Bull. Ind. Soc. Earth. Tech., Paper No.370, Vol.34 No.4, Dec. 1997, pp 171- 208

STRONG MOTION: ANALYSIS, MODELLING AND APPLICATIONS

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INTRODUCTION

Earthquakes, their occurrence and their effects on natural relief and man made structures has been a topic of concern to humanity for a long time. However it is only in recent years that major breakthrough have been achieved in the scientific and engineering understanding of earthquakes. One such significant development has been in the recording of ground motion very near the epicenter referred to as **strong motion**. Seismologists had been recording signatures from earthquakes at long distances to estimate the magnitudes of the events and the elastic properties of the intervening medium. Engineers on the other hand are interested in the safety of the structures already built and those yet to be built in the felt region. Thus, emphasis on collecting and understanding ground vibration characteristic near the epicenter is more prevalent in engineering literature. This is not to say that nearsource (or near field) motion, as strong motion is sometimes referred, is not of interest to Seismologists. Ground motion records from the epicentral region are of great help in understanding the source mechanism at the fault level. The approach of the engineers has been somewhat empirical with the focus being safe design of structures. On the otherhand the approach of Seismologists has been less empirical and more mechanistic. Both the approaches have lead to many useful results. However the present talk will be mainly from the engineering point of view.

The outline of the presentation is as follows. After a brief historical review, certain aspects of characterization of strong motion data are discussed. This is followed by a review of empirical stochastic models for strong motion accelerograms. After a presentation on the direct models based on accelerograms, indirect models based on the effect of earthquakes on structures are considered. The concepts of spectrum compatible accelerograms and spectrum compatible power spectrum density (PSD) are presented. The application of the models are highlighted by way of a few real life examples. Progress in earthquake engineering has been closely linked with how well we understand strong ground motion. Recently some new initiatives have been taken in this direction at the Central Building Research Institute. These are briefly presented towards the end of the talk.

2.0 STRONG MOTION RECORDS

John Freeman may be considered the founding father of Strong Motion Siesmometry (Hudson 1983). The earliest strong motion records are that of the Long Beach, California earthquake of 10, March 1933. The number of such records were rather limited till the Seventies. The standard information source was the EERL reports of the California Institute of Technology, USA until after the San Fernando event of 1971. The early accelerograms were recorded on film on paper and had to be manually digitized. The modern digital seismographs are sophisticated enough to record the signals in digital format. Till the SanFernando event, samples were limited to one or two from the same shock. The San Fernando event was the first one to be recorded at large number of stations. Since then there has been a steady increase in the number of strong motion accelerograms recorded around the world. In 1992, USGS brought our a data base of 4270 available accelerograms from about 500 earthquakes which occurred during the period 1933-1986 in North America. Recently a data base for free field records of the period 1933-1992 has been brought out by Naiem and Anderson (1993). This collection consists of 1155 horizontal and 390 vertical strong motion accelerograms from North America.

The earliest strong motion records in India were from the 1967 Koyna earthquake. These were manually digitized and analyzed by Jaikrishna and Chandrashekaran (1969). The strong motion instrumentation program of the Department of Earthquake Engg., University of

Roorkee(Chandrashekharan and Das 1990) has lead to valuable records of Dharmashala-1986; Uttarkashi-1991 and five other events from the N.E. region. There were no strong motion instruments in the epicentral region to record the devastating Killari earthquake 30 Sept. of 1993. However an after shock of magnitude 4.3 was recorded on 8th Oct. 1993 by Baumbach et al (1994). This record shows peak ground accelerations of 0.153g and 0.11g in the horizontal and vertical directions respectively.

3.0 CHARACTERIZATION OF STRONG MOTION

There is a large body of literature available on the question of what constitutes strong motion. From the engineering point of view, the record itself is the complete description. However it may be noted here that SM records have been found to be highly erratic and random in their temporal evolution: Since predicting the behaviour of structures to possible future earthquakes is the prime goal, there have been efforts to characterize a record in terms of a few so called strong motion parameters. These are more often taken to be the peak ground acceleration (PGA), peak velocity, displacement, duration and zero crossing rate. To these are added the causative factors such as magnitude and epicentral distance and descriptors of effects on structures such as response spectral amplitudes. All these parameters are uncertain to various degrees and hence to be handled as random variables. The line of study of seismic data wherein the faster time scale of the strong ground motion of a few seconds is not considered but the longer time scale of return periods of events is included is generally termed as **probabilistic risk analysis**. This has been a very powerful approach for estimating seismic risk at project sites and finds a place in several guidelines and codes of practice.

3.1 INTERRELATIONSHIP AMONG SM PARAMETERS

It is clear that larger magnitudes and shorter epicentral distances are associated with higher peak ground accelerations. Similarly site conditions play a role in the frequency content and duration of strong motion. Thus, many of the SM parameters are interrelated. A recent study of some of the parameters such as PGA, PGV and PGD are presented by Naiem and Anderson (1993). A multivariate statistical study of twelve parameters belonging to ninetytwo SM records was carried out by Iyengar and Prodhan (1983). The parameters selected for the study and their statistics are shown in Table 1. The correlation matrix shown in table 2, brings out the interdependence among the various parameters. This lead to the application of principal component analysis to identify the major orthogonal weighted combinations of the parameters which explain the variances in decreasing order. The first three eigen vectors of the correlation matrix are also shown in Table 1. These may be used to arrive at a classification diagram of the earthquakes of the data base. The advantage of such a diagram (Fig. 1) is that earthquakes with incomplete data or those postulated as possible in future can be marked on the classification diagram. By knowing the nearness of the marked point to past observed earthquakes, damage intensities can be predicted. However this work done way back in 1983 needs updating and revision.

3.2 TIME SERIES ANALYSIS

The general characteristics of strong motion accelerograms are by now well known. The two unmistakable features are the randomness and the quick buildup of amplitudes followed by a relatively slower decay. Thus viewed as a time series, strong earthquake motion is a nonstationary random process, which a few samples of which may be available as recorded accelerograms. Analysis of random process data (Bendat and Piersol 1971) is a well established field. The description of a random process is complete only when joint probabilities of all orders are known. A tremendous simplification is possible provided the process is Gaussian. For earthquake accelerograms, a rigorous

TABLE 1. MEAN AND STANDARD DEVIATION OF THE PARAMETERS AND THE FIRST THREE EIGENVECTORS OF THE CORRELATION MATRIX

No.	Parameters	Mean m_k	Standard deviation s_k	Q_{1j}	Q_{2j}	Q_{3j}
1	Richter's Magnitude	5.958	0.726	0.112	0.407	0.255
2	Duration; s	20.282	13.271	-0.171	0.435	-0.039
3	Peak hor. acc., a_p; $cm.s^{-2}$	113.615	140.465	0.440	0.014	-0.060
4	Peak hor. velocity, $cm.s^{-1}$	10.088	13.508	0.438	0.111	-0.060
5	Peak hor. displ; cm.	4.370	5.521	0.390	0.163	0.051
6	Time to a_p; s	5.406	5.738	-0.035	0.445	0.041
7	Other peak hor. acc/a_p	0.763	0.174	-0.026	0.114	0.560
8	Peak vert. acc/a_p	0.478	0.219	0.024	-0.006	0.595
9	Epicentral dist; km	58.741	56.625	-0.196	0.406	0.156
10	Soil condition	1.467	0.654	0.118	-0.283	0.267
11	Zero crossing rate; s^{-1}	7.174	3.060	0.120	-0.342	0.383
12	Max. P.S.V.; cm. s^{-1}	69.831	64.90	0.395	0.198	-0.110
13	RMS acc.; cm. s^{-1}	24.202	31.231	0.443	0.008	-0.010

TABLE 2. CORRELATION MATRIX

$[r_{kl}]$ =

1.000												
0.378	1.000						Sym.					
0.177	-0.331	1.000										
0.266	-0.177	0.930	1.000									
0.348	-0.073	0.751	0.888	1.000								
0.471	0.482	-0.030	0.384	0.079	1.000							
0.208	0.148	-0.040	-0.052	0.004	0.140	1.000						
0.130	-0.060	-0.066	0.029	0.218	-0.036	0.229	1.000					
0.405	0.587	-0.343	-0.246	-0.178	0.559	0.204	0.067	1.000				
-0.127	-0.456	0.237	0.141	0.006	-0.261	0.042	0.078	-0.222	1.000			
-0.086	-0.490	0.207	0.050	0.043	-0.370	0.099	0.231	-0.459	0.389	1.000		
0.493	-0.045	0.797	0.852	0.774	0.159	-0.068	-0.056	-0.248	-0.013	-0.024	1.000	
0.185	-0.367	0.976	0.929	0.764	-0.018	-0.012	-0.006	-0.335	0.259	0.233	0.788	1.000

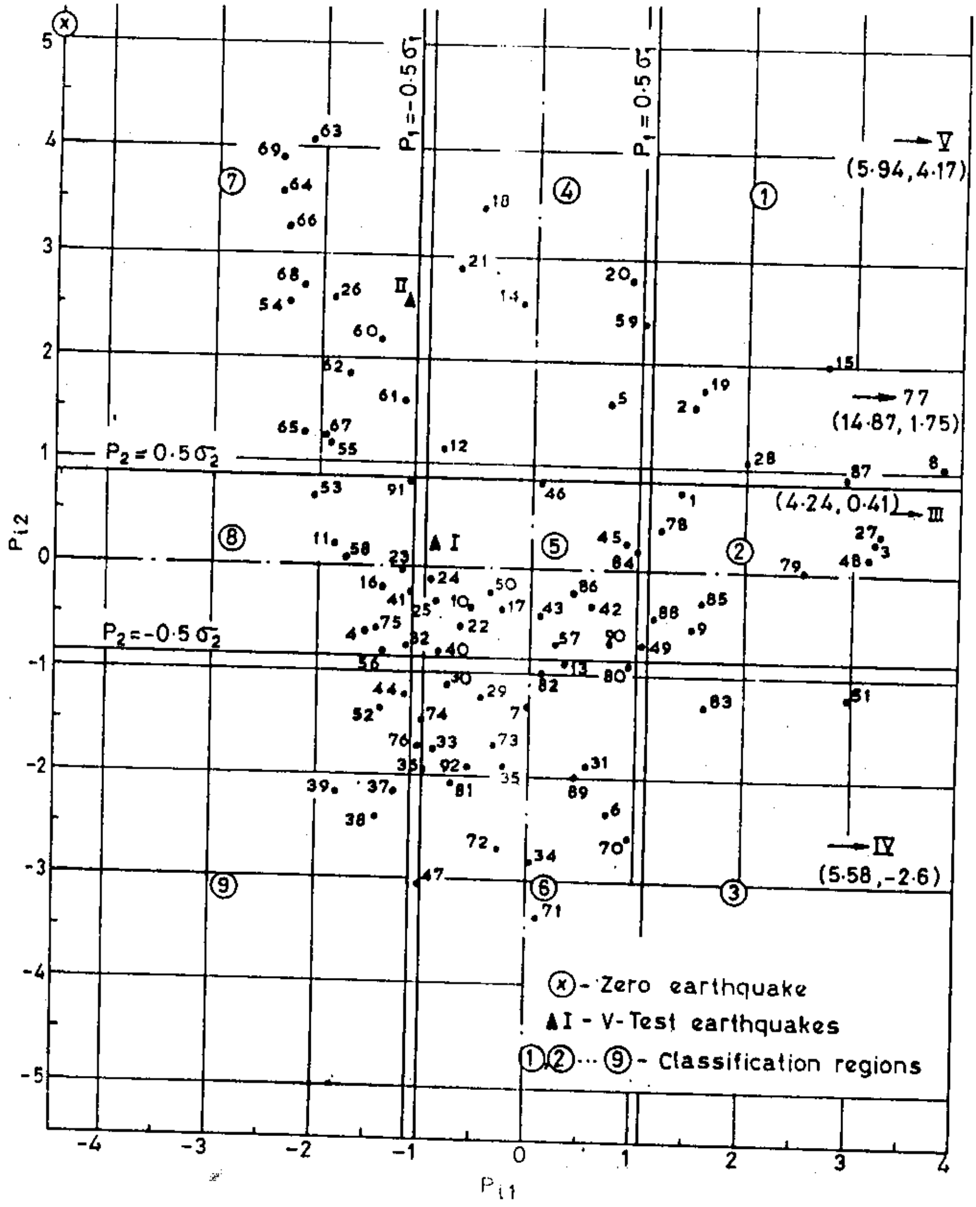


FIG. 1 - PRINCIPAL COMPONENT CLASSIFICATION DIAGRAM

statistical verification of Gaussianess, to the best of the speaker's knowledge, is yet to be undertaken. However, there is a strong case for ground acceleration to be Gaussian. The motion at a given time can be considered as the superposition of a large number random of wave forms. Thus, intuitively the Central Limit Theorem may be invoked to argue that the ground motion must be tending to be normally distributed. For a normal (Gaussian) random process, one needs to know only the mean, standard deviation and the second order correlation function to completely define the process. In an accelerogram due to perceived statistical of the to and fro oscillations, the mean is taken as zero. Thus, it may observed that even while analysing the data, some broad features of the model are presumed. Since accelerograms are nonstationary, analysis of the samples is rather complicated. For stationary process unique time domain and frequency domain representations in terms of autocorrelation function and power spectral density function are available. For a nonstationary process the autocorrelation is not just a function of the time lag and this introduces further difficulties in defining the spectrum. There are several definitions available for the spectrum of a nonstationary process; such as instantaneous spectrum, physical spectrum evolutionary power spectral density, and two dimensional power spectrum. Among the various definitions, the evolutionary PSD has been widely used by research workers. However in applications, time domain representation as a modulated stationary process is more popular.

3.3 NONSTATIONARY VARIANCE

The type of nonstationarity exhibited, namely an initial increase in the amplitudes followed by a slow decrease is typical of all strong motion accelerograms. A rigorous estimation of the nonstationary variance is possible only if an ensemble of accelerograms at the same site is available. In the absence of such an ensemble, past efforts have been (Iyengar and Iyengar 1969, Kozin 1977) to estimate the nonstationarity using a single sample. A short-term time average is the easiest estimator. Under the assumption the process has zero mean.

The variance is given as

$$v^2(t) = (1/T_e) \int_{t-0.5T_e}^{t+0.5T_e} \bar{u}^2(t)\, dt \qquad (1)$$

T_e = averaging interval
$\ddot{u}$ = ground acceleration

Numerical results obtained for the S69E acceleration component of the Taft, July 26, 1952 earthquake is shown in Fig. 2. The dotted line shown a fit of the type

$$V(t) = (a_0+a_1t)e^{-pt} \qquad (2)$$

It has been found that accelerograms can be modelled for their variance as

$$V(t) = (a_0+a_1t^m)e^{-pt^n} \qquad (3)$$

where m and n take values either 1 or 2. Other types of nonstationary variance or intensity functions, which also have a valid basis, have been suggested. Amin and Ang (1968) have proposed

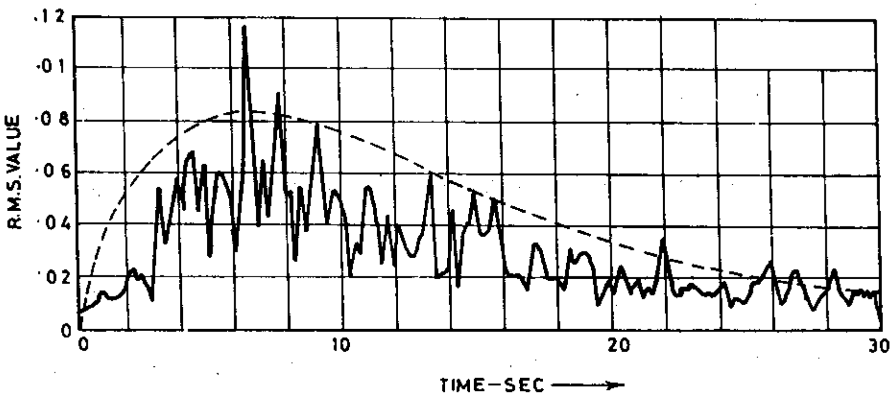
$$\begin{aligned} v(t) &= v_0t^2 && (0 < t < 1.5) \\ &= v_1 && (1.5 < t \leq 15) \\ &= v_1e^{-ct} && t \geq 15 \end{aligned} \qquad (4)$$

Shinozuka and Sato (1967) suggested the function

$$V(t) = V_0(e^{-\alpha t} - e^{-\beta t}) \qquad (5)$$

All the above are empirical, based on single sample data of one or more earthquake events. All the three forms are being used in generating spectrum compatible accelerograms, which has become a standard

Fig. 2: Short Time Average of Strong Motion



engineering practice in performance evaluation of critical facilities and equipments. A recent result obtained by ensemble averaging of the 1991 Uttarkashi strong motion data will be presented later.

3.4 POWER SPECTRAL DENSITY

A Guassian stationary random process with zero mean is completely defined by its PSD function. Thus, there has been great deal of interest in spectral analysis of random signals. For strong motion accelerograms also it has been a standard practice to find the Fourier amplitude spectrum through FFT analysis. If the nonstationarity is ignored as a first approximation, autocorrelation functions and PSD can also be estimated easily. In Fig. 3 the PSD function of a record obtained from two different approaches is shown. The broad features of the strong motion spectrum are well known. Very little energy is contained beyond about 50 Hz. Predominant peaks representing local site characteristics are generally present. Records on hard rock contain high frequencies and the spectrum tends to be broader. Soft soil sites shew predominantly lower frequencies and also the PSD tends to be narrow banded. Records on deep soil deposits, and in steep valleys may exhibit several dominant peaks in their PSD function.

4.0 MODELLING

Representation of external loads or forces in terms of mathematical expressions is routine in engineering practice. Thus, forces on machine foundations are taken as sinusoidal, blast loads are taken as triangular or exponential in time; to cite two simple examples. A similar approach to represent seismic forces on structures is very natural. However, the randomness of the recorded accelerograms precludes the possibility of representing them in terms of simple known mathematical functions. This has lead to the development of stochastic or random process models for strong motion. There are two distinct types of stochastic models, namely direct and indirect models, available for earthquakes.

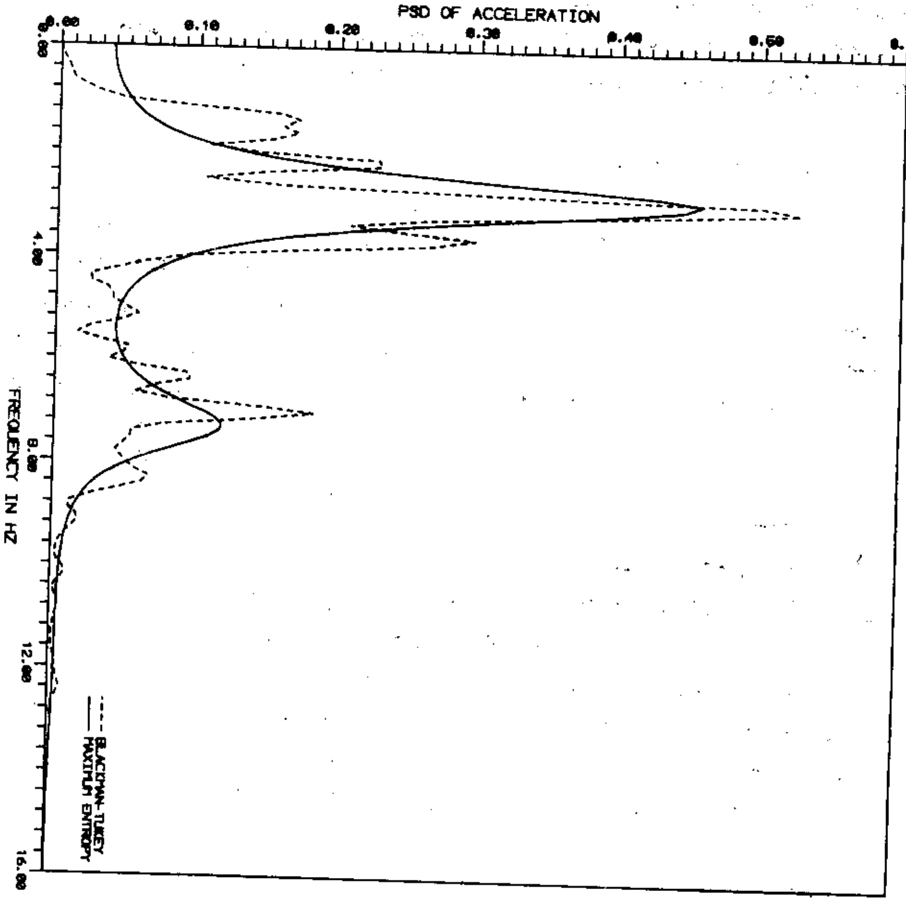


FIG. 3 : PSD OF UTTARKASHI ACCELEROGRAM (TRANSVERSE COMPONENT)

4.1 DIRECT MODELS

Between the two typical characteristics of accelerograms, namely randomness and nonstationarity the former is thought to be more important. This has lead to the postulation of stationary random process models which incorporate one or more of the directly estimated parameters of accelerograms. The first such model was proposed by Housner (1947) as a series of impulses which in effect is a white noise. Housner further suggested an improvement to this preliminary version by replacing impulses by full sine waves distributed randomly in time. A sum of sequence of Sine waves with random phases can be shown to represent a guassian stationary process under certain conditions. Such a representation has remained popular in simulating random samples, with given PSD functions. The variance of a white noise process is theoretically infinite and hence physically unrealizable, eventhough such a model is easy to use in random vibration analysis. Band limited white noise with a cut off frequency ($\Omega \geq$ 33Hz) has been the next suggested model. Again accelerograms show preference to certain frequency bands and thus the band limited white noise is also not physically realistic. The simplest PSD considered realistic is the Kanai-Tajimi spectrum.

$$G(\Omega) = G_0 \frac{[\, 1 + (2\eta\Omega/\Omega_g)^2 \,]}{[\, (1-\Omega^2/\Omega_g^2)^2 + (2\eta\Omega/\Omega_g)^2 \,]} \qquad (6)$$

This form was developed by Tajimi (1960) as a model based on the observation of Kanai (1961) that the PSD of the acceleration at the rock level can be taken as white noise. The rock level excitation passes through the soil layers to become the surface motion. This model is more phenomenological in that one can interpret the surface motion as a filtered white noise. For firm soil the suggested parameters are η=0.6 and Ω=4π rad/sec. Barstein (1960), based on data analysis of five records proposed an autocorrelation function of the type

$$r(\tau) = e^{-\alpha|\tau|} \cos \beta\tau \qquad (7)$$

which leads to a PSD very similar to eq. (6). Cornell (1964) in a detailed study on stochastic process applications in structural engineering, has discussed various models for earthquakes. He has proposed that filtered Poisson processes may be useful as models. In this approach the ground acceleration is represented as

$$\ddot{u}_g(t) = \sum_{i=1}^{N(t)} h(t-\tau_i, a_i) \qquad t \geq 0 \tag{8}$$

in which $\{N(t);\ t\geq 0\}$ is the Poisson counting process and h denotes a pulse shape. Housner's pulse model using full sine waves

$$\begin{aligned} h(t-\tau,\ a) &= a\ \mathrm{Sin}\lambda(t-\tau) && 0 \leq t-\tau \leq L \\ &= 0 && \text{otherwise} \end{aligned} \tag{9}$$

has been discussed in detail. It is shown that the autocorrelation function of the process matches with the results obtained by Barstein (1960) from actual records. However the above representation eventhough physically appealing, is not easy to handle and hence not popular.

4.2 NONSTATIONARY MODELS

Inclusion of the transient nature of the earthquakes has been of concern to engineers from the very early days of strong motion modelling. Bolotin (1960) was perhaps the first to suggest a modulated stationary process of the forms

$$\ddot{u}(t) = a\ e^{-bt} S(t) \tag{10}$$

where S(t) is a stationary process with autocorrelation given by eq. (7). Summation of transient random wave patterns with and without lag in arrival times (Bogdanoff, *et al*, 1961; Goldberg *et al*, 1964) have also been proposed. However these forms are too cumbersome to be handled by analytical methods and hence are now only of academic interest. The most popular nonstationary model has been a stationary Guassian random process multiplied by a transient modulating function of the form given by eqs.(3, 4 or 5). Other nonstationary models attempted in the literature are filtered nonstationary white noise (Lin 1963) and autoregressive-moving average (ARMA) models (Cakmak *et al* 1985)

5. INDIRECT MODELLING OF STRONG MOTION

For engineers modelling of earthquakes is only a means to an end. The end is undisputedly analysis, evaluation, design and strengthening of structures to withstand future earthquakes. This goal, as a corollary brings in the question how an earthquake hazard should be specified at a given project site. Questions arise on the best way of bringing out codes for use by practicing engineers who are not specialists. In this aspect, early researchers (Alford, Housner and Martel 1964) recognized the limitations of time domain models and studied alternates such as the Fourier spectrum (Hudson 1962) and the response spectrum. Response spectrum is similar to shock spectrum used in other branches of engineering. In earthquake engineering practice the concept of response spectrum occupies a central place. Initially response spectra were obtained as aids for designers to know the maximum response of single degree-of-freedom systems. It was quickly recognized that response spectrum is as well, a good equivalent to a frequency domain description of strong motion. This has the added advantage of depicting the effect of the earthquake on standard engineering systems in a way easily understood by the engineering community. This explains the universal popularity of the response spectrum as a way to specify future earthquake hazard at a site where a group of structures with varying material properties and stiffness have to be constructed. Newmark, Blume and Kapur (1973) analyzed statistically several past records, all scaled to the same PGA value to arrive at shapes of smooth design response spectra (SDRS). It is presently standard practice to postulate seismic threat at two risk levels (50% and 15.9% of excedance) in terms of smooth response spectral shapes, corresponding to different levels of damping. This strongly engineering approach of specifying seismic threat in terms of response spectra has lead to the need for indirect models for strong motion accelerograms.

5.1 SPECTRUM COMPATIBLE ACCELEROGRAM MODEL (SCAM)

The SDRS when given along with the peak ground acceleration or equivalently the value of the spectrum at zero period (ZPA) provides a simple specification of the earthquake hazard. The spectrum is also directly useful in the response analysis of multi-degree-freedom systems through modal summation (Clough and Penzien 1986) methods. This procedure while practical, is limited to approximate estimation of peak response values only. There are many cases when the time history of strong motion accelerogram is needed instead of just the SDRS. The inversion of the response spectrum to find which input could have lead to the spectrum is a problem with no unique solution. However indirect earthquake models try to achieve the inversion in such a way the resulting accelerogram contains as many known features of strong motion as possible. Initial efforts in the direction of SCAM were by Hadjian (1972) and Tsai (1972). Their method was to modify a selected real accelerogram and make the computed spectrum match as closely as possible with the specified SDRS. Further significant contributions were made by Scanlan and Sachs (1974). They generated accelerograms through Fourier series representation with unknown coefficients. Randomness was incorporated by selecting the phase angles to be uniformly distributed in $(0, 2\pi)$. Levy and Wilkinson (1976) proposed a similar method using Fourier representation. They also outlined a basis for selecting the number of frequencies and their spacing.

A seismic spectral shape has some internal consistencies, to be maintained. Relative to the zero period or high frequency end, the amplification at other frequencies has to be within some ranges. Levy and Wilikinson (1976) point out that some smooth response spectra may not have compatible accelerograms especially if the zero period end of the spectra has too low values. Iyengar and Rao (1979) developed an iterative method based on Fourier series representation but with random phase and amplitudes. The method includes nonstationarity and also ensures that the realized spectrum is always greater than or equal to the target. Fast convergence has been achieved by treating the time to maximum response also as a random variable. Reviews on the methods for generating spectrum compatible accelerograms have been presented by Spanos (1983), Iyengar (1984) and Preumont (1984). While SCAM is an easy way of indirect modelling there are several limitations. First of all time history response analysis involves more computational effort, particularly when primary and secondary systems in large numbers have to be evaluated as in the case of nuclear power plants. Further SCAM is not unique and hence one may arrive at several accelerograms for the same spectrum which eventually lead to different responses for the structural systems to be studied. Thus, in both direct and indirect modelling an earthquake input has to be recognized as a random process described in terms of an ensemble of samples or interms of probability distributions. This observation leads to the next stage in indirect models.

5.2 SPECTRUM COMPATIBLE POWER SPECTRAL DENSITY FUNCTIONS

Since strong motion accelerograms can be taken as Gaussian processes, the natural question is whether one can find the second order moment properties of such a process, compatible with a given SDRS. Vanmarcke (1976, 1977) developed a compatible stationary model. Nonstationarity was accommodated through a time dependent frequency response function, Kaul (1978) proposed a method for arriving at a compatible PSD, interms of a series of rational functions. Sundararajan (1980) used a simple discrete representation for the unknown PSD function. Both iterative and non-iterative schemes were presented. The initial estimate of the PSD was obtained by first assuming the input to be a white noise. Unruh and Kana (1981) extended Kaul's (1978) series representation to propose a fully automated iterative scheme. Pfaffinger (1983) used a discrete representation of PSD with unknown ordinates but with provision for polynominal interpolation between adjacent frequencies. Hwang (1985) proposed a compatible PSD which is a series of analytical functions of the Kanai-Tajimi PSD type. The unknown coefficients were found through a least square procedure.

The following important questions arise about the indirect modelling methods,

(i) Is the spectrum compatible PSD unique;

(ii) Should a fixed peak factor be used in the computations or can this be varied;

(iii) Eventhough the model is stationary, the response peak is found in an interval of time (0, T). How is this T to be selected;

(iv) Is the PSD found with reference to a particular damping value compatible with the response spectrum at other damping values;

(v) How is the strong motion duration to be accounted for;

All these five questions were been discussed in the M.Sc (Engg.) thesis of Varadarajan (1992). The findings are that any PSD representation, so long it is general and flexible enough, will lead to nearly the same results. Use of variable peak factor given at every frequency by

$$P_f(\omega) = [2\ \log(\beta T/\pi)]^{1/2} + 0.5772/[2\log(\beta T/\pi)]^{1/2} \qquad (11)$$

yields a lower estimate for the variance of the input. Similarly longer the duration T, the input variance value decreases. To study the fourth question raised above, the USNRC (1973) and the IS (1984) spectra were selected. From the PSD compatible with 2% damping spectrum, the response spectrum for 5% damping was obtained. Also from the PSD compatible with 5% damping standard spectrum, the resulting 2% spectrum was obtained. In the first case the derived spectrum is less than the target at 5% damping. In the second case when the 5% spectrum was the starting point for the compatible PSD, the 2% damping spectrum was overly conservative. Thus, the standard spectra are not internally consistent.

5.3 SPECTRUM COMPATIBLE NONSTATIONARY MODEL

While a stationary model may be sufficient, the question remains whether it is necessary to be restrictive. For example the duration of strong motion cannot be accounted for by a stationary PSD. In a random vibration study associated with a stationary model the input is theoretically of infinite duration. The maximum response of the structural system is found in an interval of time, the value of which is arbitrary. This may lead to overly conservative and hence uneconomical designs. Thus it is appropriate to demand realistic strong motion buildup and decay pattern also in the compatible input model. Spanos and Vargas Loli (1985) considered the possibility of a compatible nonstationary model. First they obtained an approximate closed form expression for the response statistics of a SDOF system by the Markov process approach. The compatible PSD was arrived at by matching the mean realized spectra with the SDRS through an empirical peak factor. This approach is complicated and at the end does not refer to the percentile (risk) level of the target spectrum A new method for generating a spectrum compatible nonstationary process, reflecting the level of excedance also was developed at IISc., Bangalore(Varadarajan 1992, Iyengar 1993). The model is of the form $u_g(t) = v(t)\ u(t)$ where v(t) is a known modulating function and u(t) is a zero mean Guassian stationary process. For v(t) one can take any suitable form as given in eqs. (3,4,5). The response statistics are found with S(λ), the PSD of u(t), being unknown. The only approximation brought in is for the highest peak distribution of x(t) in an interval (0,T). It is well known (Nigam 1983) that this can be very well approximated as

$$F_{xp}(\alpha) = \text{Prob}(x_p \le \alpha) = \exp[-\int_0^T N(\alpha,t)dt] = p \qquad (12)$$

Here N(α,t) is the nonstationary rate of upcrossings of the level α. If α_p is treated as the peak relative displacement of a SDOF oscillator at a known probability level p of non-excedance as per the above equation, the acceleration spectrum is given by

$$S_a(\omega) = \alpha_p \omega^2 \tag{13}$$

Thus the problem is reduced to finding the PSD $S(\lambda)$ of the stationary part for a given $S_a(\omega)$ such that the above equation is satisfied.

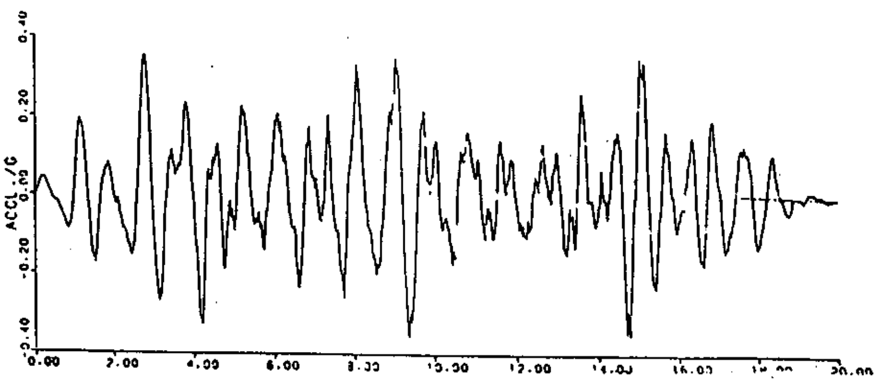
6. APPLICATIONS

In this section a few practical applications of direct and indirect modelling of strong motion are presented briefly.

The seismic response of the 110m tall ventilation stack of MAPP-Kalpakkam was to be done for two earthquakes of specified magnitudes and epicentral distances. The expected peak ground acceleration was estimated by using empirical attenuation laws. The input was modelled as a stationary process multiplied by a modulating function. Two artificial samples to suit the two seismic sources were simulated for further dynamic analysis (Iyengar 1974)

6.2 SCA GENERATION FOR PLANTS AND EQUIPMENTS

Several spectrum compatible accelerograms have been generated for use with the PWR plants of Nuclear Power Corporation(Iyengar 1983, 1986). In each case the smooth response spectrum at the ground level or at some nfloor level was specified. A typical problem was the seismic response study of the primary shut down system. The floor response spectrum to be used at 2% damping was specified by NPC. The target and realized spectra alongwith the compatible accelerogram are shown in fig. 4 (Iyengar 1990). This accelerogram was further used to compute the drop time of the control rod and the guide tube during earthquake event. Similar work has been carried out on the reactivity mechanism assembly also (Iyengar and Ramu 1990).



Spectrum Compatible Accelerogram

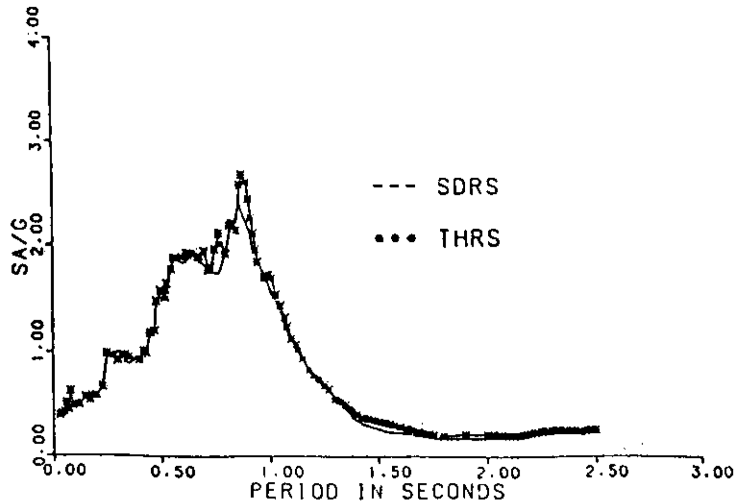


Fig. 4 HORI. ACCL. SPEC. SAMPLE (N-S)

6.3 COMPATIBLE PSD FUNCTION

A study was commissioned by NPC to compare the results of time history analysis with those of random vibration analysis. The ground level average spectrum was converted to a compatible accelerogram and the floor accelerations and response spectrum were obtained by time integration methods. The work was repeated by generating a compatible PSD and following standard linear random vibration methods to arrive at the mean floor response spectrum (Iyengar *et al* 1989). The comparisons were found to be very favourable. Compatible PSD was generated for the SSE spectrum of the 500MW plant. Similar exercise was done for review of a 235 MW plant(Iyengar 1989, 1991). The ground spectrum specified in the above cases had been obtained by the user agencies either by *ad hoc* procedures or by deterministic concepts. Thus, their excedance levels could not be specified accurately. Accordingly, the peak factor concept was used to convert the moments into peak values. Very recently IGCAR, Kalpakkam referred the work of generating the compatible PSD for the OBE and SSE spectra of the Fast Breeder Reactor (FBR) at 50% and 15.9% levels of excedance. Results on the compatible PSD and the given SSE spectrum are shown in Fig. 5 (CBRI 1996).. It is to be noted that in obtaining, these results, equation (13) has been solved to precisely maintain the percentile levels.

7. MULTI-COMPONENT STRONG MOTION

Ground motion at a point is measured in two orthogonal horizontal directions and in the vertical direction. The three components of motion (Penzien and Watabe) are generally interrelated. Analysis and modelling of ground motion as a vector process is theoretically possible (Deodatis and Shinozuka 1987). However, in practical applications, orthogonal components if needed, are more often taken to be uncorrelated.

Closely connected with the multi-component nature of ground motion is the spatial variability of strong motion. Since engineering structures

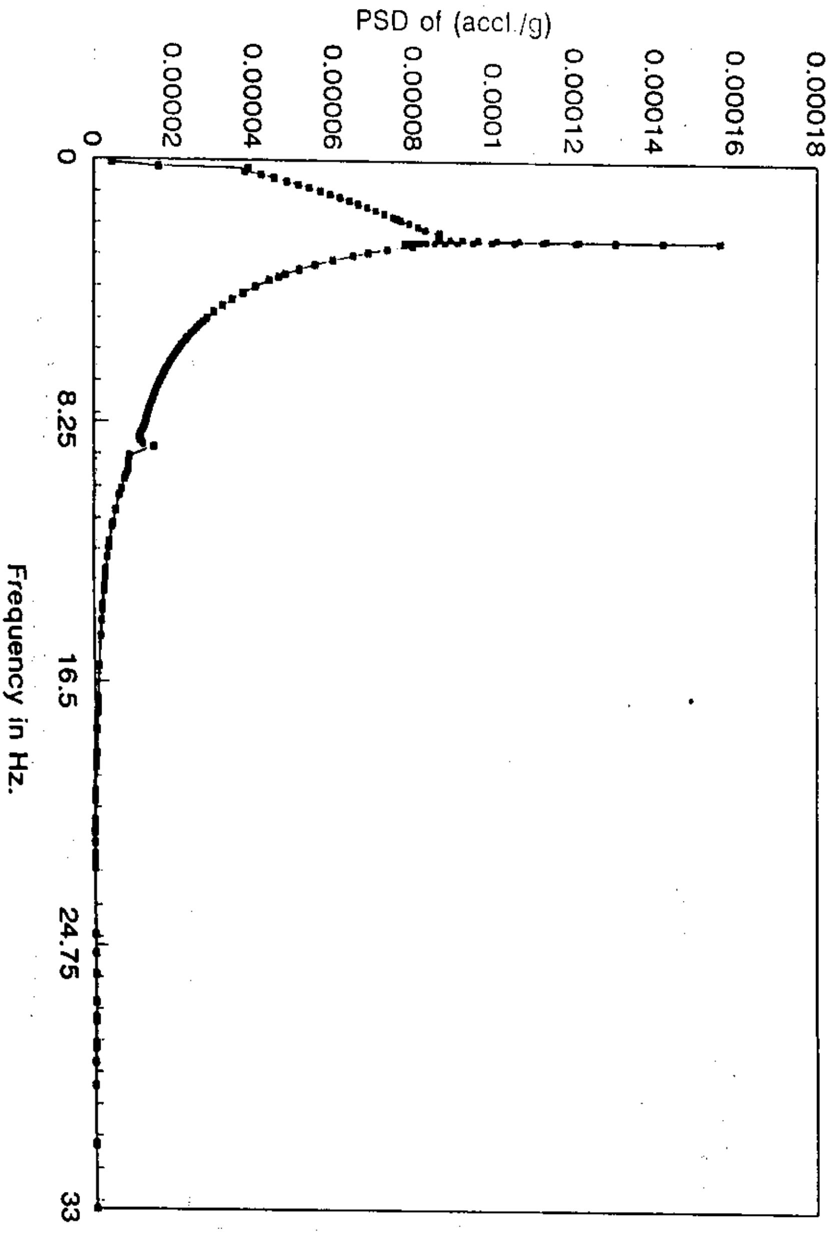


Fig. 5 Spectrum Compatible PSD
SSE Event 5% Damping PGA = 0.156G

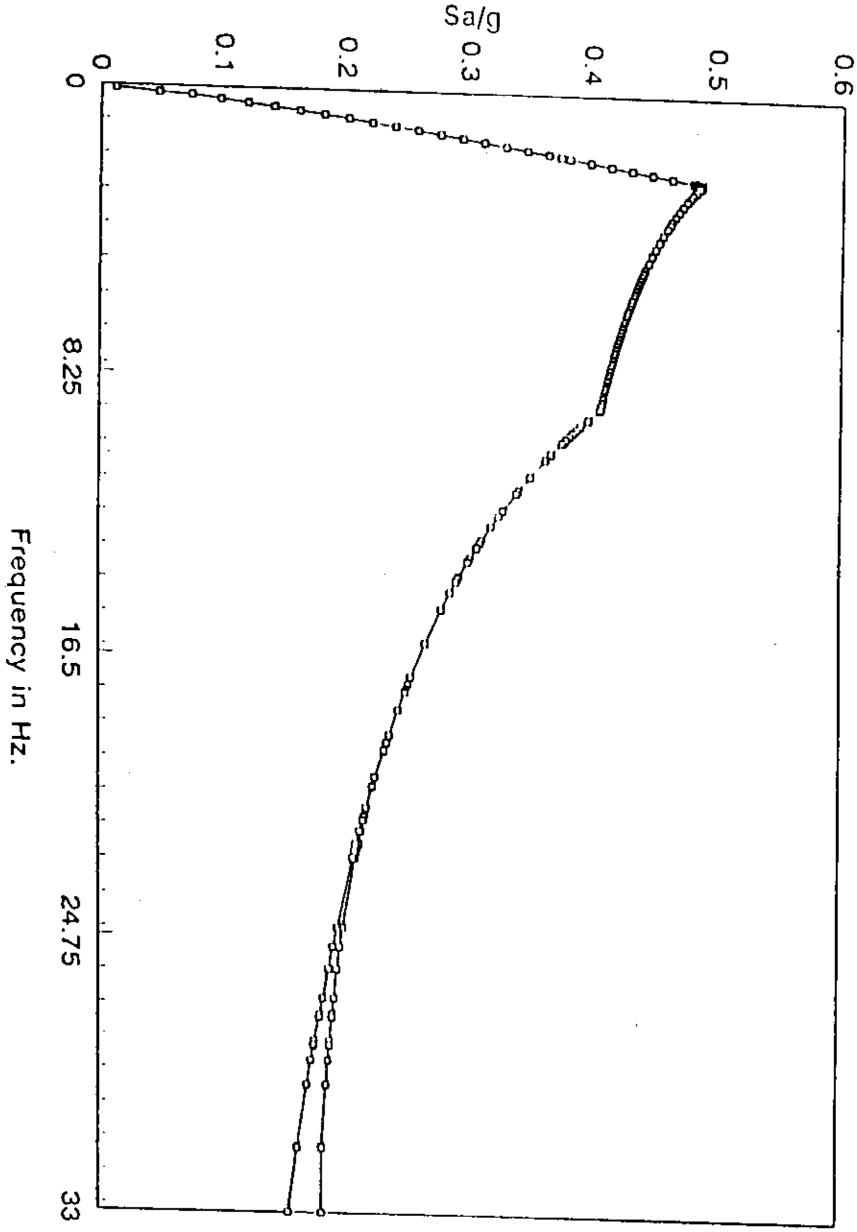


Fig. 5b Spectrum Compatible Acceleration Spectra

SSE Event 5% Damping PGA = 0.156G

can be long in comparison with the characteristic lengths of seismic waves, propagation effects become important in large foundations, pipe lines, tunnels and multiply supposed structures. To model propagation effects, special large scale arrays have been working in some highly seismic regions of the world. The SAMRT-1 seismograph array of Taiwan is one such (Iwan 1979, Bolt *et al* 1982) designed to provide information on spatial variability. A comprehensive analysis of data obtained by this array has been presented by Harichandran and Vanmarcke (1985), Loh and Yeh (1988), Zerva and Shinozuka (1991). A review of characterization of ground motion for analysing large or multiply supported structures has been presented by Banerji (1994).

8. STRONG MOTION RESEARCH AT CBRI

Subsequent to the Latur, Maharashtra earthquakes of 1993, there has been increased awareness among engineers in the country for adopting scientific approaches for reducing seismic risk to the built environment. Central Building Research Institute, being vested with the responsibility of providing R&D inputs at a national level on problems related to building science and technology, has initiated a new research program on disaster mitigation. As a part of this program, strong motion instruments have been installed in and around Delhi. Also previous strong motion data from the Himalayan region are being studied for understanding spatial variation in the Indian context.

8.1 SM STATIONS IN AND AROUND DELHI

Sixteen digital strong motion accelerographs have been installed at the locations shown in Table 3. So far a few long distance events have been recorded by some of the instruments.

8.2 ANALYSIS OF SM DATA (IYENGAR AND AGARWAL 1997)

Strong motion data of five earthquake events have been recorded by the Dept. of Earthquake Engineering, University of Roorkee (Chandra Shekharan 1994). Multiple records are available for each event and

Table 3 : LOCATION OF STRONG MOTION ACCELEROGRAPHS
(Threshold Level = 0.005 g)

Serial Number	*Location of SMAs*	*Latitude*	*Longitude*
	INSIDE DELHI		
1	INSDOC, South Delhi	28°32'40"	77°10'55"
2	CSIR Complex, NPL Campus	28°38'07"	77°10'18"
3	IMD, Ridge, Observatory	28°41'01"	77°12'33"
4	CPCB, Parivesh Bhawan, Arjun Nagar	28°37'14"	77°17'02"
5	DDA, Vikas Minar, MG Road, Near ITO	28°37'38"	77°14'50"
6	NDMC, Palika Sadan,Connaught Place	28°37'46"	77°12'47"
7	IHC Lodhi Road	28°35'26"	77°13'54"
8	CSIR Anusandhan Bhawan, Rafi Marg	28°36'11"	77°13'54"
	OUTSIDE DELHI		
1	Divisional Office, Northern Railway, Moradabad	28°50'33"	78°46'15"
2	St. John's College, Agra	27°10'00"	78°01'16"
3	Mathura Refinery, Mathura	27°30'34"	77°41'15"
4	MDA, Meerut	28°58'53"	77°44'22"
5	Municipality Office Baghpat	28°56'07"	77°13'45"
6	Engg. College, Murthal, Sonepat	29° 00'33"	76°54'52"
7	NFL, Panipat	29°23'20"	76°56'52"
8	CBRI, Roorkee	29°52'00"	77°53'52"

hence in principle the data provide important information on the sample, frequency and temporal variation of Himalayan earthquakes. Since an ensemble of records is available for the Uttarkashi event, this provides an opportunity to find the shape of the nonstationary variance. With this in view the orthogonal components of accelerogram have been scaled to unit PGA and the resultant ensemble averaged for its mean. The resulting modulating function is shown in fig. 6. It is interesting to observe that this shape appears to be different from the types assumed in the literature. Other work presently in progress is about the vertical and horizontal spatial variations in ground motion. All the five events mentioned above show amplification in their amplitudes with respect to elevation. Extensive PSD computations indicated the presence of certain strong frequencies which shift from location to location (Fig. 7). This characteristic variation may be attributable to soil condition and terrain effects. Further results on the principal displacement vectors have been obtained. The interstation distances are of the order of several kilometers and hence the data cannot be used for identifying short distance spatial relationships. However even at long distances the acceleration, veclocity and displacement are found to be well correlated. These and other results of the ongoing R&D at work at CBRI are yet to be published.

9. SUMMARY AND CONCLUSION

An overview of how strong motion records are analyzed and modelled in engineering applications has been presented in this talk. After a brief review of past research work, models are classified as **direct** and **indirect** models. Direct models are those which incorporate only the specified accelerogram characteristics. Indirect models include a measure of the effect of the earthquake on structures by specifying the design response spectrum. Both types of models have been discussed in the presentation. Due to the inherent uncertainty associated with earthquakes, the analysis and modelling approaches invariably follow probabilistic methods. In applications, this has lead to extensive use of the theory of **Random Vibration**.

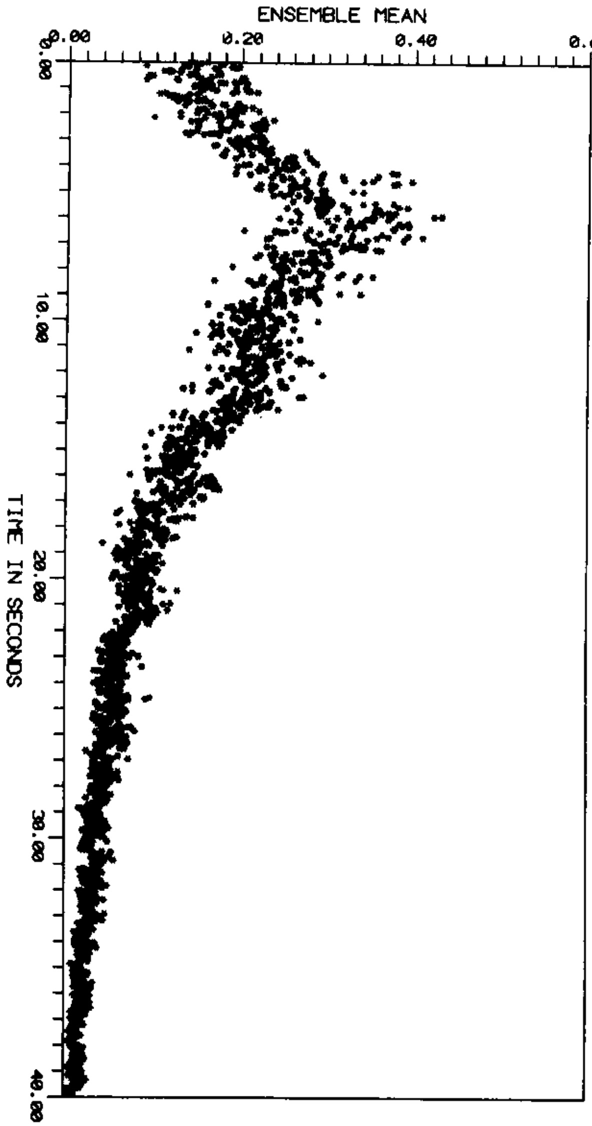


FIG. 6 : MODULATING SHAPE FUNCTION
UTTARKASHI 1991 EVENT:13 SAMPLES

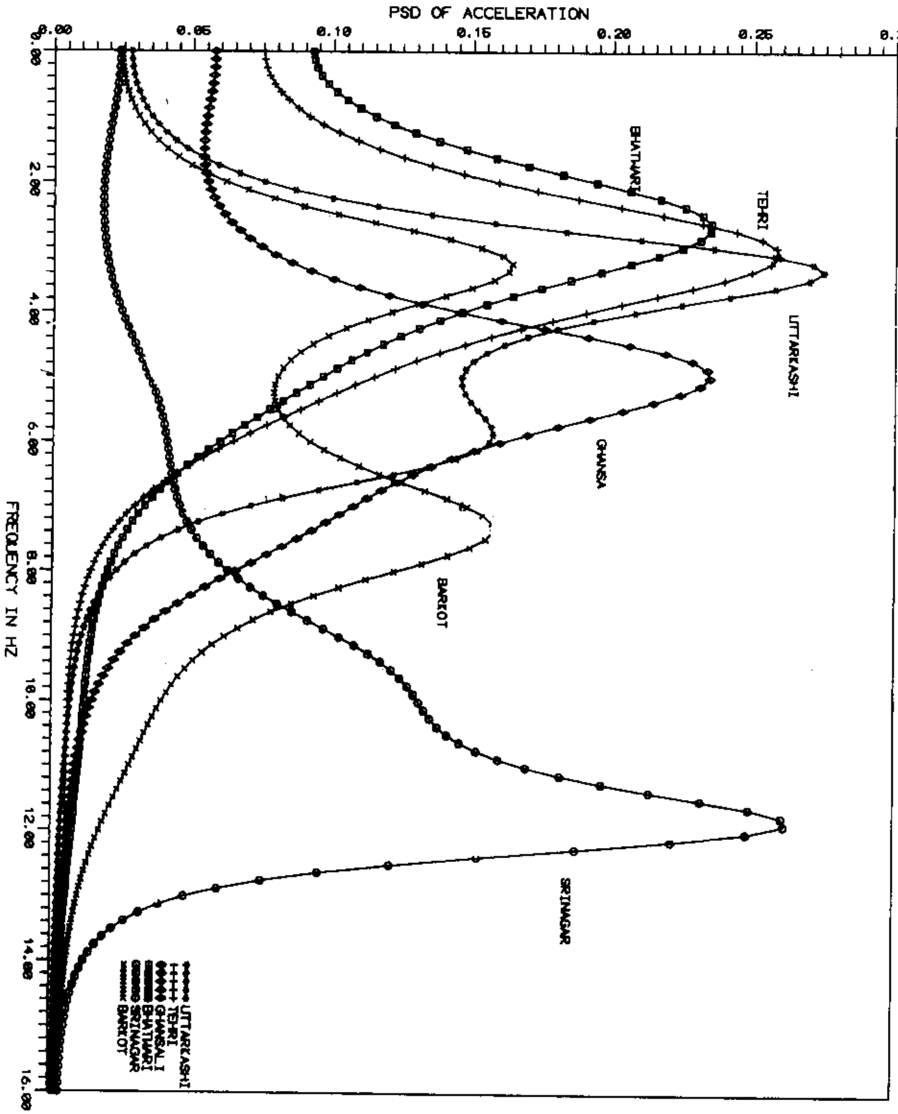


FIG. 7 : PSD OF ACCELROGRAMS (LONGITUDINAL COMPONENTS)

The support of a structure is usually idealized as a point and thus earthquake excitations are treated as point inputs. However in recent times interest has increased in understanding wave propagation effects on multiply supported and long structures. This calls for extensive study of large number of samples emanating from the same event. With this inview, large size strong motion arrays and networks are coming in India and in other seismic regions of the world. It is foreseen that research in this area will be increasingly to understand and model spatial variations keeping inview engineering applications. In the context of current applications within the country, indirect models of seismic inputs, through spectrum compatible concepts have been widely used for response computations. These efforts have to be taken to the next level of application namely to integrate the effects of uncertain seismic and manmade scenarios to arrive at quantifiable risk or safety level statements. This will help decision making and will also provide a means of addressing public perception about safety of industrial plants and other structures to earthquakes.

REFERENCES

1. Amin, M., and Ang, A.H.S. (1968), **"Non-stationary stochastic model of earthquake motion"**, Journal of Engineering Mechanics, ASCE, Vol. 94, pp. 559-583.

2. Housner, G.W. and Jennings, P.C., (1964), **"Generation of aritificial earthquakes"**, Journal of the Engineering Mechanics Division, ASCE, 90, pp. 113-150.

3. Baumbach, M., *et al* (1994), **"Study of the Foreshocks and Aftershocks of the Intraplate Latur Earthquake of September 30, 1993, India"**, Memoir Geological Society of India, No. 35, pp. 33-63.

4. Barstein, M.F., (1960) **"The application of probability methods for design: The effect of seismic forces on engineering structures"**, Proceedings, II World Conference on Earthquake Engineering, Tokyo, pp. 1467-1481.

5. Bendat, J.S., and Piersol, A.G., (1971), **"Measurement and Analysis of Random Data"**, John Wiley and Sons, New York.

6. Banerji, P, (1994), **"Earthquake ground motion characterization for large or multiply supported structures"**, Current Science, Vol. 67, No. 5, pp.386-394.

7. Bogdanoff, J.L., Goldberg, J.E., and Bernard, M.C, (1961) **"Response of a simple structure to a random earthquake type disturbance"**, Bulletin of the Seismological Society of America, 51, pp. 293-310.

8. Bolotin, V.V. (1961), **"Statistical theory of a seismic design of structures"**, Proceedings, II World Conference on earthquake engineering, Tokyo, 1960, pp. 1365-1374.

9. Bolt, B.A., *et al*, (1982), **"Earthquake strong motions recorded by a large near source array of digital seismographs"** Earthquake Engineering Structural Dynamics, Vol. 10, pp. 561-573.

10. Cakmak, A.S. Sherif, R.I., and Ellis, G., (1985), **"Modelling earthquake ground motions in California using parametric time series methods"**, Soil Dynamics and Earthquake Engg., i.e. 3, pp 124-131.

11. Chandrashekharan, A.R., and Das, J., (1990), **"Strong motion arrays in India and characteristics of recent recorded events"**, ISET Annual Lecture, 1988, Bulletin, ISET, Vol. 27, no. 1.

12. Chandrashekharan, A.R., (1994), **"Evaluation of design earthquake parameters for a site and utilization of strong motion data"**, Current Science, Vol. 67, No. 5, pp. 353-358.

13. Clough, R.W., and Penzien, J., (1968), **"Dynamics of Structures"**, McGraw-Hill, New York.

14. Cornell, C.A., (1964) **"Stochastic process models in structural engineering"**, Technical Report No. 34, Dept. of Civil Engineering, Stanford University, Stanford, May, 1964.

15. Deodatis and Shinozuka, M, (1989), **"An autorepressive model for nonstationary stochastic process"**, J. Engg. Mechanics, ASCE.

16. Goldberg, J.E., Bogdanoff, J.L., and Sharpe, D.R., (1964) **"The response of simple nonlinear systems to a random disturbance of the earthquake type"**, Bulletin of the Seismological Society of America, Vol. 54, 1, 1964, pp. 263-276.

17. Hadjian, A.H., (1972) **"Scaling of earthquake accelerograms - A simplified approach"**, Journal of Structural Engineering, ASCE, Vol. 98, pp. 547-551.

18. Harichandran, R.S. and Vanmarcke, E.H., (1986), **"Stochastic variation of earthquake ground motion in space and time"**, J. Eng. Mech. ASCE, Vol. 112, pp. 154-174.

19. Housner, G.W., (1947) **"Characteristics of strong motion earthquakes"**, Bulletin of the Seismological Society of America, 37, 1, 1947, pp.19-31.

20. Hudson, D.E., (1962) **"Some problems in the application of spectrum techniques to strong motion earthquake analysis"**, Bulletin of the Seismological Society of America, 52, 2, 1962, pp. 417-430.

21. Hudson, D.E., (1983) **"History of Accelerograph Development"**, Proc. Golden Annual Workshop on Strong Motion Seismometry, UCLA, California, USA, pp. 29-56.

22. Hwang, H., Pires, J., Reich, M., and Chokshi, N.C., (1985), **"Generation of Consistent power/response spectra"**, Transactions of the 8th International Conference on SMIRT, Vol. K)b), Paper K12/3, Brussels, Belgium, pp. 7-11.

23. I.S.:1893 (1984), **"Criteria earthquake resistant design of structures"**, (fourth revision), Bureau of Indian Standards, New Delhi, India.

24. Iyengar, R.N., (1969), **"A nonstationary random process model for earthquakes and its application"**, Ph.D. Thesis, Dept. of Civil Engineering, IISc., Bangalore.

25. Iyengar , R.N. and Iyengar, K.T.S., (1969), **"A non-stationary random process model for earthquake accelerogram"**, Bulletin of the Seismological Society of America, Vol. 59, pp. 1163-1188.

26. Iyengar, R.N. and Iyengar, K.T.S., (1970), **"Probabilistic Response Analysis to Earthquake"**, J. Engg., Mechanics, ASCE, 96, EM3, pp. 207-225.

27. Iyengar, R.N. and Rao, P.N., (1979), **"Generation of spectrum compatible accelerograms"**, Earthquake Engineering and Structural Dynamics, Vol. 7, pp. 253-263.

28. Iyengar, R.N., and S.A. Ramu (1983), **"Seismic Response of Reactivity Mechanism Assembly"**, Tech. Rept. Nuclear Power Corporation , Bombay.

29. Iyengar, R.N. and Prodhan, K.C, (1983), **"Classification and Rating of Strong-Motion Earthquake Records"**, Earthquake Engineering and Structural Dynamics, Vol. 11, 415-426.

30. Iyengar, R.N. and Raghuprasad, B.K., (1983), **"Spectra Compatible Accelerogram for KAPP"**, Tech. Rept. to PPED, Dept. of Atomic Energy, Dept. of Civil Engg., IISc., Bangalore.

31. Iyengar, R.N., (1984), **"Spectrum compatible accelerograms"**, Symposium on Earthquake effects on Plant and Equipment, Hyderabad, India, pp. 25-32.

32. Iyengar, R.N., (1986), **"Safety Systems and Coolant Channels of Nuclear Reactor under Seismic Forces"**, Nuclear Power Board, Department of Atomic Energy.

33. Iyengar , R.N., (1989), **"Spectrum compatible PSD and floor response spectra"**, Tech. Rept. to Nuclear Power Corporation, Dept. of Civil Engg., IISc., Bangalore.

34. Iyengar, R.N. and Goray, J.S and Khushwah, (1989), **"Development of Floor Response Spectra using PSD functions"**, Trans. 10th Int. Conf. on SMIRT, Vol. K2, pp 545-550.

35. Iyengar, R.N., (1989), **"Spectrum Compatible PSD Functions and Foor Response Spectra"**, Tech. Rept. to Nuclear Power Corporation, Bombay, Dept. of Civil Engg., IISc., Bangalore.

36. Iyengar, R.N., (1990), **"Seismic Response of the NAPP Primary Shutdown System"**, Tech. Rept. to Nuclear Power Corporation, Bombay, Dept. of Civil Engg., IISc., Bangalore.

37. Iyengar, R.N., (1991), **"Spectra Compatible PSD Functions and Response Spectra of NAPP"**, Tech. Rept. to Nuclear Power Corporation, Bombay, Dept. of Civil Engg., IISc., Bangalore.

38. Iyengar, R.N., and S.K. Agarwal (1997), **"Analysis of Strong Motion Records from the Himalayas"** (Under Review)

39. Iwan, W.D., (1979), **"The Deployment of strong motion earthquake instrument arrays"**, Earthquake Engineering and Structural Dyanics, Vol. 7, No. 5, pp. 413-426.

40. Jaikrishna, Chandrashekharan, A.R. and Saini, S.S., (1969), **"Analysis of Koyna accelerogram of December 11, 1967"**, Vol. 59, No. 4, Aug. 1969, BSSA, pp. 1719-1732.

41. Kanai, K., (1957), **"Semi-empirical formula for seismic characteristics of the ground"**, Bulletin of the earthquake Research Institute, Japan, 35, 1957, pp. 309-325.

42. Kanai, K., (1961), **"An empirical formula for the spectrum of strong earthquake motions"**, Bull. Earthquake Res. Instt. U. of Tokyo, 39, 85, 1961.

43. Kaul, M.K., (1978), **"Stochastic characterization of earthquakes through their response spectrum"**, Earthquake Engineering and Structural Dynamics, Vol. 6, pp. 497-509.

44. Kozin, F., (1977), "**An approach to characterizing, modelling and analyzing earthquake excitation records**", Random Excitation of Structures by Earthquake and Atmospheric Turbulence, (Ed. by Parkus, H.), Springer Varlay, New York.

45. Levy, S., and Wilkinson, J.P.D., (1976), "**Generation of artificial time histories, rich in all frequencies from given response spectra**", Nuclear Engineering and Design, Vol. 38, pp. 241-251.

46. Lin, Y.K., (1963), "**Application of nonstationary shot noise in the study of system response to a class of nonstationary excitations**", Journal of Applied Mechanics, ASME, 30, 1963, pp. 555-561.

47. Loh, C.H. and Yeh, Y.T., (1986), "**Spatial variation and stochastic modelling of seismic differential ground movement**", J. Earthquake Engg. Struct. Dyn. Vol. 16, pp. 583-596.

48. Naiem and Anderson (1993), "**Classification and evaluation of earthquake records for design**", EERI, USA.

49. Newmark, N.M., and Rosenblueth, E., (1971), "**Fundamentals of Earthquake Engineering**", Prentice Hall, Engle Wood Cliffs.

50. Newmark, N.M, Blume, J.A., and Kapur, K.K., (1973), "**Seismic design spectra for nuclear power plants**", Journal of the Power Division, ASCE, Vol. 9, pp. 287-303.

51. Nigam, N.C., (1983), "**Introduction to Random Vibrations**", The MIT Press, London.

52. Penzien, J and Watabe M., (1975), "**Characteristics of 3-dimensional earthquake ground motions**", Earthqu. Eng. Struct. Dyn., 3, 365-373.

53. Pfaffinger, D.D., (1983), "**Calculation of power spectra from response spectra**", Journal of Engineering Mechanics, ASCE, Vol. 109, No. 1, pp. 357-372.

54. Preumont, A., (1980), "**A method for the generation of artificial earthquake accelerograms**", Nuclear Engineering and Design, Vol. 59, pp. 357-368.

55. Preumont, A., (1984), "**The generation of spectrum compatible accelerograms for the design of nuclear power plants**", Earthquake Engineering and Structural Dynamics, Vol. 12, pp. 481-497.

56. Scanlan, R.H., and Sachs, K., (1974), "**Earthquake time histories and response spectra**", Journal of Engineering Mechanics, ASCE, Vol. 100, pp. 635-655.

57. Shinozuka, M., and Sato, Y., (1967), "**Simulation of nonstationary random process**", Proc. ASCE, EMD Journal, 93, EM 1, pp.11-40, 1967.

58. Spanos, P.D., (1983), "**Digital synthesis of response design spectrum compatible earthquake records for dynamic analysis**".

59. Spanos, P.D., and Vargas loli, L.M., (1985), "**A statistical approach to generation of design spectrum compatible earthquake time histories**", Soil Dynamics and Earthquake Engineering, Vol. 4, No. 1, pp. 2-8.

60. Sundararajan, C., (1980), "**An iterative method for the generation of seismic power spectral density functions**", Nucleaar Engineering and Design, Vol. 61, pp. 13-23.

61. Tajimi, H., (1960), "**A statistical method for determining the maximum response of a building structure during an earthquake**", Proceedings II World Conference on Earthquake Engineering, Tokyo, II, 1960, pp. 781-797.

62. Tsai, N.C., (1972), "**Spectrum compatible motions for design purposes**", Journal of Engineering Mechanics, ASCE, Vol. 98, pp. 345-356.

63. United States Nuclear Regulatory Commission, (1973), "**Design responses spectra for seismic design of nuclear power plants**", Regulatory Guide 1.60, Washington, D.C., USA.

64. Unruh, J.F. and Kana, D.D., (1981), "**An iterative procedure for the generation of consistent power/response spectrum**", Nuclear Engineering and Design, Vol. 66, pp. 427-435.

65. Varadarajan, M, (1992), "**Spectrum compatible random processes as earthquake excitations**", M.Sc. (Engg.) Thesis, Dept. of Civil Engineering, IISc., Bangalore.

66. Vanmarcke, E.H., (1976), "**Structural response to earthquakes**", in Seismic Risk and Engineering Decisions (Editors: C. Lomnitz and E. Rosenblueth), Elsevier, Amsterdam.

67. Vanmarcke, E.H., and Gasparini, D.A., (1977), "**Simulated earthquake ground motions**", Transactions of the 4th International conference on SMIRT, Paper K1/9, SanFrancisco, USA, pp. 1-12.

68. Zerva, A. and Shinozuka, M., (1991), "**Stochastic differential ground motion**", Struct. Safety, Vol. 10, pp. 129-144.