secondary systems are to be considered. Further, in this approach, the SDOF oscillator is considered to be in cascade with the primary system, thus ignoring the dynamic interaction or the feed-back effect between the two systems. This decoupled analysis gives too conservative floor spectra, particularly when the secondary system is not very light and when it is tuned to one or more of the dominant primary system modes.

Various alternative approaches of generating floor spectra which directly use the design spectrum ordinates through the use of an appropriate modal combination rule, e.g. those by Igusa and Der Kiureghian (1985), Gupta and Jaw (1986), Suarez and Singh (1987), are limited in scope since those do not consider inherent variations in the design ground motion due to random phasing of the constituent waves. These can also not be used to obtain the floor response spectra for the higher order peaks, while the knowledge of the higher order peaks may be crucial in estimating the damage in the secondary systems (Basu and Gupta (1995, 1996a,b)). In contrast, a PSDF-based stochastic approach can be used to obtain the floor response spectra for desired orders of peaks with a given level of confidence.

A PSDF-based approach is implicitly based on the assumption that the input excitation process is stationary and that no additional nonstationarity is introduced into the response process due to the sudden application of the excitation. Hence, it has been an accepted practice to consider the PSDF of a fictitious 'equivalent stationary' ground motion process such that it is compatible with the specified design spectrum within the assumption of stationarity for the response process. Such a PSDF used to characterize the seismic ground motion is called as the spectrum-compatible PSDF and is determined from the given design spectrum by using iterative schemes, e.g., those by Kaul (1978), Sundararajan (1980), Unruh and Kana (1981). However, the design spectra for different damping ratios do not correspond to the same spectrum-compatible PSDF. This is partly due to the lack of inherent compatibility between the design spectra corresponding to different damping ratios after the averaging and smoothing operations, and partly due to ignoring the nonstationarity in response due to finite operating time of the excitation process. The iterative scheme proposed by Shrikhande and Gupta (1996a,b) for spectrum-compatible PSDFs accounts for the effects of response nonstationarity as it is based on the use of time-dependent transfer function for the response process. Alternatively, by using the 'envelope PSDF' i.e. the PSDF which envelops the PSDFs corresponding to the design spectra for different damping ratios, one can conveniently obtain the conservative stochastic responses of a dynamical system (Gupta (1994)).

To include the effects of dynamic interaction between the SDOF oscillator and the primary system, it has been a usual practice to consider a coupled analysis and to calculate the eigenproperties of the combined system. Due to the different damping characteristics of the two systems, the combined system is usually a non-classically damped system even though the primary system is assumed to be a classically damped system. The direct and exact state-space approach of finding the eigenproperties by Foss (1958) is not always convenient due to numerical difficulties. Also, this does not make use of the already known modal properties of the primary system. Among the approximate approaches, those based on the perturbation technique are the most popular approaches. These include the formulations by Sackman et al. (1983), Igusa and Der Kiureghian (1985). These approaches are suitable for the light secondary systems and most of these are based on the classical damping assumption for the combined system. Another set of approximate approaches has been based on the mode synthesis approach e.g., that by Suarez and Singh (1987). Singh and Suarez (1987) obtained the exact eigenproperties by using the individual properties of the primary and secondary systems in a non-linear characteristic equation. In a more recent development, Gupta (1996) proposed an alternative formulation for the transfer function of the absolute acceleration response of a SDOF secondary system supported on a earthquake-excited classically damped primary system. This formulation is based on expressing the system displacements in terms of the (fixed-base) mode shapes of the primary system, and thus does not require the computation of the modal properties of the combined system.

A new stochastic approach is proposed in this paper to directly generate the seismic floor spectra with the desired level of confidence from a set of design spectra. It has three key steps:

(a) determination of the 'envelope' power spectral density function (PSDF) consistent with a given set of design spectra,

(b) determination of the PSDF for the secondary system response by relating this to the input excitation in frequency domain through a transfer function, and

(c) generation of the floor response spectra from the response PSDFs for a series of secondary systems with different damping ratios and time periods.

For step (a), the approach of Unruh and Kana (1981) has been slightly modified to include more realistic expressions of the peak factors as in Gupta (1994) and Todorovska et al. (1995). These peak factors are based on the formulation of Gupta (1988) assuming statistical independence between the local maxima. Those have been shown to be reasonable by Basu and Gupta (1994) and Basu et al. (1994, 1996c,d) for the first few ordered peaks by modelling the interdependence between the unordered peaks in a stationary Gaussian process. Same peak factors are to be used in the calculation of floor spectra ordinates from the PSDFs in step (c). For step (b), the transfer function formulation of Gupta (1996) using the (fixed-base) primary system modes has been considered. The proposed approach has been illustrated by considering an example building and two example sets of design spectra. Through a parametric study, it is shown that the observed trends in the estimated floor spectra by using the proposed approach are consistent with the findings of the earlier studies.

DETAILS OF THE PROPOSED APPROACH

Let us consider an n-degree-of-freedom linear primary system as shown in Fig. 1, with a SDOF secondary system e.g., an equipment, attached to it in such a way that it is only affected by the motion, $X_p(t)$, along the pth degree of freedom. Let the mass, damping and stiffness of the secondary system be represented by M_S, C_S and K_S respectively. Thus, the damping ratio, ζ_S, and natural frequency, ω_S of the secondary system are respectively given by $C_S/2\sqrt{K_S M_S}$ and $\sqrt{K_S/M_S}$. The primary system is subjected to the ground acceleration, $\ddot{U}_g(t)$ at its base. Assuming the primary system to be classically damped and expressing its response in terms of the undamped mode shapes, the transfer function relating the absolute acceleration response of the secondary system to the ground acceleration may be written as (Gupta (1996))

$$\mathcal{H}(\omega) = \frac{(\omega_S^2 + 2i\zeta_S\omega_S\omega)\left[1 + \omega^2 \sum_{r=1}^{n} \phi_p^{(r)} \alpha_r H_r(\omega)\right]}{(\omega_S^2 - \omega^2 + 2i\zeta_S\omega_S\omega)\left[1 - \omega^2 M_S \sum_{r=1}^{n} \phi_p^{(r)^2} H_r(\omega)\right] - \omega^4 M_S \sum_{r=1}^{n} \phi_p^{(r)^2} H_r(\omega)} \quad (1)$$

for the case when the secondary degree of freedom, $X_{n+1}(t)$ is in the same direction as the earthquake ground motion. In Eq. 1, $\phi_p^{(r)}$ is the pth element of the rth orthonormal mode shape, $\{\phi^{(r)}\}$, of the primary system, and $\alpha_r = \{\phi^{(r)}\}[M_P]\{U_{bP}\}$ is the modal participation factor for the rth primary mode, where $[M_P]$ is the mass matrix of the primary system and $\{U_{bP}\}$ denotes the displacement influence vector of the primary system. Further, in Eq. 1,

$$H_r(\omega) = \frac{1}{\omega_r^2 - \omega^2 + 2i\zeta_r\omega_r\omega} \quad (2)$$

is the transfer function for the displacement response in the rth primary mode to base excitation where ω_r and ζ_r respectively represent the natural frequency and damping ratio in this mode.

It may be observed that the expression of $\mathcal{H}(\omega)$ as in Eq. 1 does not require the computation of damped mode shapes and natural frequencies of the combined system. It is sufficient to know the modal properties of the fixed-base primary system and the dynamic characteristics of the secondary system in this formulation. This formulation also accounts for the non-classicality of the combined system damping apart from accounting for the primary-secondary system interaction effects. Calculation of $\mathcal{H}(\omega)$ may be further simplified by taking the summations over lesser number of primary system modes and thus by ignoring the higher modes with little contributions within the frequency range of interest (Gupta (1996)).

On multiplying $|\mathcal{H}(\omega)|^2$ with the (one-sided) PSDF, $\Phi_g(\omega)$, of the input ground acceleration, the PSDF, $\Phi(\omega)$, for the absolute acceleration response of the SDOF system can be obtained (e.g., see Newland (1993)). Peak amplitude of desired order and level of confidence in this response may now be estimated by computing the root-mean-square (r.m.s.) value of the response as the square-root of the area under $\Phi(\omega)$ and by multiplying this with the corresponding peak factor. The peak factor for the rth peak may be determined by using its probability density and distribution functions given by (Gupta and Trifunac (1988))

$$p_{(r)}(\eta) = r\binom{N}{r}[P(\eta)]^{r-1}[1-P(\eta)]^{N-r}p(\eta) \tag{3}$$

and

$$P_{(r)}(\eta) = \sum_{k=0}^{r-1}\binom{N}{k}(P(\eta))^k(1-P(\eta))^{N-k} . \tag{4}$$

Whereas the distribution function here can be used iteratively to obtain the peak factor for any desired confidence level, the density function can be used to find the peak factors for the expected and the most probable peak amplitudes. In Eqs. 3 and 4, $p(\eta)$ is the probability density function of the (unordered) peaks in the absolute response of the SDOF system given by (Gupta (1994))

$$p(\eta) = \frac{1}{\sqrt{2\pi}}\left[2\varepsilon e^{-\eta^2/2\varepsilon^2} + (1-\varepsilon^2)^{1/2}\eta e^{-\eta^2/2}\int_{-\eta(1-\varepsilon^2)^{1/2}/\varepsilon}^{\eta(1-\varepsilon^2)^{1/2}/\varepsilon} e^{-x^2/2}\mathrm{d}x\right] \; ; \quad \eta \geq 0 , \tag{5}$$

$P(\eta) = \int_\eta^\infty p(u)du$ is the probability distribution function of these peaks, and N is the total number of these peaks given by

$$N = \frac{T}{2\pi}(1+\sqrt{1-\varepsilon^2})\left[\frac{\lambda_4}{\lambda_2}\right]^{1/2} \tag{6}$$

where, T is the stationary duration of the response, taken same as that used in obtaining the ground PSDF, $\Phi_g(\omega)$, from the design spectra. In Eq. 5, ε is the band-width parameter given by

$$\varepsilon = \sqrt{1 - \frac{\lambda_2^2}{\lambda_0 \lambda_4}} \tag{7}$$

with λ_0, λ_2 and λ_4 respectively denoting the zeroth, second and fourth moments of the PSDF, $\Phi(\omega)$. To account for the effect of finiteness of the ground motion duration, $H_r(\omega)$ in Eq. 2 may be modified by modifying ζ_r on the right hand side to $(\zeta_r + 2/\omega_r T)$ (Kaul (1978)).

The above procedure gives the floor response spectrum ordinate at the period, $2\pi/\omega_S$ for the absolute acceleration response of a SDOF oscillator with mass, M_S and damping ratio, ζ_S. By taking several SDOF oscillators with different values of ω_S and ζ_S, and then by computing the peak response value for each of these as above, a complete set of floor response spectra for the desired level of confidence, order of peak and equipment mass can be constructed.

Since the seismic hazard at a site is usually specified in the form of a set of design spectra, it becomes necessary to obtain the ground PSDF, $\Phi_g(\omega)$ from these spectra for using the above procedure. These spectra for different damping ratios generally lead to different PSDFs on the inverse transformation as mentioned in the introductory remarks. For this reason, the ground PSDF, $\Phi_g(\omega)$ is considered to be an 'envelope PSDF', i.e. the envelope of the PSDFs corresponding to different damping ratios. The iterative procedure followed for obtaining each of these PSDFs is, in essence, similar to that by Unruh and Kana (1981). It is slightly different as it makes use of more accurate peak factors as discussed above and considers the pseudo acceleration response instead of the absolute acceleration response of the SDOF oscillator. Following are the steps of the iterative procedure considered in this study:

(1) Obtain an initial estimate of trial PSDF, $\Phi^{(j)}(\omega)$ corresponding to the jth design spectrum, $R^{(j)}(\omega_0)$, for pseudo spectral acceleration as

$$\Phi^{(j)}(\omega)|_{\omega=\omega_0} = \frac{4(\zeta_j + 2/\omega_0 T)}{\pi \omega_0 \eta^2} \{R^{(j)}(\omega_0)\}^2 \ , \tag{8}$$

where, ζ_j is the damping ratio of the SDOF oscillators for which the design spectrum, $R^{(j)}(\omega_0)$ has been specified, η is the peak factor taken arbitrarily and independent of ω_0 as 3.0, and T is the stationary duration of design ground motion. This initial estimate of the trial PSDF is obtained for all the N_P values of ω_0 at which the design spectrum has been specified.

(2) Define the trial PSDF at smaller interval, $\Delta\omega$, by linearly interpolating the intermediate values, and obtain the PSDF for the pseudo acceleration response of SDOF oscillator with natural frequency, ω_0 as

$$\Psi^{(j)}(\omega,\omega_0) = \frac{\omega_0^4}{(\omega^2-\omega_0^2)^2 + 4(\zeta_j + \frac{2}{\omega_0 T})^2\omega^2\omega_0^2}\Phi^{(j)}(\omega)\,. \tag{9}$$

(3) Calculate the largest peak value, $\tilde{R}^{(j)}(\omega_0)$ of the pseudo acceleration response of the SDOF oscillator by taking the spectral moments of PSDF, $\Psi^{(j)}(\omega,\omega_0)$ and then by estimating the 'expected' peak factor for the largest peak ($r=1$).

(4) Repeat steps (2) and (3) for all the N_P values of ω_0 at which the design spectra have been specified, and modify the trial PSDF at $\omega=\omega_0$ by multiplying it with the ratio, $[R^{(j)}(\omega_0)/\tilde{R}^{(j)}(\omega_0)]^2$.

(5) Compare the calculated spectrum, $\tilde{R}^{(j)}(\omega_0)$ with the target spectrum, $R^{(j)}(\omega_0)$ and calculate the average error in the calculated spectrum as

$$\mathcal{E} = \frac{1}{N_P}\sum_{\omega_0}\frac{|\tilde{R}^{(j)}(\omega_0) - R^{(j)}(\omega_0)|}{R^{(j)}(\omega_0)}\,. \tag{10}$$

If $\mathcal{E}$ is greater than the maximum permitted error, $\mathcal{E}_{\max}$, go back to step (2).

(6) Repeat steps (1) to (5) for different design spectra, and then calculate the ground PSDF as

$$\Phi_g(\omega) = \max_j \Phi^{(j)}(\omega)\,. \tag{11}$$

ILLUSTRATION OF THE PROPOSED APPROACH

The proposed approach has been illustrated through an example building and two sets of design spectra. The example building is a 6-story shear building (see Fig. 2) and its mass and stiffness properties are: $m_1 = m_2 = 7.0 \times 10^7$ kg, $m_3 = m_4 = 5.0 \times 10^7$ kg, $m_5 = m_6 = 4.0 \times 10^7$ kg, $k_1 = k_2 = 3.0 \times 10^8$ kN/m, $k_3 = k_4 = 2.4 \times 10^8$ kN/m, and $k_5 = k_6 = 2.1 \times 10^8$ kN/m. The natural frequencies of this building are 18.5, 47.7, 75.4, 103.1, 119.0, 132.5 rad/sec. The modal damping ratio is assumed to be 0.05 for all the modes in the building. To characterize the input ground motion, the design spectra specified by Atomic Energy Regulatory Board (1990) for 2%, 5% and 10% damping ratios, 1.0g peak ground acceleration, and for soil and rock sites have been considered. The calculations for the 'envelope' PSDFs (for the soil and rock sites) are based on $\Delta\omega \simeq 0.1$ rad/sec, Newton-Cotes' formula for the numerical integration, $T = 15$ sec, and $\mathcal{E}_{\max} = 0.01$ with maximum of 5 iterations being allowed.

Fig. 3 shows the floor response spectra obtained for the mass ratios equal to 0.5, 0.05 and 0.005 while the SDOF oscillator or equipment is kept at the 4th floor, oscillator damping is 2%, the building is situated at a soil site, probability of exceedance is 16%, and the largest response peak is considered for each spectrum ordinate. These spectra show two distinct peaks, one large peak at around 0.35 sec and one small peak at around 0.08 sec, respectively corresponding to the first and third natural frequencies of the building. Peak for the second frequency is suppressed due to the modal node being close to the 4th floor. It may be observed that both distinct peaks show substantial effects of mass ratio while at the periods far away from these peaks, there is no noticeable effect of mass ratio. This is so because when the equipment is tuned to the significant building frequencies, the effects of equipment-structure interaction become quite appreciable, and then the equipment to floor mass ratio becomes a dominating parameter with the peaks becoming smaller for the heavier equipments. Obviously, if the interaction effects are completely ignored, we should get a curve independent of the equipment mass which will effectively correspond to the zero mass ratio and thus to even larger peaks than those shown in the curve for 0.005 ratio. Ignoring equipment-structure interaction may thus be conservative but the degree of conservatism is just too high to be overlooked except in the case of the equipment being very light. If the equipment is not tuned to any of the significant structure frequencies, equipment-structure interaction can be easily ignored in calculating the peak equipment response.

To illustrate the effect of the order of peak, the floor spectrum curve for mass ratio, 0.05 in Fig. 3 has been compared with the corresponding curves for the third order and fifth order peaks of absolute equipment acceleration in Fig. 4. As expected, the curves of the higher order peaks are lower than the curve for the largest peak at all time periods.

Placing the equipment at different floors leads to different floor spectra because the size of the peak in a floor spectrum is governed largely by the ordinate of the floor, to which the equipment is attached, in the mode corresponding to that peak. To illustrate this, the equipment with 0.05 mass ratio as considered for Fig. 3 is alternatively attached to the 2nd and 6th floors. The comparison of the spectra for these two alternative locations with the spectrum in Fig. 3 for the location at the 4th floor is shown in Fig. 5. It is seen that the largest floor spectrum peak becomes higher for the 6th floor location and lower for the 2nd floor location which is in accordance with the first mode shape variation with the building height. On the other hand, in the case of the spectrum peak corresponding to the second structure mode, 4th floor peak becomes smaller than the 2nd floor peak. This is also consistent with the second mode shape of the building.

To illustrate how a building system situated at different sites may lead to different floor response spectra, two curves corresponding to the example building situated at soil and rock sites have been compared in Fig. 6 with the equipment located at the 6th floor. This figure clearly shows how a different characterization of design spectra leads to different floor spectra.

CONCLUSIONS

A stochastic approach has been proposed in this paper to generate the seismic floor spectra with the desired level of confidence from a given set of design spectra. The key features of this approach are: i) it can be used to obtain the floor response spectra for the higher order peaks of the secondary system response, and for any desired level of confidence, not just for the 'expected' level, ii) it properly accounts for the effects of structure-equipment interaction and non-classicality of damping in the combined system, and iii) it makes use of all the design spectra available for the different damping ratios. Central to the proposed approach is the use of primary system modes in calculating the transfer function of the absolute acceleration response of the SDOF oscillator to seismic excitation. Thus, the proposed approach does not require the calculation of the complex-valued natural frequencies and mode shapes of the non-classically damped combined system. The proposed approach has been illustrated through an example building and two example design motions, and the results have been found to be in agreement with the state-of-the-art understanding of the dependence of floor spectra on various governing parameters. This approach can be easily extended to estimate the stochastic response of the multiply-supported secondary systems as shown by Dey and Gupta (1996).

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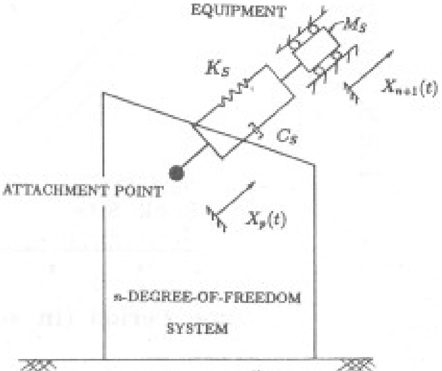

Fig. 1 Schematic Diagram of SDOF Oscillator Attached to n-Degree-of-Freedom System.

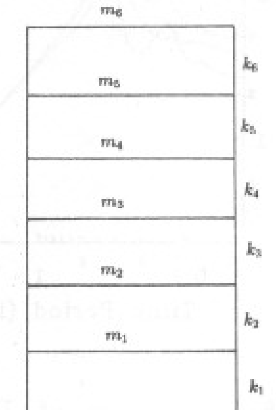

Fig. 2 Idealized Model for Example Building.

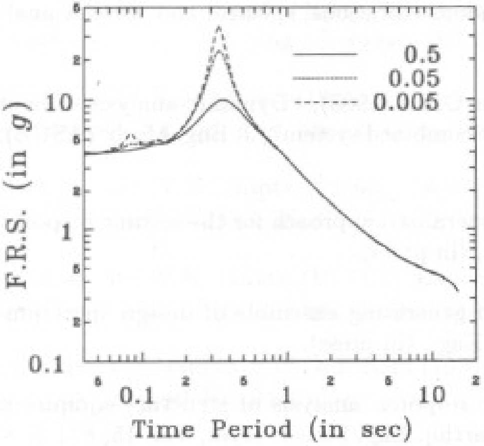

Fig. 3 Comparison of Floor Response Spectra for Different Mass Ratios.

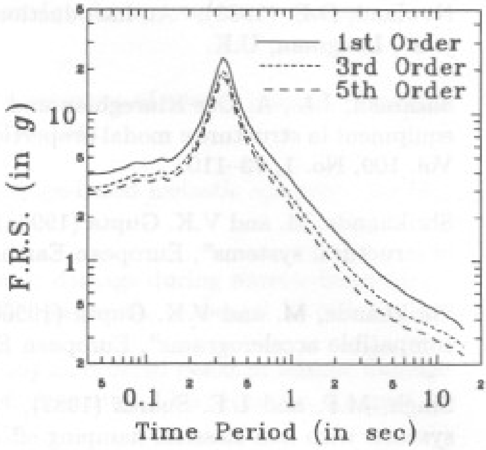

Fig. 4 Comparison of Floor Response Spectra for Different Orders of Peaks.

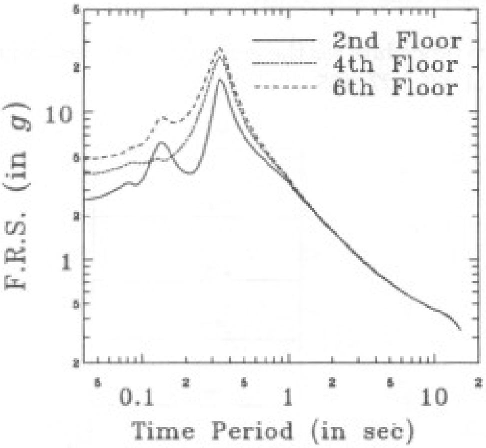

Fig. 5 Comparison of Floor Response Spectra for Different Equipment Locations.

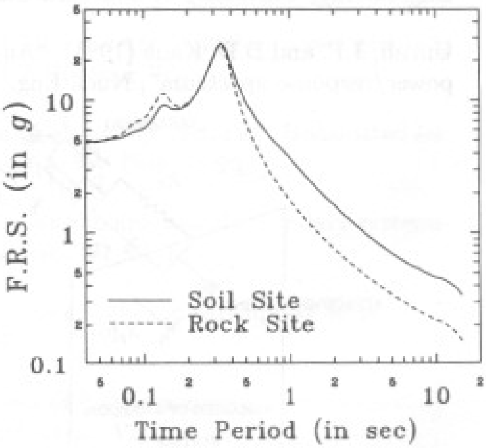

Fig. 6 Comparison of Floor Response Spectra for Soil and Rock Sites.