Estimation of Seismic Hazard in Peninsular India

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Introduction

Peninsular India, which is taken here as south of 24^0 N latitude, has faced several devastating earthquakes in the past, the most recent shocks being: Khillari (30.9.1993), Jabalpur (22.5.1997) and Kutch (26.1.2001) events. The largest of these have originated in the Kutch region, which has remained a region of great scientific and engineering interest. While considerable recorded data and earthquake related literature are available about North India, very little information is available about Peninsular India (PI). Since the available quantified scientific information is scanty, engineers currently face a problem in estimating reliable design basis ground motion for important project sites in PI. Occurrence of devastating earthquakes in this part of India has been a reminder that engineers have to use seismological approaches in estimating region specific design ground motion, instead of relying on thumb rules and *ad hoc* seismic zones. But, at the same time, analytical source mechanism models are not simple enough to be directly applicable in engineering problems. The major requirement in application is for estimating future hazard, rather than just understanding the past. The need is to know the ground motion due to all causative sources in a region of about 300 Km radius around a given site. However, in India engineers have been using a standard spectral shape as recommended by the code IS-1893 all over the country, modified only by a zone factor as a proxy to peak ground acceleration (PGA). Such an approach neither recognizes the seismo-tectonic details of the region nor accounts for the residual risk associated with the standard response spectrum. Hence, the planned design life of important structures cannot be rationally harmonized with the existing earthquake hazard. Clearly, whereas underestimation of hazard leads to questionable safety margins, overestimation makes the projects uneconomical. Thus, socio-economic goals suffer in either case. It is in this context probabilistic seismic hazard analysis (PSHA) has become indispensable to address engineering safety issues in terms of quantified risk levels. The expected site PGA and the response spectrum with a specified return period or risk can be derived from PSHA. Such a response spectrum, which has the same return period at all frequencies, is known as uniform hazard response spectrum (UHRS). In order to obtain UHRS, one has to first establish regional attenuation equations relating spectral amplitudes with magnitude and distance. The present paper addresses some of the above issues and proposes an attenuation relation paving the way for estimating rational design response spectra, for sites in PI. The available strong motion accelerograph (SMA) data in PI does not cover the entire region and lacks multiple SMA recordings of individual events.

Moreover, PI is not homogenous with respect to its seismogenic properties. Hence any empirical equation obtained solely with the help of the available incomplete SMA data will be unreliable. This difficulty can be overcome by adopting a stochastic seismological model as demonstrated by Boore (1983, 2003). In this approach, regional differences of quality factor within PI, uncertainties in stress-drop, radiation coefficient, cut-off frequency and focal depth can be included. With the help of a large synthetic database a frequency dependent attenuation relation can be obtained corresponding to bedrock conditions. Correction factors can also be found for different site conditions defined in terms of the average shear wave velocity in the top 30 meters (V_{30}) of the soil. This new attenuation relation will be useful in prescribing design response spectrum in PI. The proposed attenuation relation can be evaluated by comparing it with available recorded data of past earthquakes in PI.

Peninsular India

The region of the Indian subcontinent south of 24^0N latitude is taken here as Peninsular India (PI). This landmass is far away from the Himalayan collision zone, which is a well known boundary between the Indian and the Asian plates. Nonetheless, it is recognized that Cambay and Rann of Kutch in Gujarat are among the very active regions of India. Leaving this region and the Andaman-Nicobar Islands, the remaining part of continental PI has reliably experienced some 400 earthquakes in a period of 600 years. This number will be much larger if all instrumentally recorded shocks of small magnitudes were to be included. A list of damage causing earthquakes of engineering importance that have occurred in PI in the last 100 years, is presented in Table 1. General discussions on seismicity of PI, have been previously presented by Chandra (1977), and Rao and Rao (1984). A catalogue of earthquakes of magnitude ≥ 3 for PI has been compiled by Guha and Basu (1993). It is generally held that seismic activity is more at the intersections of the Dharwad, Aravali and Singhbhum proto-continents which together constitute PI (Fig. 1a). With data available upto 1984, Rao and Rao (1984) fitted the frequency-magnitude relationship

$$\mathrm{Log}_{10}\, N = a - bM \qquad (1)$$

to get a=4.4 and b=0.85, for PI. They also demonstrated that the interval 1870-1920 had been a period of quiescence, whereas prior to and after this time window PI showed higher levels of seismic activity. Seeber *et al* (1999) studied the seismicity of PI with particular reference to Maharashtra. They concluded that between 1960 and 1990 the seismicity of PI shows a threefold increase. This was the period during which industrial development also increased several fold in PI. Thus, engineers recognize that the seismic risk to man made structures in PI is more than what was previously believed to be.

Ground Motion Database

A brief review of strong motion data available for PI is presented in this section. The only region with SMA data is the Koyna-Warna region of western India (Fig. 1b). The earliest available PGA value for PI is from the Koyna earthquake record of 11^{th} December 1967. After this, a large number of records of smaller magnitudes have been obtained in the Koyna region. This set of data, taken from the reports of Gupta *et al* (1992) is presented in Table 2. For the main shock of the Khillari earthquake of 1993 no near source ground motion records are available. SMA records were obtained by Baumbach *et al* (1994) for a few aftershocks of this event. Three such PGA values are given in Table 3. A few instrumental velocity records within epicentral distances of 300 km are available for the Jabalpur earthquake of 1997 (Singh *et al* 1999). Similarly a few data are available for the main event and aftershocks of the Kutch earthquake of 2001. PGA values obtained by differentiating the instrumental velocity records of the Jabalpur earthquake and Kutch aftershock (Singh *et al* 2003) are also shown in Table 3.

Seismological Model

A critical review of the available strong motion data in PI has been presented previously by Iyengar and Raghukanth (2004). The moment magnitude (M_w) of events for which SMA data is available in PI is in a small range of 4 to 6.5. The database does not have instrumental values in all distance ranges of engineering importance and hence not usable for empirical attenuation studies. Ideally, multiple strong motion accelerogram (SMA) data from the same event should be available for distances varying from zero to 300 Km. In addition, magnitude values ranging from 4 to 8 should have been covered at reasonable increments. PI is similar to many other stable continental regions (SCR) of the world where data is scarce and not representative of the existing hazard. Attenuation equations in such regions have to be based on simulated ground motions and not on limited past recordings. The theory and application of stochastic seismological model has been discussed in detail by Boore (1983, 2003). Briefly, the Fourier amplitude spectrum of ground acceleration A(*f*) is expressed as

$$A(f) = C\,S(f)\,D(f)\,P(f)\,F(f) \tag{2}$$

Here, C is a scaling factor, S (*f*) is the source spectral function, D (*f*) is the diminution function characterizing the quality of the region, P (*f*) is a filter to shape acceleration amplitudes beyond a high cut-off frequency f_m, and F (*f*) is the site amplification function, which is unity at bedrock level. In the present study, for the source, the single corner frequency model

$$S(f) = (2\pi f)^2 \frac{M_0}{\left[1 + (f/f_c)^2\right]} \tag{3}$$

of Brune (1970) is used, where the corner frequency f_c, the seismic moment M_0 and the stress drop $\Delta\sigma$ are related through

$$f_c = 4.9x10^6\, V_s \left(\frac{\Delta\sigma}{M_0}\right)^{1/3} \tag{4}$$

Here the shear wave velocity V_s in the source region, corresponding to bedrock conditions, is taken as 3.6 km/s. The diminution function D(*f*) is defined as

$$D(f) = G \exp\left[\frac{-\pi f R}{V_s Q(f)}\right] \tag{5}$$

in which, G refers to the geometric attenuation and the remaining term denotes anelastic attenuation. In this equation, Q is the quality factor of the region. The high-cut filter in the seismological model is given by

$$P(f, f_m) = \left[1+\left(\frac{f}{f_m}\right)^8\right]^{-1/2} \quad (6)$$

Here, f_m controls the high frequency fall of the spectrum. The scaling factor C is

$$C=\frac{<R_{\theta\phi}>\sqrt{2}}{4\pi\rho V_s^3} \quad (7)$$

where $<R_{\theta\phi}>$ is the radiation coefficient averaged over an appropriate range of azimuths and take-off angles. The coefficient √2 in the above equation arises as the product of the free surface amplification and partitioning of energy in orthogonal directions. Following the work of Singh *et al* (2003), the geometrical attenuation term G, for the Indian shield region, is taken to be equal to 1/R for R < 100 km and equal to $\frac{1}{10\sqrt{R}}$ for R > 100 km. PI can be broadly divided into three regions, as far as the quality factor Q is concerned. Mandal and Rastogi (1998) have found for the Koyna-Warna (K-W) region Q to be $169f^{0.77}$. For the southern India (SI) region Q is $460f^{0.83}$ as per Rao *et al* (1998). Similarly for the Western-Central (W-C) region Q is found to be $508f^{0.48}$ by Singh *et al*(1999). These three regions, which make up PI are shown in Fig.1b. The seismological model is implemented in the time domain in each region through computer simulation, consisting of three steps. First, a Gaussian stationary white noise sample of length equal to strong motion duration, $T=(1/f_c+0.05R)$ is simulated. This sample is multiplied by the modulating function of Saragoni and Hart (1974) to introduce nonstationarity and then Fourier transformed into the frequency domain. This Fourier spectrum is normalized by its root-mean-square value and multiplied by the terms of equation 2, derived from the seismological model. The resulting function is transformed back into time domain, to get a sample of acceleration time history. For calculating spectral accelerations S_a, the generated acceleration time history is passed through a single degree-of-freedom oscillator with damping coefficient equal to 0.05. This way an ensemble of acceleration time histories and corresponding response spectra are obtained. The acceleration samples are conditioned on a given set of model parameters, which are by themselves uncertain. Thus the generated samples will not still reflect all the variability observed in real ground motion. To account for this, important model parameters namely stress drop, focal depth, f_m and the radiation coefficient are treated as uniformly distributed random variables. The stress drop is taken to vary between 100-300 bars (Singh *et al* 1999). The focal depth is taken as a uniform random variable in the range 5-15 km. The cut-off frequency, based on past strong motion data is taken in the interval 20-50 Hz. The S-wave radiation coefficient is taken in the interval 0.48-0.64, following Boore and Boatwright (1984). Spectral acceleration values are simulated for moment magnitude (M_w) ranging from 4 to 8 in increments of 0.5 units. The distance parameter is varied in intervals of $ln(r)$ = 0.13, where r stands for the epicentral distance. The combinations of M_w and r are presented in Table 4. A lower limit on the epicentral distance has to be imposed since the present model is based on point source assumption. The number of distance samples considered for each magnitude is also shown in Table 4. In all, there are 101 pairs of magnitudes and distances. For each magnitude, 100 samples of seismic parameters are used, with each set of seismic parameter representing a synthetic earthquake of a particular magnitude. Thus, the database consists of 10,100 S_a samples from 900 simulated earthquakes. This synthetic database has been generated separately for K-W, W-C and SI regions of PI using their respective quality factors.

Attenuation Relation

Attenuation of S_a with respect to magnitude and distance is central to hazard analysis. The attenuation equation chosen for PI is similar in form to the one used in the literature for other intra-plate regions (Iyengar and Raghukanth 2004). The attenuation equation is of the form

$$ln(Y_{br})=c_1+c_2(M-6)+c_3(M-6)^2-ln R-c_4R+ln(\varepsilon_{br}) \quad (8)$$

In the above equation, Y_{br} = (S_a/g) stands for the ratio of spectral acceleration at bedrock level to acceleration due to gravity. M and R refer to moment magnitude and hypocentral distance respectively. The average of the error term $ln(\varepsilon_{br})$ is zero. The standard deviation of this term is of importance in probabilistic hazard analysis. The coefficients of the above equation are obtained from the simulated database of S_a by two-step stratified regression. As an illustration, for M_w= 6 the 5% damped response spectra corresponding to two epicentral distances with focal depth of 10 Km are shown in Fig.2. There is considerable similarity in the shape of the response spectrum of all the three regions. At long distances, attenuation is slower at the low frequency end of the spectrum in South India. However, in the frequency range of engineering interest, the spectra are not sensitive to variation in Q-factor. Hence, it would be convenient to have a single composite formula for PI. The three regions namely K-W, W-C and SI cover PI nearly in the ratio 1:4:5. With this in view, fresh spectral acceleration samples have been selected from the three regional populations in the above ratio to create a new synthetic database for PI. This contains 10,100 samples as previously, covering the same magnitude and distance ranges. For the proposed attenuation relation of equation 8, the parameters obtained by stratified regression for PI are reported in Table 5 at 27 natural period values. At this point it would be interesting to compare the new spectral attenuation relation of PI with that of other stable continental regions of the world. In Fig. 3, response spectrum of PI for M_w=6 calculated at two hypocentral distances, is plotted along with the results of Atkinson and Boore (1995), Toro *et al*(1997), Hwang and Huo (1997) and Campbell (2003). Even though there are differences, all results peak at high frequencies, which is characteristic of intra-plate regions. It is noted the above attenuation relation is valid at the bedrock level, with V_s nearly equal to 3.6 km/s. For other site conditions, the results have to be modified as follows.

Site Correction Coefficients

The surface level ground motion at a given site may be visualized as the bedrock motion modified by the soil layers. The local site property is conveniently expressed in terms of the average shear wave velocity in the top 30 meters of the soil. This is the recognized FEMA-NEHRP (2001) approach, wherein sites are classified as A: (V_{30} > 1.5 Km/s); B:(0.76 Km/s <V_{30} ≤ 1.5 Km/s); C: (0.36 Km/s < V_{30} ≤ 0.76 Km/s); D: (0.18 Km/s < V_{30}≤ 0.36 Km/s). E- and F-type sites with V_{30} ≤ 0.18 Km/s are susceptible for liquefaction and failure. The general approach of spectral attenuation described above can be extended to A, B, C and D-type sites with the help of soil profiles and V_s values, sampled from the region. In addition to uncertainties in magnitudes and epicentral distances, one has to consider the variations in local soil properties for estimating spectral accelerations at the ground surface. It has to be noted that V_{30} being an average value, one can have any number of combinations leading to the same value. Thus, for a specific site, precise correction of the bedrock results will be possible only when soil section data is available including the variation of V_s with depth. However, when one is interested in a broad region like PI and the purpose is to develop a general design response spectrum, statistical simulation is a viable alternative. A random sample of ten profiles in each site category A, B, C and D is selected for further study. These are realistic in as much as they are drawn from actual borehole data from project sites in the country. In Tables 6(a, b, c, d) a few typical samples of such profiles are presented. The details of B, C and D type soil profiles are likely to vary widely according to the region. Here it is assumed that these are lying above A-type rock layers specific to that region. Modification between bedrock and A-type site is a linear problem in one dimension and hence for such sites amplification can be directly found by the quarter-wavelength method of Boore and Joyner (1997). However, for B, C and D-type profiles soil layering, viscoelastic properties and nonlinear effects become important. These can be handled with the software SHAKE91 (Idriss and Sun 1992), which requires the basement rock to be of A-type. Accordingly, acceleration time histories are first generated for A-type rock profiles and used as input to B, C and D-type profiles. The site coefficient F_s, (s = A, B, C, D) defined as the ratio of spectral acceleration at the surface to the bedrock value is determined for all the previous 27 natural periods. An important aspect of soil amplification studies is the possibility of reduction of S_a values between bedrock and surface due to softening of soil layers. To highlight this effect, in Fig. 4, the dependence of site coefficient is shown for S_a at zero period with respect to the corresponding bedrock value. This in effect is the ratio of the surface PGA to the bedrock value. It can be observed that F_A and F_B are randomly scattered indicating that these are nearly independent of the bedrock PGA values. However, site coefficients for C- and D-type sites exhibit strong dependence on bedrock values. This relation can be empirically expressed as,

$$\ln F_s = a_1 Y_{br} + a_2 + \ln \delta_s \qquad (9)$$

Where a_1 and a_2 are the regression coefficients and δ_s is the error term. These coefficients along with the standard deviation of $\ln \delta_s$ are presented in Table 7. The site coefficient F_s is a function of the natural period and is like a modification factor on the average S_a value at bedrock. With the help of Tables 5 and 7, the average 5% response spectrum can be easily found for any A, B, C and D-type site in PI from the expression

$$Y_s = Y_{br} F_s \qquad (10)$$

The deviation from the mean ε_s is characterized in terms of its standard deviation expressed as

$$\sigma(\ln \varepsilon_s) = \sqrt{\sigma(\ln \varepsilon_{br})^2 + \sigma(\ln \delta_s)^2} \qquad (11)$$

As an example of using the present theory, in Fig.5 the average response spectrum for an event of magnitude M_w=6 occurring at a hypocentral distance of 30 Km is presented for four different site conditions. As the site changes from A to D, the shift of the predominant frequency from higher to lower values is clearly brought out by this figure.

Validation

The above frequency dependent spectral attenuation model for PI has been validated using instrumental data of Koyna (11^{th} December 1967) and Kutch (26^{th} January 2001) earthquakes. The Koyna earthquake is the earliest event in India with a near source strong motion acceleration record. The location was the basement of Koyna dam on hard rock nearly corresponding to A-type site. In Tables 2 and 3, the analytical and recorded PGA values for events in the K-W region and other parts of PI are compared. In Fig. 6 the response spectrum analytically computed from the attenuation equations 8 and 10, is compared with the average of the recorded response spectrum of the two horizontal components of the 1967 Koyna event. The instrumental spectrum compares favourably with the predicted mean spectrum, with fluctuations within the sigma band. The recorded time history exhibits presence of high frequencies, which is reflected well in the predicted spectrum. The Kutch earthquake produced data on structural response recorders (SRR) at thirteen stations. This directly gives S_a at a particular period on the response spectrum corresponding to local site conditions. In Table 8, SRR data for two natural periods, 0.4s and 0.75s at 5 % damping are reported. The site conditions estimated approximately by Cramer and Kumar (2003) at these stations are also shown. The predictions from the present spectral attenuation relation for M_w=7.7 are presented in the same table for comparison. It is observed that the present predictions match well with observed values of PGA and S_a.

Discussion

In the absence of sufficient number of instrumental data, attenuation of spectral response and PGA, as a function of distance has to be estimated through analytical methods. Here, such a model has been presented for use in Peninsular India, taken as that part of India lying south of 24^0 N latitude. The model predictions have been validated with respect to two sets of available recorded data. This region is broadly made up of three sub regions for which information on quality factor as a function of frequency is available in the literature. The analysis has been carried out for all the three regions separately, but only results as applicable for PI broadly are presented here. It is found that the acceleration response spectrum in the range of frequencies of interest in engineering problems is not too sensitive to inter-regional variations. In view of this, a composite formula valid for PI is derived. It is felt that this general relation is sufficient for preliminary development of engineering design spectrum. In situations where the location of the site is given or when an existing important structure such as a nuclear power plant or a dam has to be studied, one may use specific regional attenuations, presented elsewhere. It has been verified that for the Koyna earthquake response spectrum, both the PI model and the K-W model give almost the same results. However, in Table 8 recorded spectral attenuation data from Kutch earthquake matches better with the W-C regional model than with the broad PI model. It may be noted here that variation in response spectrum will be pronounced due to local soil conditions. This is characterized by the average shear wave velocity in the top 30 meters of the soil, denoted as V_{30}. Based on this, a site is labeled as of A, B, C or D-type. The approach proposed here is to find the values corresponding to bedrock conditions and then to correct these values to suit the site conditions using the factors of Table 7. Sites classified, as E and F with very low V_{30} values are susceptible for failure and hence are not considered here. These sites demand more rigorous nonlinear dynamic analysis, which is not accounted by the present approach. Engineers in India generally use the spectral shape recommended by the BIS code IS-1893, further scaled by a zonal factor supposedly representing the expected PGA at the site. The BIS code recommends two normalized spectrum shape for rock and soil conditions as being valid all over India for all magnitudes and hypocentral distances. Thus, it would be interesting to compare these code spectra with the present results. The normalized analytical spectral shape corresponding to equation 8 can be easily obtained by considering M and R as random variables. Here the moment magnitude M is taken as exponentially distributed in 5 to 8. The distance term is distributed as a uniform random variable in 25-250 Kms. The average spectra so obtained is scaled to unit PGA and presented in Fig.7 along with the recommendations of IS-1893. It is seen that the provisions in the code have serious limitations as far as Peninsular India is concerned. The rock site of IS code is between C- and D-type site with V_{30} being less than 0.76 km/s. For hard rock sites that are commonly met in PI the code values underestimate the forces at the high frequency or short period end, leaving stiff structures more vulnerable to ground motion. On the other hand, at soil sites the code overestimates force levels at longer periods, making tall structures costlier than necessary.

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Table 1. Earthquakes of Peninsular India

Location	Date	Epicenter ^{0}N - ^{0}E	Focal Depth (km)	Mag. (M_w)	Epicentral Intensity (I_o)
Coimbatore	7.2.1900	10.8 76.8	?	6.1	VIII
Vijayanagaram	17.4.1917	18.0 84.0	?	5.5	VII
Anjar	21.7.1956	23.0 70.0	?	6.1	IX
Ongole	13.10.1959	15.6 80.1	?	5.0	VII
Ongole	27.3.1967	15.6 80.0	?	5.8	VII
Koyna	13.9.1967	17.4 73.7	?	5.8	VIII
Koyna	10.12.1967	17.5 73.7	10	6.5	VIII-IX
Bhadrachalam	13.4.1969	17.9 80.6	25	5.7	VII
Broach	23.3.1970	21.7 72.9	8	5.8	VII
Coimbatore	29.7.1972	11.0 77.0	?	5.0	VI
Shimoga	12.5.1975	13.8 75.3	10	5.0	V
Krishnagiri	20.3.1984	12.58 77.78	6	4.5	VI
Idukki	7.6.1988	9.81 77.21	5	4.5	V
Khillari	29.9.1993	18.06 77.5	7	6.2	VIII
Bonaigarh	29.03.1995	21.66 84.59	21	4.7	V
Jabalpur	21.5.1997	23.0 80.0	35	5.8	VIII
Bhuj, Kutch	26.1.2001	23.4 70.28	24	7.7	XI
Bhuj, Kutch	28.1.2001	23.61 70.46	15	5.7	VII

Table 2. Instrumental PGA for Koyna-Warna Region

Epicenter ^{0}N - ^{0}E	Date	M_w	Epi.Dist. (km)	Depth (km)	Rec. PGA (g)	PGA (g) Eq. 8
17.50 73.73	13.09.1967	5.6	13	3	0.1640	0.2651
17.48 73.74	13.09.1967	4.3	11	5	0.0200	0.0726
17.50 73.73	10.12.1967	6.5	13	10	0.4860	0.4827
17.28 73.69	12.12.1967	4.5	14	13	0.0360	0.0546
17.29 73.78	13.12.1967	4.4	12	15	0.0410	0.0483
17.35 73.75	24.12.1967	4.8	7	20	0.0500	0.0676
17.35 73.75	24.12.1967	4.8	7	20	0.0350	0.0676
17.33 73.70	04.03.1968	4.0	4	10	0.0190	0.0576
17.36 73.76	04.03.1968	4.0	9	10	0.0090	0.0450
17.36 73.76	01.01.1970	4.1	9	11	0.0130	0.0479
17.32 73.71	27.05.1970	4.2	11	3	0.0698	0.0688
17.48 73.81	26.09.1970	4.2	11	13	0.0420	0.0439
17.36 73.65	17.02.1974	4.5	17	19	0.0214	0.0387
17.49 73.77	29.07.1974	4.1	8	24	0.0360	0.0244
17.27 73.75	02.09.1980	4.1	18	13	0.0293	0.0286
17.23 73.74	02.09.1980	4.1	18	13	0.0110	0.0286
17.23 73.74	20.09.1980	4.5	21	8	0.0310	0.0450
17.20 73.76	20.09.1980	4.7	17	8	0.0220	0.0697
17.25 73.70	20.09.1980	4.7	17	8	0.0219	0.0697
17.24 73.71	25.04.1982	4.1	18	13	0.0293	0.0286
17.24 73.71	25.04.1982	4.1	18	13	0.0110	0.0286
17.35 73.70	12.03.1995	4.5	20	10	0.0130	0.0452
17.32 73.67	13.03.1995	4.2	25	10	0.0055	0.0255

Table 3. Instrumental PGA for Western-Central Region

Epicenter ^{0}N - ^{0}E	Date	M_w	Epicentral Dist. (km)	Focal Depth(km)	Rec. PGA (g)	PGA (g) Eq. 8
17.93 76.40	08.10.1993	4.3	21	5	0.0640	0.0373
17.93 76.40	08.10.1993	4.3	11	5	0.0103	0.0709
17.93 76.40	08.10.1993	4.3	13	5	0.0655	0.0608
23.8 80.06	21.05.1997	5.8	237	36	0.0125	0.0043
23.8 80.06	21.05.1997	5.8	271	36	0.0086	0.0030
23.61 70.46	28.01.2001	5.7	101	15	0.0079	0.0218
23.61 70.46	28.01.2001	5.7	249	15	0.0017	0.0035

Table 4. Ranges of epicentral distance

Moment Magnitude M_w	Epi. distance r Km	No. of distance samples
4	1-300	20
4.5	1-300	20
5.0	5-300	14
5.5	15-300	10
6.0	25-300	9
6.5	35-300	8
7.0	40-300	7
7.5	45-300	7
8.0	60-300	6

Table 5. Coefficients of Attenuation Equation. Peninsular India

Period	C_1	C_2	C_3	C_4	σ (ε)
0.000	1.6858	0.9241	-0.0760	0.0057	0.4648
0.010	1.7510	0.9203	-0.0748	0.0056	0.4636
0.015	1.8602	0.9184	-0.0666	0.0053	0.4230
0.020	2.0999	0.9098	-0.0630	0.0056	0.4758
0.030	2.6310	0.8999	-0.0582	0.0060	0.5189
0.040	2.8084	0.9022	-0.0583	0.0059	0.4567
0.050	2.7800	0.9090	-0.0605	0.0055	0.4130
0.060	2.6986	0.9173	-0.0634	0.0052	0.4201
0.075	2.5703	0.9308	-0.0687	0.0049	0.4305
0.090	2.4565	0.9450	-0.0748	0.0046	0.4572
0.100	2.3890	0.9548	-0.0791	0.0044	0.4503
0.150	2.1200	1.0070	-0.1034	0.0038	0.4268
0.200	1.9192	1.0619	-0.1296	0.0034	0.3932
0.300	1.6138	1.1708	-0.1799	0.0028	0.3984
0.400	1.3720	1.2716	-0.2219	0.0024	0.3894
0.500	1.1638	1.3615	-0.2546	0.0021	0.3817
0.600	0.9770	1.4409	-0.2791	0.0019	0.3744
0.700	0.8061	1.5111	-0.2970	0.0017	0.3676
0.750	0.7254	1.5432	-0.3040	0.0016	0.3645
0.800	0.6476	1.5734	-0.3099	0.0016	0.3616
0.900	0.4996	1.6291	-0.3188	0.0015	0.3568
1.000	0.3604	1.6791	-0.3248	0.0014	0.3531
1.200	0.2904	1.7464	-0.3300	0.0013	0.3748
1.500	-0.2339	1.8695	-0.3290	0.0011	0.3479
2.000	-0.7096	1.9983	-0.3144	0.0011	0.3140
2.500	-1.1064	2.0919	-0.2945	0.0010	0.3222
3.000	-1.4468	2.1632	-0.2737	0.0011	0.3493
4.000	-2.0090	2.2644	-0.2350	0.0011	0.3182

Table 6a. Random Sample Profile of A-type Site

A-1 (V_{30}= 1.5 Km/s)				A-2 (V_{30}= 2.00 Km/s)			
Th. (m)	**Density (g/cm^3)**	**V_s (m/s)**	**Q**	**Th. (m)**	**Density (g/cm^3)**	**V_s (m/s)**	**Q**
500	2.4	1.50	50	1000	2.1	2.00	100
1500	2.5	2.00	500	4000	2.4	2.20	500
500	2.5	2.30	2000	5000	2.5	3.10	2000
9000	2.6	2.95	1500	4000	2.9	3.20	1000
10000	2.6	3.00	1000				
Bedrock				Bedrock			

Table 6b. Random Sample Profiles of B-type Site

B-1 (V_{30}=1.01 Km/s)				B-2 (V_{30}=0.89 Km/s)			
Material	**Th. (m)**	**Density (g/cm^3)**	**V_s (Km/s)**	**Material**	**Th. (m)**	**Density (g/cm^3)**	**V_s (Km/s)**
C	10.0	2.11	0.68	C	8.0	2.10	0.65
C	5.0	2.12	0.97	R	6.0	2.11	0.76
R	5.0	2.12	1.10	R	6.0	2.12	0.90
R	8.0	2.10	1.30	R	8.0	2.15	1.13
R	15.0	2.16	1.40	R	1.0	2.17	1.34
A-2				A-2			

Table 6c. Sample Soil Profile of C-type Site

C-1 (V_{30}= 0.39 Km/s)				C-2(V_{30}= 0.38 Km/s)			
Material	**Th. (m)**	**Density (g/cm^3)**	**V_s (Km/s)**	**Material**	**Th. (m)**	**Density (g/cm^3)**	**V_s (Km/s)**
C	1.5	2.01	0.24	C	3.2	2.02	0.32
C	4.0	2.02	0.36	C	4.5	2.05	0.36
S	10.0	2.12	0.39	C	10.2	2.07	0.41
S	11.2	2.10	0.41	C	5.6	2.11	0.46
S	9.3	2.06	0.39	S	15.4	2.01	0.31
S	5.6	2.08	0.47	S	18.4	2.12	0.29
C	10.9	2.16	0.56	C	7.4	2.13	0.36
C	7.3	2.13	0.66	C	10.4	2.01	0.59
C	15.1	2.21	0.48	C	14.3	2.16	0.58
C	25.1	2.14	0.56	C	10.5	2.12	0.54
R	10.0	2.11	0.74	R	10.0	2.11	0.74
R	8.0	2.12	0.60	R	8.0	2.12	0.60
R	11.0	2.11	0.98	R	11.0	2.11	0.98
R	5.0	2.14	1.10	R	5.0	2.14	1.10
R	16.0	2.12	1.20	R	16.0	2.12	1.20
A-2				A-2			

Table 6d. Sample Soil Profile of D-type Site

D-1 (V_{30}= 0.27 Km/s)				D-2 (V_{30}=0.26 Km/s)			
Material	**Th. (m)**	**Density (g/cm^3)**	**V_s (Km/s)**	**Material**	**Th. (m)**	**Density (g/cm^3)**	**V_s (Km/s)**
S	3.7	1.76	0.16	C	3.2	1.65	0.13
C	2.8	2.08	0.41	S	4.5	1.82	0.18
S	6.4	2.16	0.24	S	10.2	2.01	0.24
S	3.7	2.01	0.23	C	5.6	2.11	0.33
S	18.6	2.01	0.30	C	15.4	2.01	0.34
C	9.2	2.08	0.35	C	18.4	2.00	0.35
C	10.9	2.16	0.36	C	7.4	2.10	0.38
C	7.3	2.08	0.58	C	10.4	2.14	0.49
C	6.1	2.01	0.40	C	14.3	2.16	0.52
C	31.4	2.08	0.58	C	10.5	2.12	0.59
R	10.0	2.11	0.74	R	10.0	2.11	0.74
R	8.0	2.12	0.60	R	8.0	2.12	0.60
R	11.0	2.11	0.98	R	11.0	2.11	0.98
R	5.0	2.14	1.10	R	5.0	2.14	1.10
R	16.0	2.12	1.20	R	16.0	2.12	1.20
A-2				A-2			

C-Clay, R-Rock, S-Sand

Table 7. Site coefficients

Period (sec)	**F_A (a_1=0)**		**F_B(a_1=0)**		**F_C**			**F_D**		
	a_2	**$\sigma(\ln\delta_A)$**	**a_2**	**$\sigma(\ln\delta_B)$**	**a_1**	**a_2**	**$\sigma(\ln\delta_C)$**	**a_1**	**a_2**	**$\sigma(\ln\delta_D)$**
0.000	0.36	0.03	0.49	0.08	-0.89	0.66	0.23	-2.61	0.80	0.36
0.010	0.35	0.04	0.43	0.11	-0.89	0.66	0.23	-2.62	0.80	0.37
0.015	0.31	0.06	0.36	0.16	-0.89	0.54	0.23	-2.62	0.69	0.37
0.020	0.26	0.08	0.24	0.09	-0.91	0.32	0.19	-2.61	0.55	0.34
0.030	0.25	0.04	0.18	0.03	-0.94	-0.01	0.21	-2.54	0.42	0.31
0.040	0.31	0.01	0.29	0.01	-0.87	-0.05	0.21	-2.44	0.58	0.31
0.050	0.36	0.01	0.40	0.02	-0.83	0.11	0.18	-2.34	0.65	0.29
0.060	0.39	0.01	0.48	0.02	-0.83	0.27	0.18	-2.78	0.83	0.29
0.075	0.43	0.01	0.56	0.03	-0.81	0.50	0.19	-2.32	0.93	0.19
0.090	0.46	0.01	0.62	0.02	-0.83	0.68	0.18	-2.27	1.04	0.29
0.100	0.47	0.01	0.71	0.01	-0.84	0.79	0.15	-2.25	1.12	0.19
0.150	0.50	0.02	0.74	0.01	-0.93	1.11	0.16	-2.38	1.40	0.28
0.200	0.51	0.02	0.76	0.02	-0.78	1.16	0.18	-2.32	1.57	0.19
0.300	0.53	0.03	0.76	0.02	0.06	1.03	0.13	-1.86	1.51	0.16
0.400	0.52	0.03	0.74	0.01	-0.06	0.99	0.13	-1.28	1.43	0.16
0.500	0.51	0.06	0.72	0.02	-0.17	0.97	0.12	-0.69	1.34	0.21
0.600	0.49	0.01	0.69	0.02	-0.04	0.93	0.12	-0.56	1.32	0.21
0.700	0.49	0.01	0.68	0.02	-0.25	0.88	0.12	-0.42	1.29	0.21
0.750	0.48	0.02	0.66	0.02	0.36	0.86	0.09	-0.36	1.28	0.19
0.800	0.47	0.01	0.63	0.01	-0.34	0.84	0.12	-0.18	1.27	0.21
0.900	0.46	0.01	0.61	0.02	-0.29	0.81	0.12	0.17	1.25	0.21
1.000	0.45	0.02	0.37	0.11	0.24	0.78	0.10	0.53	1.23	0.15
1.200	0.43	0.01	0.57	0.03	-0.11	0.67	0.09	0.77	1.14	0.17
1.500	0.39	0.02	0.51	0.04	-0.10	0.62	0.09	1.13	1.01	0.17
2.000	0.36	0.03	0.44	0.06	-0.13	0.47	0.08	0.61	0.79	0.15
2.500	0.34	0.04	0.40	0.08	-0.15	0.39	0.08	0.37	0.68	0.15
3.000	0.32	0.04	0.38	0.10	-0.17	0.32	0.09	0.13	0.60	0.13
4.000	0.31	0.05	0.36	0.11	-0.19	0.35	0.08	0.12	0.44	0.15

Table 8. Comparison between analytical results with SRR data of Kutch earthquake

Station	Hypo. Distance (km)	Site condition	S_a/g, 0.4s, period		S_a/g, 0.75 s, period	
			Recorded	Eq. 8 & 10	Recorded	Eq. 8 & 10
Anjar	49	C	1.62	0.93	0.70	0.63
Kandla	57	C	0.86	0.79	0.57	0.52
Niruna	99	D	0.81	0.54	0.65	0.39
Naliya	148	C	0.72	0.25	0.22	0.17
Khambaliya	151	B	0.18	0.19	0.07	0.13
Jamjodhpur	167	B	0.22	0.17	0.15	0.12
Dwaraka	189	D	0.21	0.26	*	0.18
Porbander	207	D	0.19	0.23	0.25	0.16
Junagarh	217	B	0.19	0.14	0.06	0.10
Amreli	226	B	0.09	0.12	0.07	0.08
Ahmedabad	239	D	0.29	0.19	0.23	0.14
Cambay	266	D	0.49	0.16	0.04	0.12
Anand	288	D	0.14	0.14	0.06	0.10

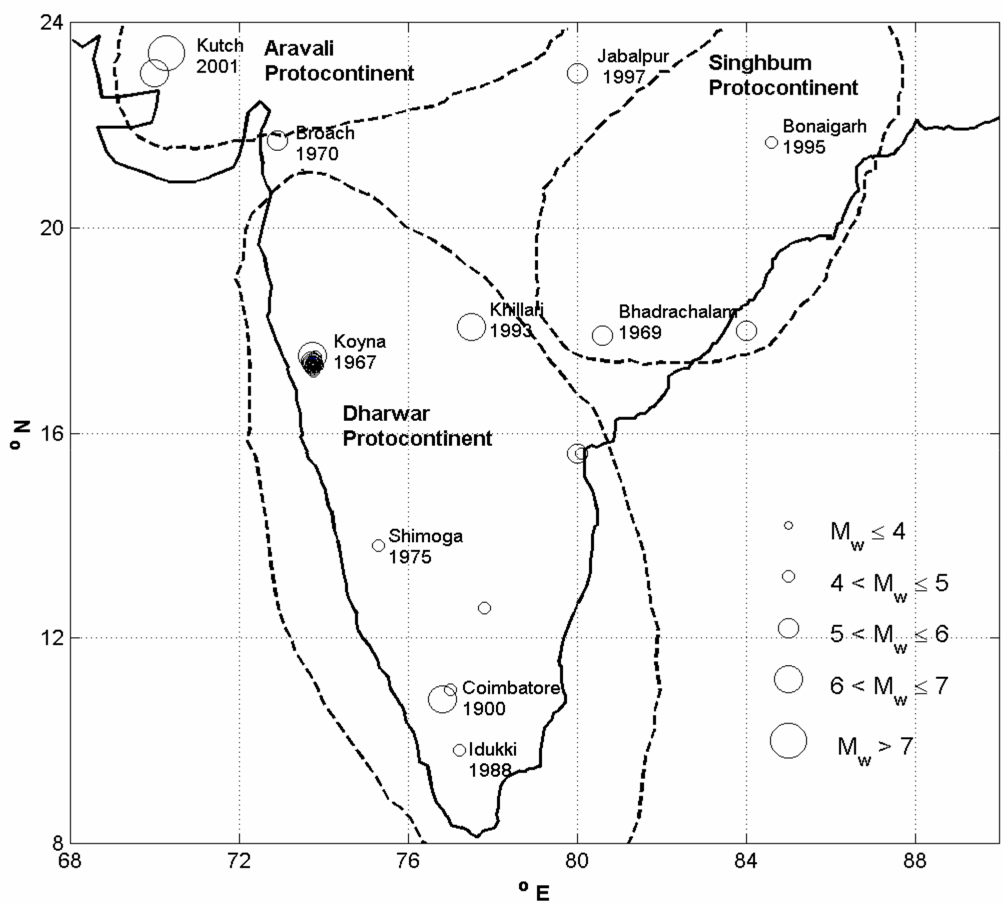

Fig 1a. Peninsular India

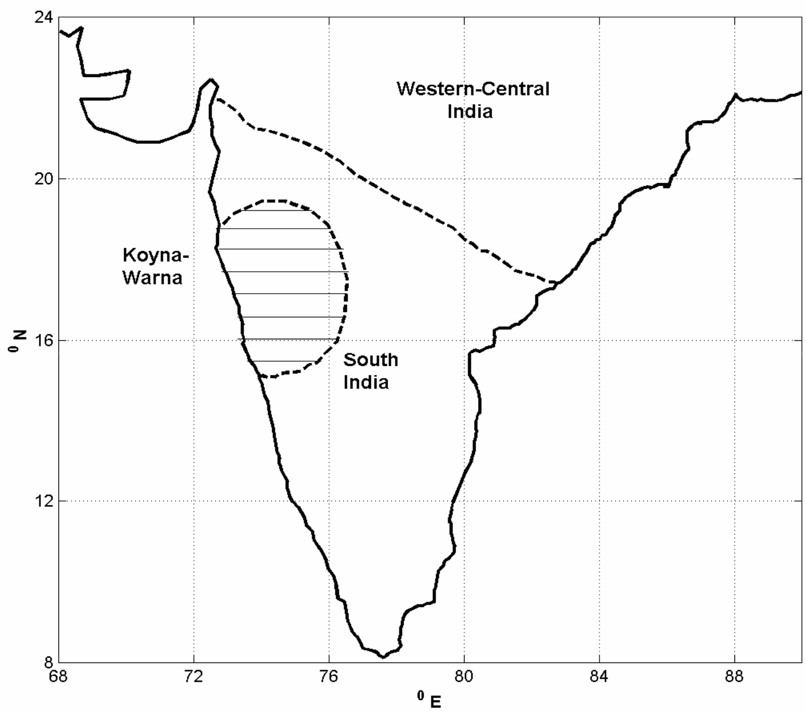

Figure 1b. Three Sub-regions of Peninsular India

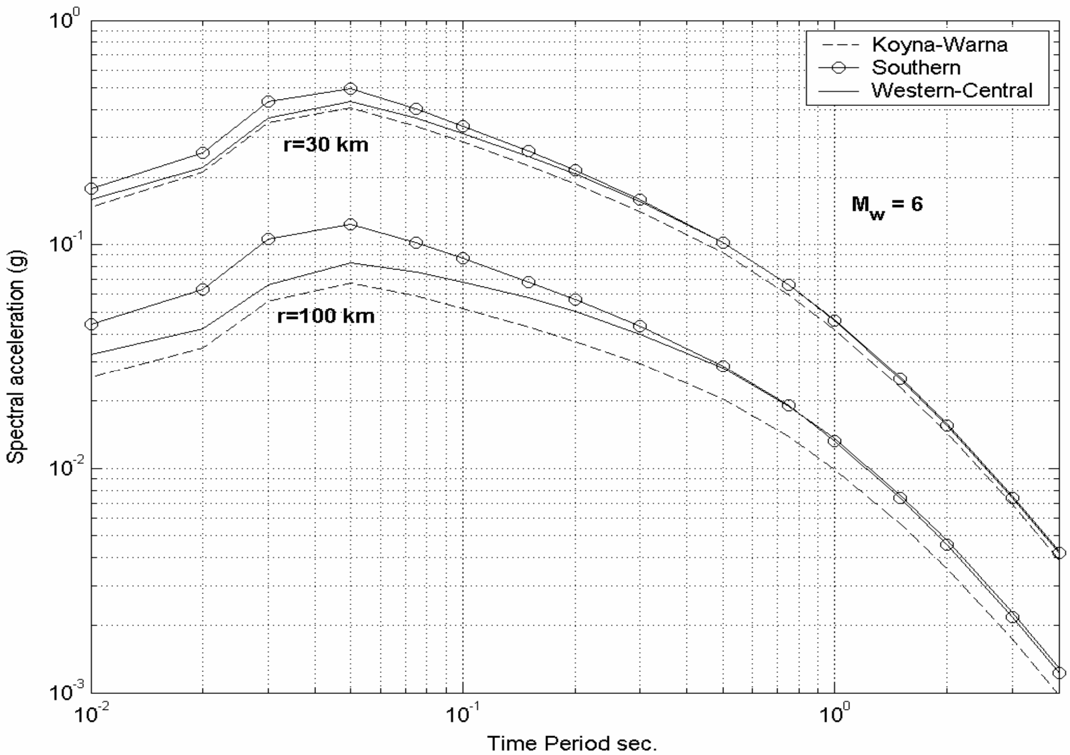

Figure 2. Response Spectrum for the three regions of PI.

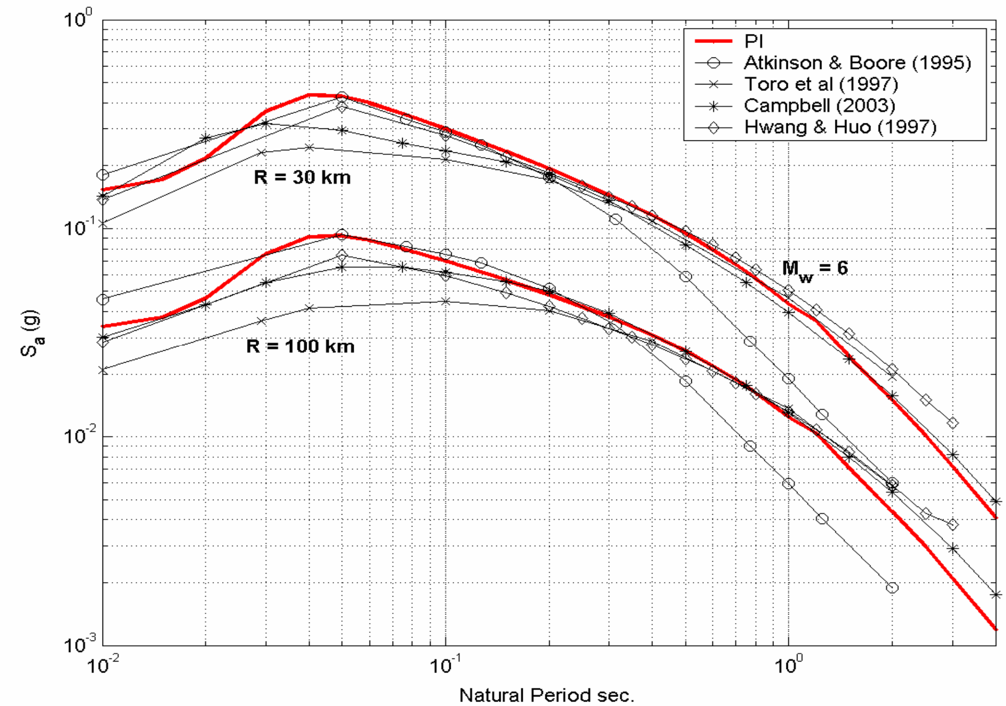

Figure 3. Comparison of SCR Spectral accelerations

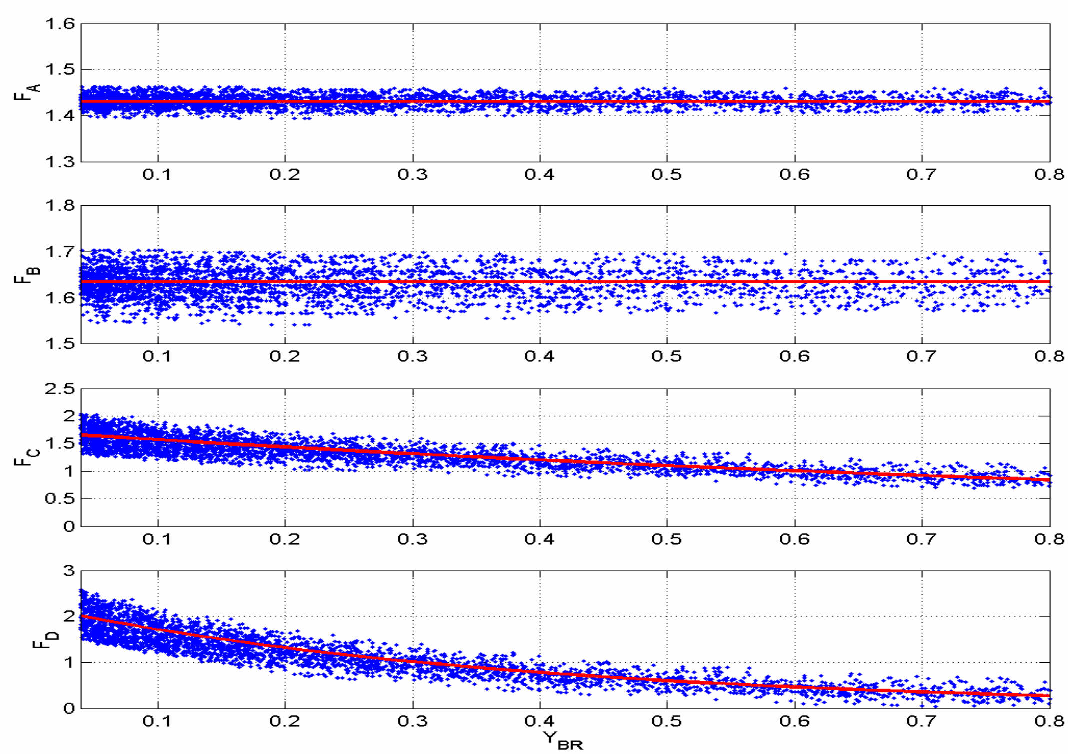

Figure 4. Dependence of surface level PGA on bedrock (Vs=3.6 Km/s) PGA

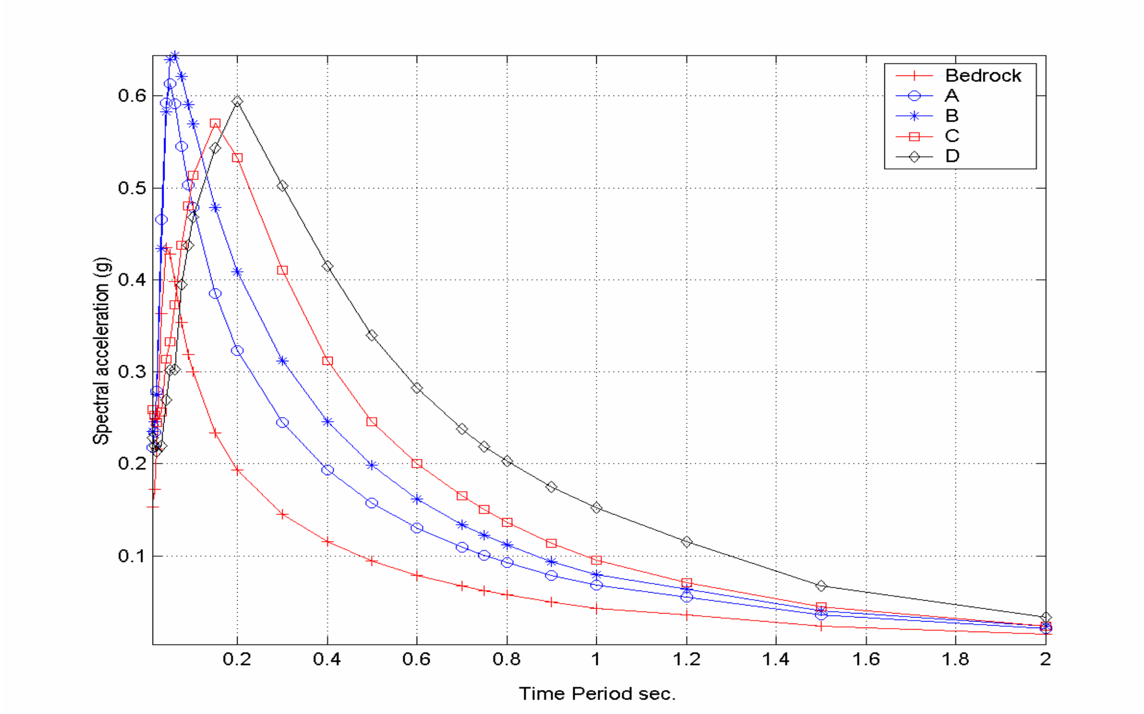

Figure 5. Effect of local site condition on response spectrum (Mw=6; r=30km)

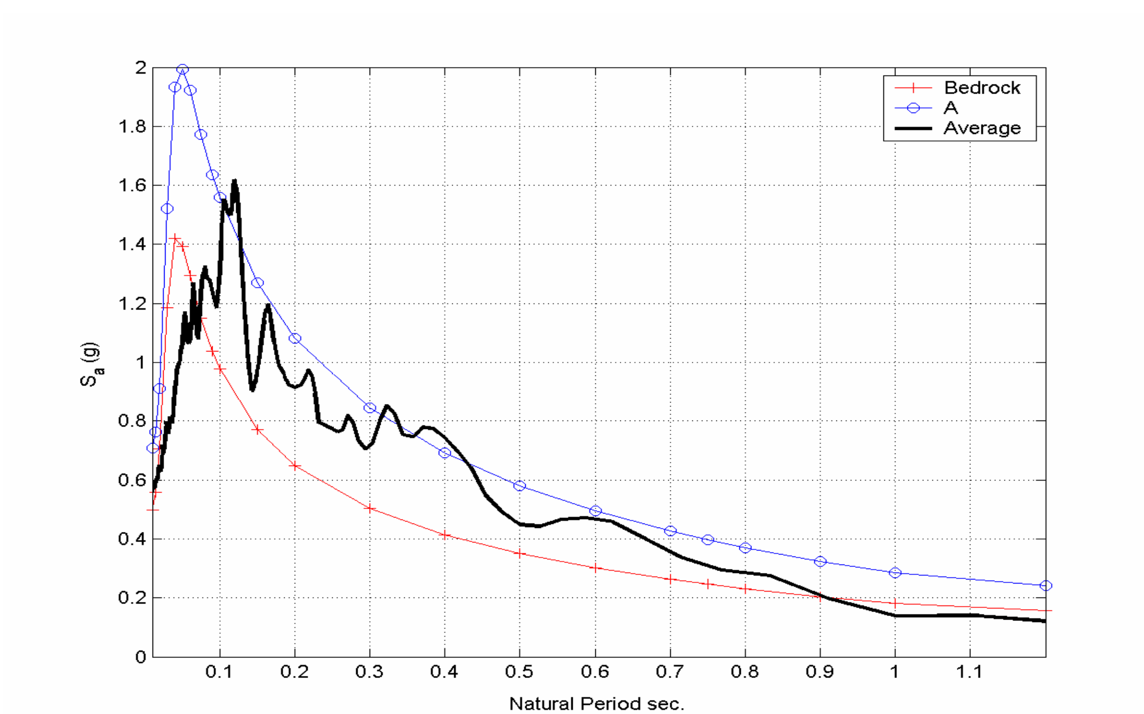

Figure 6. Analytical response spectra and recorded Koyna (11-12-1967) earthquake spectra (Mw=6.5; r=13km; Focal Depth=10 km, η=5 %)

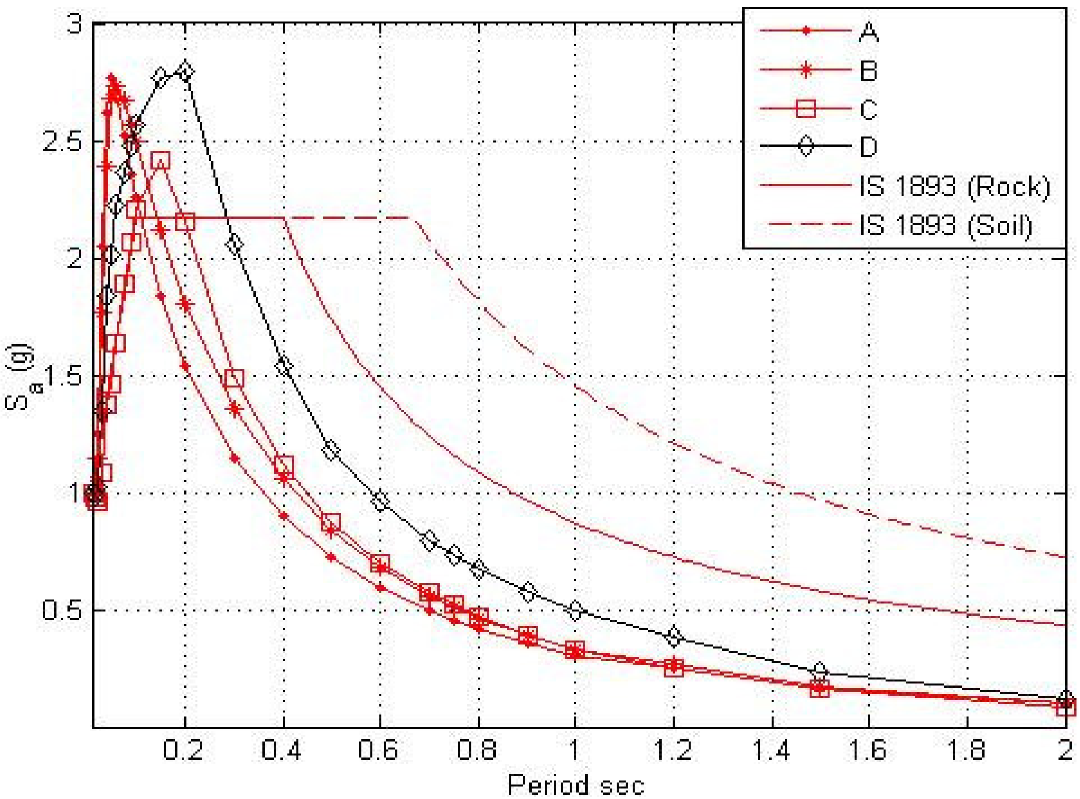

Figure 7. Comparison between analytical response spectra and IS-1893 design spectrum (η=5 %)