Chapter 2

Strong Motion and Estimation of Seismic Hazard

2.1. General

The propagation of seismic waves and resulting ground displacement during an earthquake is picked up even at far off places. But scientists had noticed that the damages caused by earthquakes were restricted to within few hundreds of kilometers from the causative fault. The quest for recording, understanding and characterizing the ground motion so as to make it amenable for structural design was initiated well before the beginning of 20th century and the efforts commenced in design of accelerographs. The latest accelerographs are capable of providing digital records of ground acceleration with frequency content from DC to even upto 100Hz with a sampling frequency of 200 sps or more.

The recorded ground motions are used to analyze related site and earthquake characteristics and its impact on seismic behavior of structures and equipments. For this purpose, various types of parameters derived from ground motion records are used. For designing a structure against earthquake at a particular site calls for not only understanding of characteristics controlling ground motion but also detailed understanding of seismo-tectonic characteristics of site and evaluation of seismic hazard in the region surrounding the site. The evaluation of seismic hazard primarily hinges upon past seismicity, rate of earthquake activity, and tectonic potential of the region. The evaluation procedure could be based on a deterministic approach where in only the maximum values of estimates are considered or based on a probabilistic approach which is amenable for incorporation of rate of earthquake activity and incorporation of uncertainties in a better way.

This section describes the instruments for measurement of earthquake ground motion as used in evaluation of structural response (also termed as strong ground motion), various parameters derived from strong ground motion to represent the motion characteristics and approaches for evaluation of seismic hazard.

2.2. Earthquake Ground Motion

For the design of structures to resist earthquakes, it is necessary to have some knowledge of ground motions. Earthquakes motion can be recorded in terms of ground displacement, velocity or acceleration. During earthquakes, the ground movement is very complex, producing translations in any general direction combined with rotations about arbitrary axes. Modern strong motion accelerographs are designed to record three translational components of ground acceleration, switching on by themselves automatically once an earthquake ground motion reaches a certain threshold level,

usually about 0.005 g. The first complete record of strong ground motion was obtained during the 1940 El-Centro earthquake in California (Figure 2.1). Over a period of years increasing numbers of strong motion recorders have been installed in many parts of the world and have yielded much useful data.
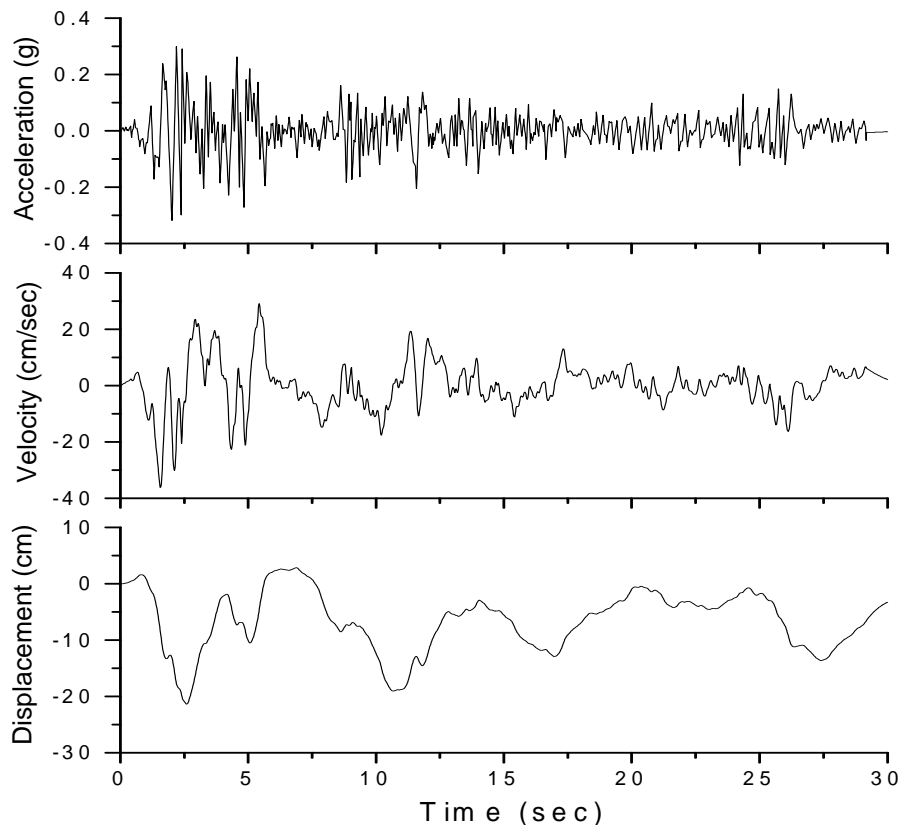

Figure 2.1 Example of strong motion earthquake record (N-S component of El-Centro, 1940 earthquake).

The strong ground motion is recorded with the help of accelerometers. When the natural frequency of the instrument is very high compared to that of the vibrations to be measured, the instrument picks up the acceleration of the motion measured. Hence accelerometers have high natural frequency. Alternately this implies that stiffness K of accelerometer should be very large and mass m should be small. Therefore, the accelerometers are compact in size.

Before the arrival of digital era, the accelerations were recorded on light sensitive paper. However, these records were often exposed to stray light and during large high frequency oscillations, the optical density of the trace would become faint due to faster movement of light beam. With the advent of new technologies, the design strong motion instruments have taken large strides in terms of types of devises used for triggering of recording, measurements of motion and recording of motion. The recent digital

instruments are also capable of recording certain length of pre-event history, thus including data before exceedence of trigger level. However, any strong motion instrumentation essentially requires the following components:

1. Vibrating machine
2. Vibration transducer
3. Signal conversion
4. Display / recording.
5. Data analysis.

The recorded data is corrected to remove instrumental error, if any, and is analysed to derive the relevant characteristics of recorded motion.

2.3.   Errors in Strong Motion Records

Errors are introduced into recorded motion at various stages in the processes leading to their final form. The source of these errors and approximations for their magnitudes, wherever possible, are summarized here.

2.3.1.   Errors in Recording

The trace produced by a strong-motion accelerograph is considered to be a record of ground acceleration during an earthquake. The basic element of an accelerograph is essentially a damped, simple oscillator. Since an earthquake motion contains a range of frequencies, some distortions in amplitude and phase invariable occur, depending upon the damping of the recording element and the ratio of the natural frequency of the element to the input frequencies. From an analysis of the instrument response it can be shown that the percentage of amplitude distortion and the phase distortion in degrees given by

$$e_A = 100\,(k-1) \qquad\qquad\qquad\qquad (2.1)$$

$$e_P = (\phi - 90\beta) \qquad\qquad\qquad\qquad (2.2)$$

in which e_A and e_P are the amplitude and phase errors, respectively and

$$k = \frac{1}{\sqrt{\left(1-\beta^2\right)^2 + \left(2\xi\beta\right)^2}} \qquad\qquad\qquad\qquad (2.3a)$$

$$\beta = \frac{\omega}{\omega_0} \;\; ; \qquad\qquad\qquad\qquad (2.3b)$$

$$\phi = \tan^{-1}\frac{2\xi\beta}{1-\beta^2} \qquad\qquad\qquad\qquad (2.3c)$$

in which ω = input frequency in radians per second, ω_0 = natural frequency of the element, ξ = fraction of critical damping.

For damping of the order of 60 percent (usually provided in the accelerographs) and $0 < \beta < 1$, it can be shown from above equations that amplitude distortion is less than 10 percent and phase distortion less than 5 degrees. Thus, the accelerograph will record with this accuracy, frequency content from zero up to its natural frequency, which is typically about 25 cycles per second in the case of analog accelerographs and 50-100 cycles per second for digital accelerographs. If the ground motion contains frequencies higher than the natural frequency of the accelerograph, both the amplitude and the phase of these frequency components will be distorted significantly.

2.3.2.   Errors in Digitization

1.   Scaling Error – This error arises from the inherent limitations of the resolving power of any scaling device. For most instruments now in use it is of the order of 0.01 in.

2.   Random Error in Time and Acceleration Records – The thickness of the line defining the record makes the choice of points at which discernible changes of slope occur and the scaling of magnitudes a matter of individual judgment. This leads to errors in both time and acceleration coordinates. If the same record is digitized by different persons, the standard deviations of the random errors in time and acceleration typically may be 0.018 secs and 0.001 g respectively. These reading errors may in turn, causes errors up to 20 percent in undamped spectra calculated from the records.

3.   Baseline Correction – The unknown distortion introduced into the ground acceleration during recording and digitization is corrected to some degree by adjusting the baseline, herein by a technique which minimizes the resulting ground velocity. A detailed discussion on various baseline correction schemes and their impact is available in Boore (2001) and Boore and Bommer (2005).

4.   Distortion of the Record – For data sampling at equal time intervals, the cutoff frequency, called the Nyquist frequency, is given by

$$f_c = \frac{1}{2\Delta t} \tag{2.4}$$

in which Δt is the sample interval. Such sampling causes aliasing error, since frequency content higher than f_c is folded into the lower frequency range 0 to f_c and confused with the data in this lower range. In earthquake records, with closely spaced, sharp peaks and many changes of slope this problem is important and it is necessary to use small intervals of digitization.

2.4. Strong Motion Arrays in India

Starting from 1976, Department of Earthquake Engineering, Indian Institute of Technology, Roorkee (formerly known as University of Roorkee), operated a network of about 200 analog strong motion accelerographs covering parts of Himachal Pradesh, Punjab, Haryana, Uttaranchal, Uttar Pradesh, Bihar, West Bengal, Sikkim, and northeastern India.

However, due to technological obsolescence of the components/instruments used for the network Department of Science and Technology (DST), sanctioned a project titled "National Strong Motion Instrumentation Network" to the Indian Institute of Technology, Roorkee (IITR), in 2004 to install 300 state-of-the-art digital strong motion accelerographs in northern and northeastern India to monitor earthquake activity in seismic zones V and IV, and in some heavily populated cities in seismic zone III. The locations of instruments in this network are given in Figure 2.2.
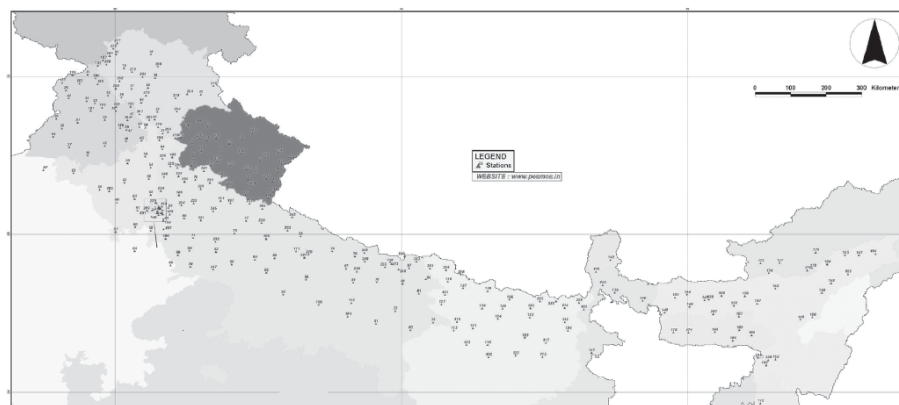

Figure 2.2 Location of instrumental in Indian strong motion network (based on Ashok Kumar et.al, 2012).

2.5.   Ground Motion Characteristics

Several earthquake parameters are reported in the literature for quantitatively describing the various characteristics of the ground motion. These cover characteristics such as amplitude of motion, frequency content of motion, duration of motion, etc. Loading effect of earthquake ground motion at a site is generally represented by three ground motion (GM) parameters viz. peak ground acceleration, response spectrum and acceleration time history. The combined influence of the amplitude of ground accelerations, their frequency content and the duration of the ground shaking on different structures is represented by means of response spectrum.

The three ground motion parameters i.e. peak ground acceleration (PGA) value, response spectrum and acceleration time history of a site, commonly used in the design of structure, are known as design basis ground motion parameters (DBGM).

2.6. Amplitude Parameters

2.6.1. Peak Ground Acceleration

The earthquake time history contains several engineering characteristics of ground motion and maximum amplitude of motion is one of the important parameter among them. The PGA is a measure of maximum amplitude of motion and is defined as the largest absolute value of acceleration time history.

The response of very stiff structures (i.e., with high frequency) is related to PGA. Though PGA is not a very good measure of damage potential of ground motion; due to its close relation with response spectrum and usability in scaling of response spectrum, PGA is extensively used in engineering applications.

Generally, at distances several source dimensions away, vertical PGAs are found to be less than horizontal PGA though at near source distances it could be equal to higher than the corresponding horizontal PGA. For engineering purposes, vertical PGA is assumed to be two thirds of the horizontal PGA.

2.6.2. Peak Velocity

Peak velocity is the largest absolute value of velocity time history. It is more sensitive to the intermediate frequency components of motion and characterizes the response to structures that are sensitive to intermediate range of ground motions, e.g. tall buildings, bridges, etc.

2.6.3. Peak Displacement

Peak displacements reflect the amplitude of lower frequency components in ground motion. Accurate estimation of these parameters is difficult as the errors in signal processing and numerical integration greatly affect the estimation of amplitude of displacement time history.

2.7. Frequency Content of Motion

Earthquake ground motion is an amalgamation of harmonic motion with a range of frequency components and amplitudes. Several approaches have been proposed in the literature to quantitatively estimate these characteristics. Some of these are discussed below

2.7.1. Response Spectra

A plot showing the maximum response induced by ground motion in single degree of freedom oscillators of different fundamental time periods having same damping is known as response spectrum. The maximum response could be spectral acceleration, spectral velocity or spectral displacement.

The spectral velocity and spectral acceleration are related by:

$$SA = \omega_0 SV \tag{2.5}$$

where SA is the spectral acceleration, SV spectral velocity and ω_0 the natural circular frequency. Similarly, it can be shown that

$$SV = \omega_0 SD \tag{2.6}$$

where SD is the spectral displacement.

As response spectra represents the frequency content of the motion after propagation through earth's crust, large amount of variability is expected across the response spectra. Figure 2.3 depicts the time histories (all normalized to 1g PGA) and corresponding response spectra, bringing out the variations observed in the response spectra with respect to time histories.
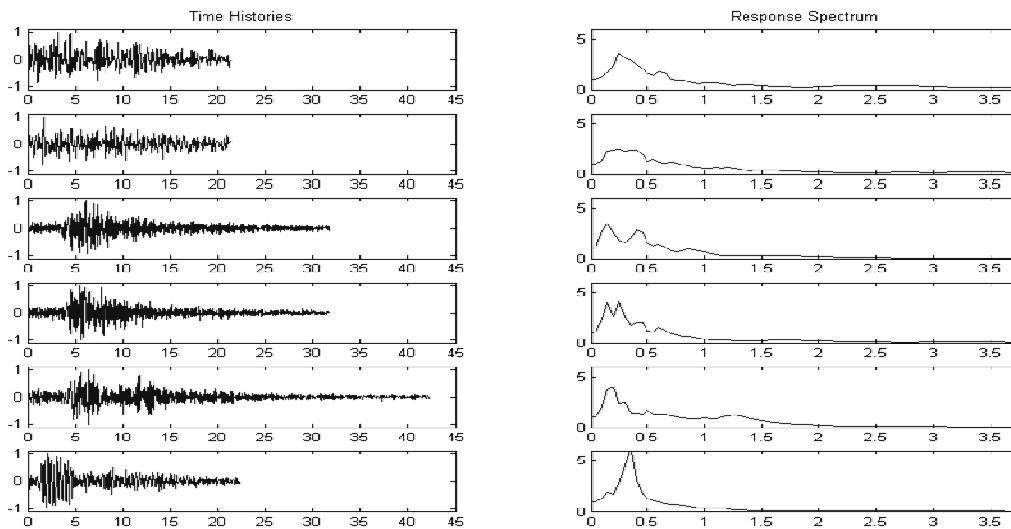

Figure 2.3 Plot of time histories and corresponding response spectra (Abscissa is in seconds and ordinate is in 'g').

The shape of response spectrum and location of peaks are controlled by characteristics of site condition (soil/rock) at the location of measurement, magnitude of earthquake, distance, etc. It is seen that in general, the motion on rock contains more shore period content of motion compared to that in soil. Similarly, the response spectra from a low magnitude event recorded at closer distances will be rich in small period or high frequency components compared to a large magnitude event recorded at farther distances. The design response spectral shape, as suggested by Indian standard, BIS 1893, for three types of site conditions are given in Figure 2.4.
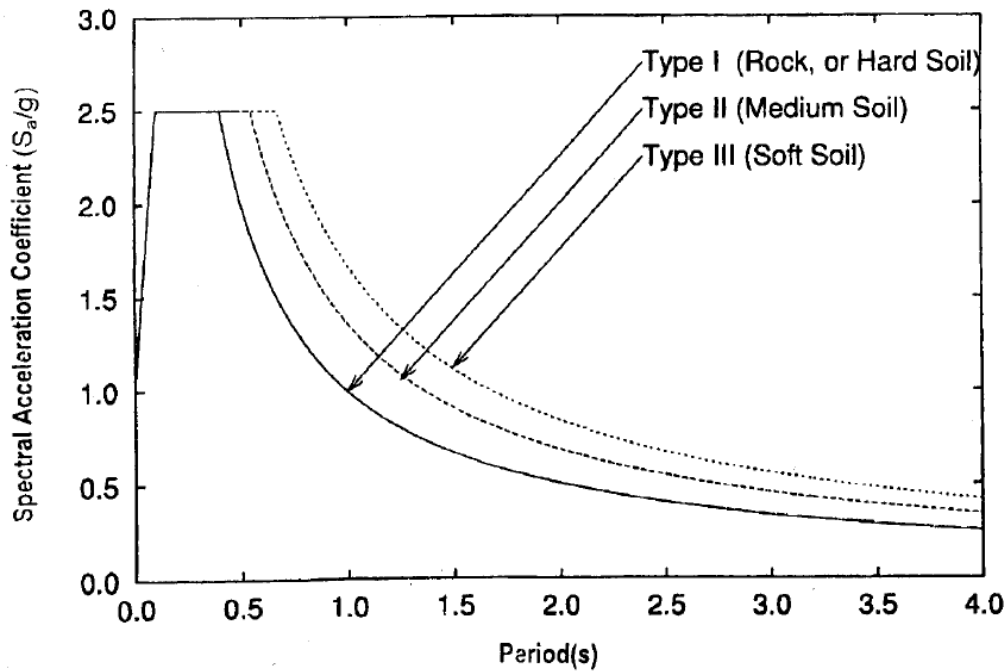
Figure 2.4 Design response spectral shape suggested by BIS (IS 1893-2002).

The response spectra can be plotted with any of the three parameters (acceleration, velocity and displacement) as mentioned above as ordinate and period/frequency as abscissa. Since these parameters are interconnected through the expressions (2.5 and 2.6) as given, all three parameters can also be represented in a single graph known as tripartite plot or Displacement velocity acceleration (DVA) spectrum. Figure 2.5 depicts a typical tripartite plot of a response spectrum for two levels of damping. It can be also noted from the figure that the effect of the damping on the response spectrum is greatest in the velocity sensitive region, and is least in the acceleration sensitive and displacement sensitive regions. This is possible due to the fact that in logarithmic domain, these relationships boils down to a group of straight lines, which are at 45 degree angles with the line corresponding to the spectral velocity.

It can be seen that there are three main regions in a DVA spectrum. The portion of the response spectrum to the left of point period = 0.1sec is almost constant and is most directly related to the maximum ground acceleration. Similarly, the portion of response spectrum to the right of 10 sec period is most directly related to the maximum ground displacement, which is also constant in that region. The intermediate portion is related to the maximum velocity of the ground motion.
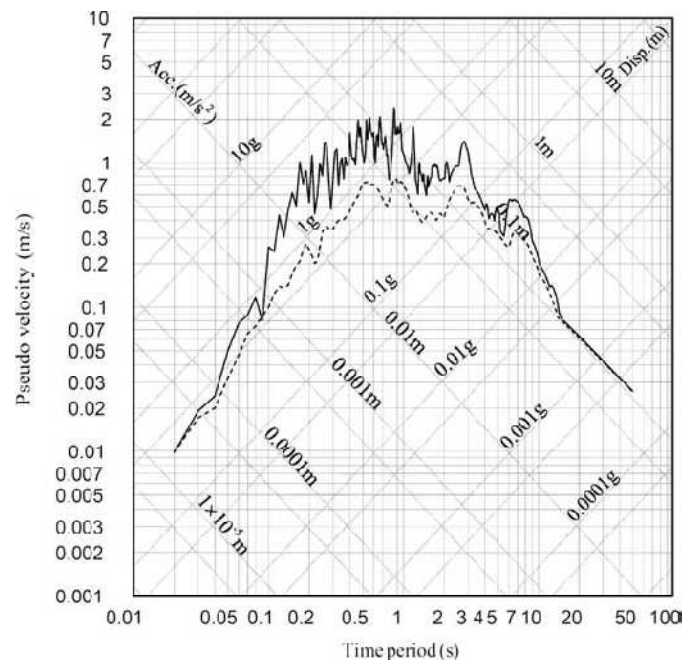
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Figure 2.5 A typical tripartite plot or DVA spectrum (From Datta, 2010).

Based on this information, a three zone model of the tripartite plot can be postulated. These are a displacement sensitive region (that is, long period region), an acceleration sensitive region (that is, the short period region), and a velocity sensitive region (that is, the intermediate period region), Figure 2.6. This input is used for estimation of a design response spectrum from the inputs of peak ground acceleration, peak velocity and peak displacement.
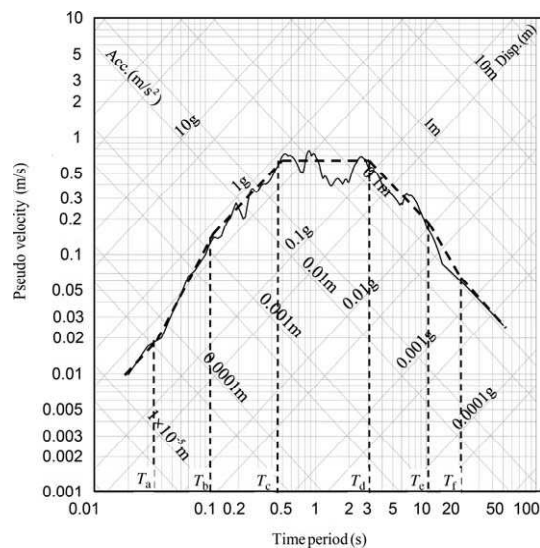

Figure 2.6 A typical tripartite plot of response spectrum magnifying the constant acceleration, velocity and displacement regions [From Datta, 2010].

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2.7.2. Fourier Spectra

The plot of Fourier amplitude of input time history vs time period or frequency is known as Fourier spectrum. Since the Fourier analysis provides both amplitude and phase angles, Fourier spectra could either be a Fourier amplitude spectrum or Fourier phase spectrum. The Fourier amplitude spectrum provides inputs on the frequency content of the motion and helps to identify the predominant frequency of motion. Similar to observation made in the case of response spectra, Fourier spectra of two time histories could be vastly different.

The shape of Fourier spectra is related to seismic moment. The smoothened Fourier amplitude spectra when plotted in log-log scale shows a shape similar to that given in Figure 2.5 above, i.e. with a raising limb, a horizontal portion and a falling limb. The lowest frequency of the horizontal portion is known as corner frequency and the highest frequency of the horizontal limb as known as cutoff frequency. It is seen that the corner frequency is inversely proportional to the cube root of seismic moment. This means large earthquakes produces motions with higher low frequency content compared to smaller earthquakes (Kramer, 2007).

2.7.3. Power Spectra

Frequency contents of ground motion can also be represented by a power spectrum or power spectral density function. The ordinate of power spectra is calculated as

$$G(\omega) = \frac{1}{\pi T_d} C_n^2 \qquad (2.7)$$

where $G(\omega)$ is the spectral density at natural circular frequency, ω; T_d the duration of time history and C_n the Fourier amplitude at natural circular frequency, ω.

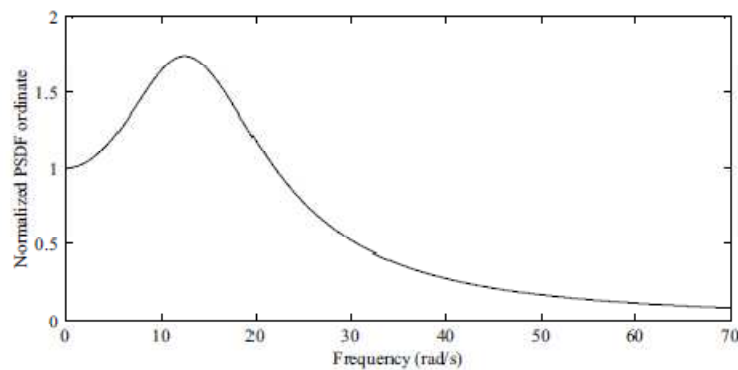Figure 2.7 depicts a typical plot of power spectral density function.

Figure 2.7 Typical power spectral density function.

2.8. Instruments for Direct Recording of Response Spectral Accelerations

Under the Indian National Strong Motion Network (INSMIN) Program, Department of Earthquake Engineering (DEQ), IIT Roorkee has installed more than three hundred Structural Response Recorders (SRR) in different parts of India. The SRR consists of six recording instruments, in the form of conical pendulums, which measure the vector sum of horizontal component of motion on a smoked glass plate (Figure 2.8a). These seismoscopes are relatively inexpensive instruments and do not require a power source to operate. Their natural periods are adjusted to 0.40sec, 0.75sec and 1.25sec and the damping provided is 5% and 10% of critical damping. Thus the output from a SRR provides ordinates of vector sum of spectral acceleration at natural periods 0.4sec, 0.75sec and 1.25sec for 5% and 10% damping. A typical SRR recording is shown in Figure 2.8(b).
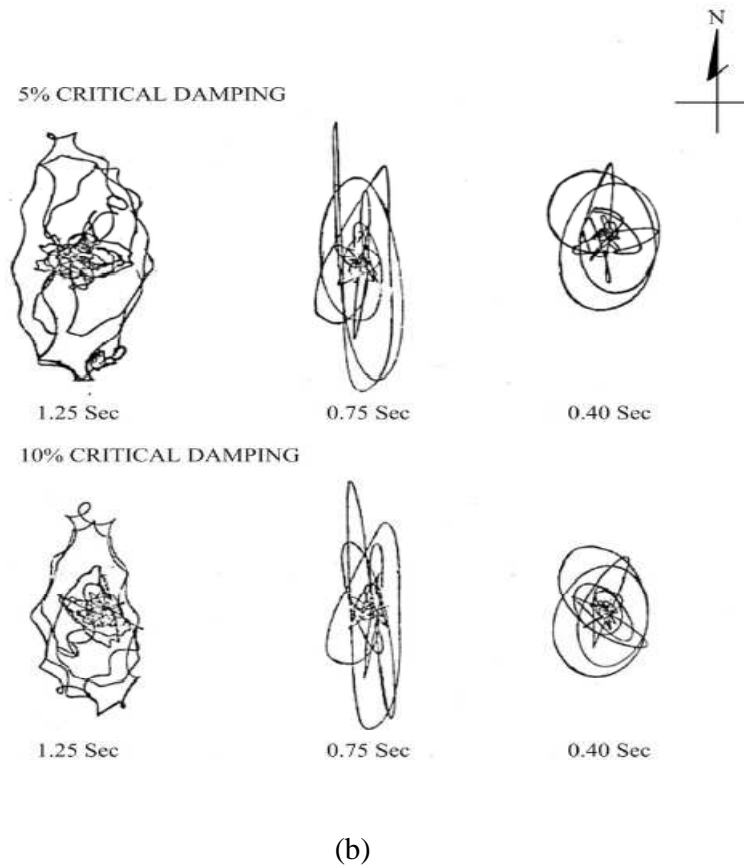

(a)

5% CRITICAL DAMPING

1.25 Sec   0.75 Sec   0.40 Sec

10% CRITICAL DAMPING

1.25 Sec   0.75 Sec   0.40 Sec

(b)

Figure 2.8: (a) Photograph of SRR; (b) A typical record from SRR (from Jain et.al, 2012).

2.9. Predictive Relationships for Earthquake Parameters

It is well known fact the strength of earthquake waves generally decrease as they propagate away from the source. Anomalies to this on observed behavior could be contributed by reflections from the underlying strata or local site effects. In general, the attenuation of ground motion parameter depends on the distance from the source and the magnitude of the earthquake and it is one of the important parameters used in seismic hazard evaluation of site. The ground motion parameter predicted by the attenuation relation can be peak ground acceleration, peak ground velocity, peak ground displacement, intensity of shaking, or shape of the response spectrum. The

attenuation relationships developed are constantly updated based on the availability of new data for the particular region.

2.9.1. Predictive Relationships for PGA

The acceleration produced by an earthquake is a function of earthquake magnitude and distance from the source. The attenuation of ground motion is represented by attenuation relationships. Generally, these empirical relationships have the following form:

$$Ln(y) = C_1 + C_2 m - C_3 R \tag{2.8}$$

where 'm' is the magnitude of the earthquake and R is the distance from site. C_1, C_2 and C_3 are constants and are a function of the regional geology and soil conditions. 'y' is the acceleration at site due to earthquake of magnitude 'm' occurring at distance R.

In addition to the above terms, recent attenuation relationships also include functions to account for non linear dependence of attenuation on distance (usually a log (R) function), site conditions (soft soil, stiff soil, rock, etc), source type and location of measurement (reverse/strike slip/normal, hanging wall side or foot wall side), etc.

So a more comprehensive form of attenuation relation would be of the type:

$$\ln(y) = C_1 + C_2 m + C_3 m^{c_4} + C_5 \ln\left[R + C_6 e^{C_7 m}\right] + C_8 R + C_9 f\left(site\_effects\right) + C_{10} f\left(source\right) \tag{2.9}$$

The coefficients of the equation are determined from observed data using regression techniques, which uses minimization of error between the measured and predicted values to calculate the coefficients. Because of this, the predicted value of parameter would represent a mean estimate with an associated value of standard deviation. It can be seen from the equation that the acceleration is directly proportional to magnitude and inversely proportional to distance. Hence, for estimating the maximum acceleration at a site, one needs to estimate the upper limit magnitude and lower limit of distance.

The attenuation relation for peak ground acceleration (in terms of g) for shallow crustal earthquakes, as reported by Boore et. al. (1997), is given by

$$\ln Y = b_1 + 0.527(M - 6) - 0.778 \ln r - 0.371 \ln \frac{V_S}{1396} \tag{2.10}$$

where

$$b_1 = \begin{cases} -0.313 \, \text{for strike} - \text{slip faults} \\ -0.117 \, \text{for reverse} - \text{slip faults} \\ -0.242 \, \text{if mechanism is not specified} \end{cases}$$

r is the closest distance to surface projection of rupture and V_S is the average shear wave velocity which depends on the site class.

The standard deviation of the predicted acceleration is given as $\sigma_{\ln Y} = 0.520$. With the availability of more strong motion data, separate relationships have been developed for different regions. These include shallow crustal earthquakes in active tectonic regimes, shallow crustal earthquakes in stable continental regions, subduction zone earthquakes, and earthquakes in extensional regimes.
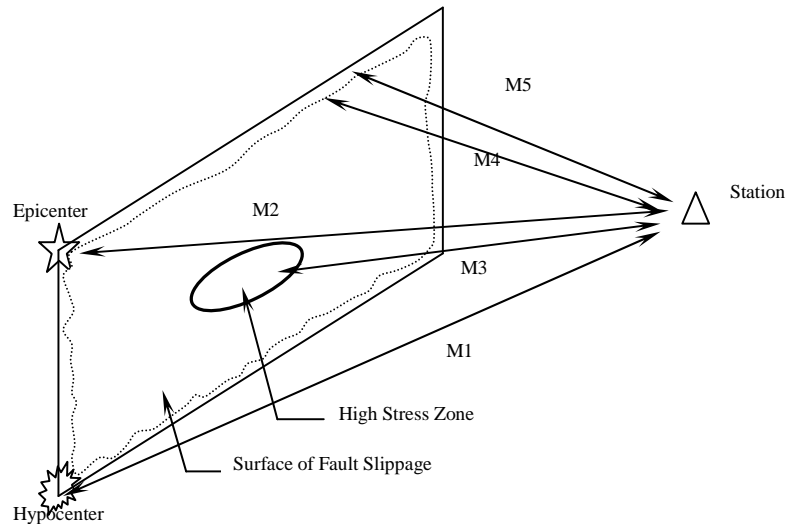

Figure 2.9 Several type of distance measures used in attenuation relationships, M1: hypocentral distance, M2 : Epicentral distance, M3: distance to zone of highest energy release, M4: Distance zone of seismogenic rupture R_{seis}, M5: Distance to surface projection of fault, r_{jb}.

Different attenuation relationships use different forms of distance measures (such as R_e, R_{hypo}, R_z, R_{rup}, r_{jb}, etc) for prediction of acceleration, Figure 2.9. For smaller earthquakes and at larger distances, the difference between these may not be of much concern, but for large events and at closer distances these would be significantly different. Similarly, depending on the attenuation relation, the predicted parameter 'y' could be mean of two horizontal components of acceleration, or geometric mean, or largest component, etc.

User should be aware of issues with respect to the distance measure adopted b the particular attenuation relation, nature of predicted parameter, validity range of attenuation relation with respect to magnitude, distance, source mechanism etc, before implementing them in analysis. Figure 2.10 depicts the variability in the predicted values of peak ground acceleration over the distance by different attenuation relations.
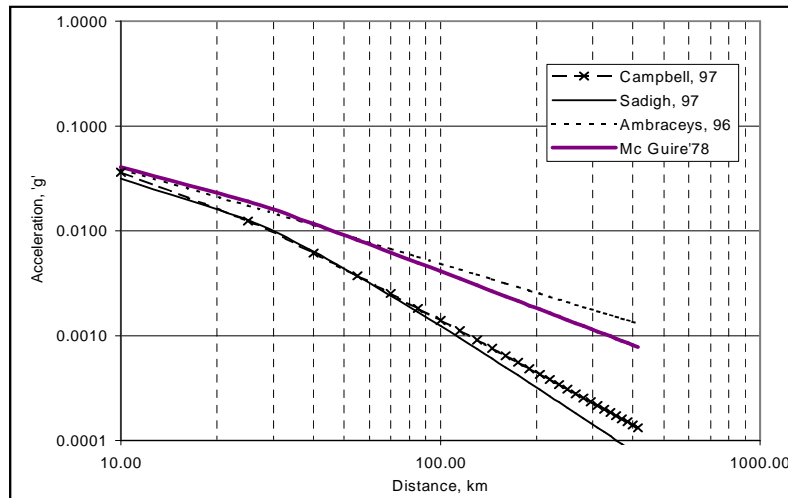
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Figure 2.10 Variation of Peak ground acceleration with distance as predicted by attenuation relationships developed by Campbell (1997), Sadigh et.al, (1997), Ambraseys (1996), and McGuire (1978).

2.9.2. Predictive Relationships for Response Spectrum

Attenuation relationships are not only available for predicting the peak ground acceleration but also the spectral ordinates of the response spectrum. In all the available relationships, the ordinates of response spectrum are calculated for a single degree of freedom system with 5% of critical damping, Figure 2.11. In these relationships, the coefficients, C_i's associated with the attenuation relation will also be a function of time period/frequency.
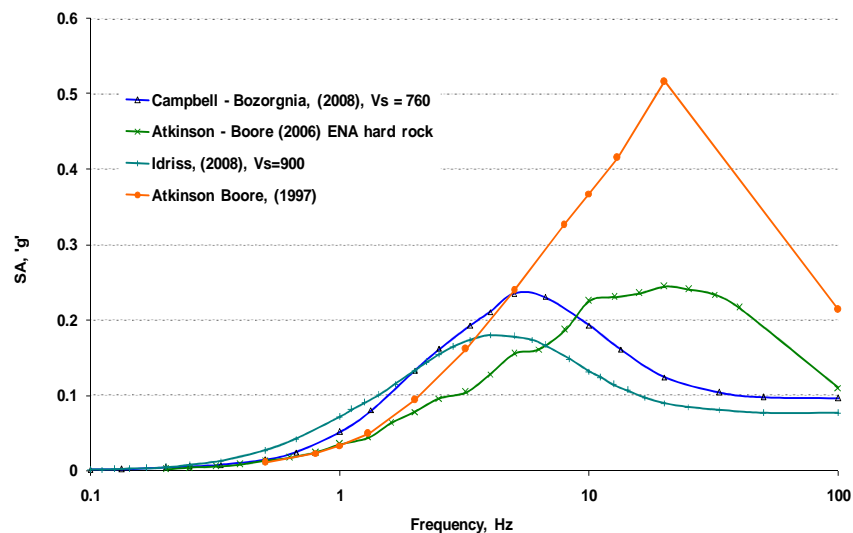

Figure : 2.11 Comparison of attenuation relationships (developed for intraplate and interplate regions) for response spectral ordinates corresponding to 6.5 magnitude event with r_{jb} of 30km.

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2.10. Earthquake Site Effects

Depending on the soil cover underlying the point of observation and the topographical location; it is observed that the amplitude as well as the frequency content of the earthquake motion varies. Some of the contributing factors that are responsible for ground motion modification are discussed below.

2.10.1. Effect of Soil Cover

The magnitude 8.1 Mexico earthquake of 1985 caused heavy causalities in the city of Mexico. About 10,000 people are estimated to be dead during this event. Since the epicenter of the earthquake was about 350km away, severity of damage in the city perplexed the scientific community. It was noticed that majority of the damage was restricted to the part of the city which was built on an ancient lake bed. The soft sediment layers of lake bed amplified the earthquake waves in certain frequencies that caused the damage. Similarly, Narayan and Sharma (2004) reported that the damage patterns during Bhuj earthquake of 2001 illustrated the strong influence of local geology conditions on the severity of the damage at many places like soil amplification in Ahmedabad, Morbi city,etc.

The ground motion amplitude could vary significantly depending on the properties and configuration of the material located along the near surface. The parameters that govern this behavior are known as impedance and absorption. It is observed that seismic waves at the same epicentral distance would be higher on low density, low velocity soil compared with the high density, high velocity rock. The second parameter, absorption, counteracts the increase in amplitude. Absorption is the damping associated with the propagation media and is higher in soils compared to rocks.

When an elastic wave travels through a layered media, at the interface, part of the wave is transmitted and part of it gets reflected, and the process is governed by the term, impedance ratio, α_z. Impedance ratio is defined as

$$\alpha_z = \rho_2 V_2 / \rho_1 V_1 \tag{2.11}$$

where ρ_1 and V_1 are the density and wave velocity of the bottom layer and ρ_2 and V_2 are that of top layer. The amplitude of reflected and transmitted waves in case of one dimensional wave propagation are:

$$A_r = \frac{1 - \alpha_z}{1 + \alpha_z} A_i \tag{2.12}$$

$$A_t = \frac{2}{1 + \alpha_z} A_i \tag{2.13}$$

where A_i, A_r and A_t are the amplitudes of incident, reflected and transmitted waves.

From these, it can be observed that for a value of impedance ration equal to zero, i.e., free surface, the amplitude of transmitted wave will be twice that of incident wave. Similarly, an impedance ratio of 0.25 implies that transmitted wave will have 60% more amplitude compared with incident wave. A comparison of the peak ground accelerations estimated in soil sites viz-a-viz that in rock sites are given in Figure 2.12. It is noted that the site conditions effects not only the peak acceleration at the site, but also the frequency content of the motion. The deeper soil layer is found to shift the predominant period of the ground motion into the longer periods. But the amount of amplification or de-amplification shift depends on the depth of soil layer and the related soil properties. Figure 2.13 depicts the relative amplification of motion with respect to depth of soil cover.
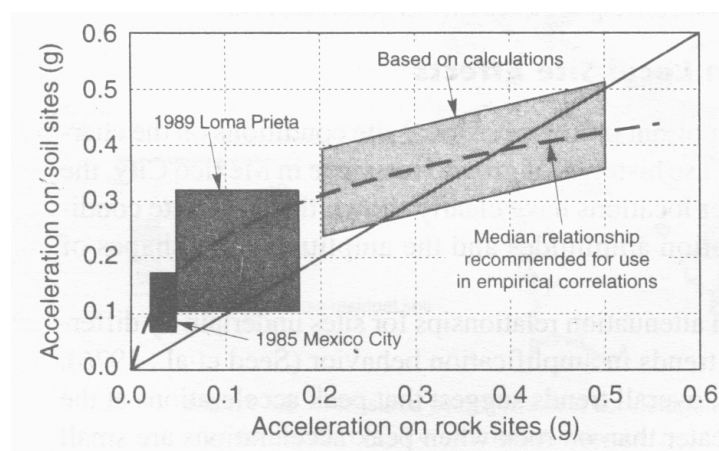

Figure 2.12 A comparison of ground motions recorded on soil and rock sites [From Kramer, 2008].
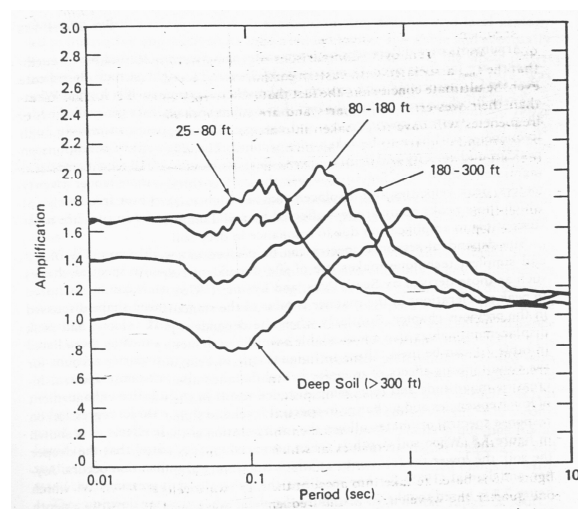

Figure 2.13 Relative amplificaiton factors for a 5% damped response spectrum for sites with different depths of overlying soil [From Reiter, 1989].

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2.10.2. Effect of Site Topography

The location of the site in a ridge or a valley will have profound effects on the incident motion. The theoretical formulations indicate that the in case of a ridge that is approximated as a triangular wedge, the apex displacements is amplified by a factor of $2\pi/\phi$, where ϕ is the vertex angle of the wedge.

Analysis of topographic irregularities pose a complex problem owing to interaction of amplification and de-amplification arising from irregular geometry, frequency content of motion and incident wave angles.

2.10.3. Basin Effect

The curvature of the basin where the soft soil is deposited can trap the waves and amplify the motion experienced on the surface. This could also significantly increase the duration of the earthquake motion.

2.11. Seismic Hazard Analysis

Seismic hazard analysis is the process by which the site specific design basis ground motion (DBGM) parameters are arrived at. For estimating the DBGM parameters of a site, the earthquake sources (e.g. faults) around the site needs to be identified and maximum potential earthquake of each source need to be estimated. This is achieved by conducting a detailed investigation of geological and seismological environment of the site. The data on historical and pre-historical seismicity are also collected.

The areas are investigated through satellite imageries, aerial photographs, detailed maps to determine tectonic structures that could be considered as the sources for earthquakes. The historic earthquake data available in earthquake catalogues are also collected. Information on prehistoric seismicity can be obtained by paleoseismic studies. Paleoseismology is the study of the timing, location, and size of prehistoric earthquakes. This focuses on instantaneous deformation of landforms and sediments during individual earthquakes. Paleoseismic history helps to understand aspects of earthquake geology such as regional patterns of tectonic deformation and the long-term behavior of specific faults. It can be used to supplement the calculation of seismic hazard.

Using the information obtained from the investigations, all regional geological and seismological information are compiled, and all related tectonic information around the site are plotted on a map. Epicenters of all known earthquakes are superimposed on the same. Based on these compiled information, one would be able to identify seismogenic faults (faults that are capable of generating seismicity) and tectonic provinces (areas with diffused seismicity) in the region. Subsequently, the size and shape of earthquake source and its distance from site and maximum earthquake potential associated with each source are estimated.

2.11.1. Deterministic Hazard Analysis

In deterministic approach, depending on the seismotectonic conditions and number of earthquake sources, one or more than one earthquakes will be postulated in the region and the PGA is estimated for each postulated earthquake using appropriate attenuation relationship. The parameters that are necessary for estimation are: size of the earthquake (magnitude or intensity) and distance from the site. For example, Figure 2.14 shows various faults/areas of diffused seismicity and their estimated maximum earthquake potential. This information along with the input on distance (usually minimum distance) from the site can be used to estimate the peak ground acceleration using the appropriate attenuation relationships.
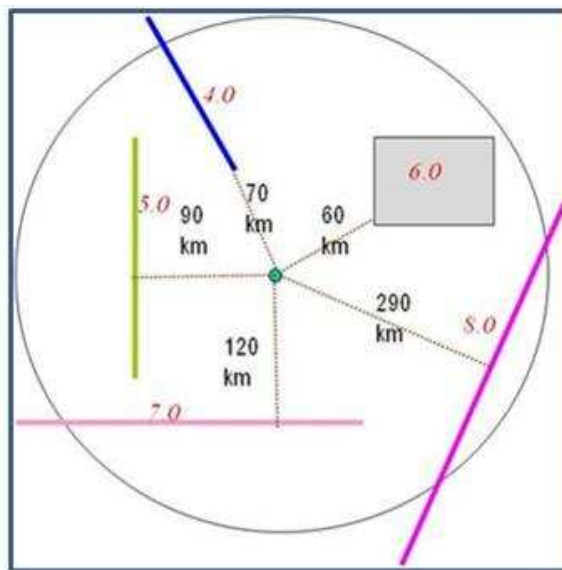

Figure 2.14 Calculation model showing the sources around a site with associated maximum earthquake potential (m) and shortest distance (R).

Figure 2.15 depicts predictions by attenuation relation for PGA with respect to distance for different values of maximum earthquake potential. Using this information, the acceleration at site due to earthquakes from each source (with associated maximum earthquake potential, m and minimum distance to site, R) is determined. Table 2.1 tabulates the maximum acceleration at site due to each fault/tectonic province estimated from Figure 2.9. The maximum acceleration among these is considered as the site specific PGA for design.
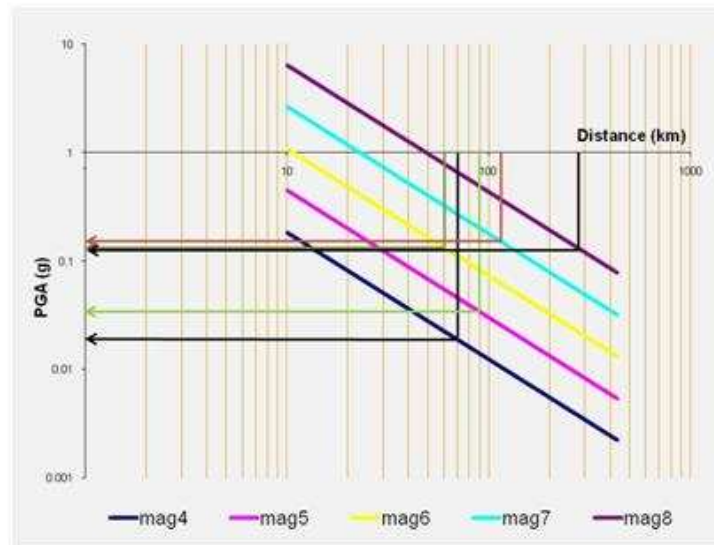
Figure 2.15: Predictions by attenuation relation for PGA with respect to distance for different values of maximum earthquake potential.

Table 2.1 Maximum acceleration at site due to different faults/tectonic provinces.

SI No.	Max potential of fault/tectonic province	Distance from site	PGA at site
1	4.0	70km	0.02g
2	5.0	90km	0.04g
3	6.0	60km	0.12g
4	7.0	120km	0.15g (Max PGA)
5	8.0	290km	0.11g

Response Spectrum Shape

Due considerations are given for size of the earthquake, source mechanism, distance from the source, transmission path characteristics and site characteristics during the development of site specific response spectra to be adopted in the design. Response spectral shape for site specific spectra is generally derived from records of strong motion time histories at site. In case of non-availability of sufficient records, response spectral shapes derived for sites having seismic, geological and soil characteristics similar to that of the site under consideration can be used.

Depending on the importance and failure consequences of the structure being designed, the regulations require use of mean or mean + 1 sigma response spectrum in the design. For estimating the design response spectrum, the response spectral shape is scaled with the PGA, as described in the preceding paragraphs.
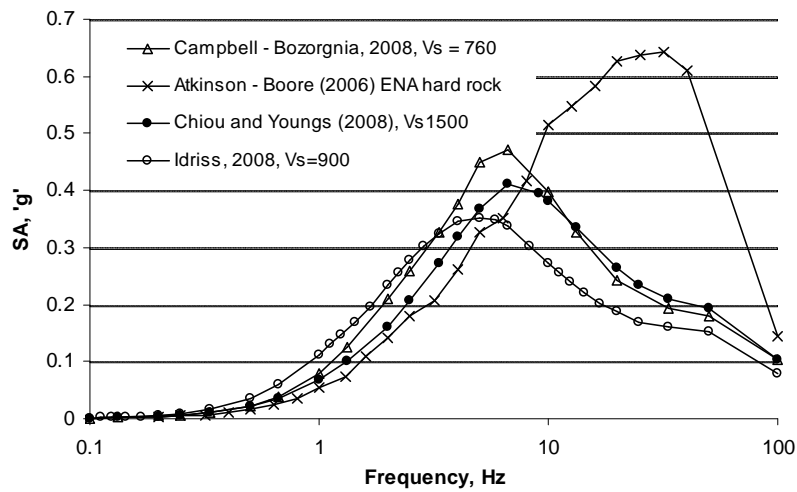
Figure 2.16   Mean + 1 sigma spectra predicted by Campbell & Bozorgnia (2008), Atkinson & Boore (2006), Chiou & Youngs (2008) and Idriss (2008) corresponding to a M6.0 earthquake at 20km distance and 15km focal depth.

The recent attenuation relations also report the coefficients from which not only PGA but also the spectral ordinates can also be derived. Using this approach, a complete response spectrum can be derived directly from attenuation relations. Figure 2.16 depicts the mean + 1 sigma spectra obtained using the attenuation relationships available in the literature

For some sites the design spectrum could be the envelope of two or more different spectra. Such sites are affected by more than one active fault. The design spectra obtained by considering the earthquake occurring from the two faults are different, Figure 2.17.
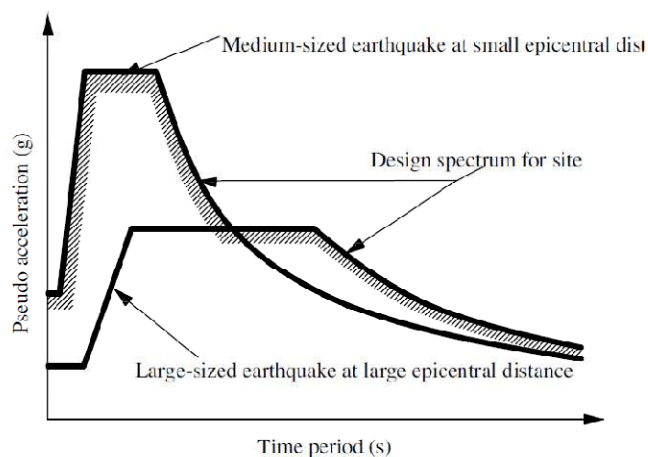

Figure 2.17: Estimation of design response spectrum from multiple scenarios (From Datta, 2010].

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2.11.2. Probabilistic Seismic Hazard Analysis [AERB, 2008; Roshan and Basu, 2010]

Determination of ground motion parameters by probabilistic method is accomplished by performing a probabilistic seismic hazard analysis (PSHA). The subject of PSHA of a site was initiated by Cornell (1968). Unlike maximisation of single valued earthquake events as in deterministic approach, probabilistic approach takes into account the probable distribution of earthquake magnitudes in each source, probable distances within that source where earthquakes could originate and dispersion of acceleration estimated using attenuation equations. In PSHA methodology, occurrence of earthquakes is usually considered as Poisson process. This means that the events have an average occurrence rate and could occur independent of the time elapsed since last event.

PSHA involves four steps (Figure 2.18):
- Specification of the seismic-hazard source model(s) (zonation);
- Specification of earthquake recurrence relationships which reflect earthquake activity in the source
- Specification of the ground motion model(s) (attenuation relationship(s)); and
- The probabilistic calculation.

The seismic hazard is determined from the following form of expression:

$$E(Z > z) = \sum_{i=1}^{N} \alpha_i \int_{m_{\min}}^{m_{\max,i}} \int_{r=0}^{r=\infty} f_i(m) f_i(r) P(Z > z | m, r) dr dm \qquad (2.14)$$

Left side of equation (2.14), *E(Z>z)*, is the frequency that acceleration Z being greater than z. For obtaining the probability, one has to consider the temporal distribution of the earthquake, which is normally taken as a Poisson process.

For PSHA of a site, earthquake sources within a defined region containing the site are considered. These sources, depending on its characteristics are modeled as point, or line, or aerial, or volume sources. Each source is assigned a maximum potential magnitude $m_{\max,i}$ of earthquake. Total number of such sources (N) to be considered in the PSHA study, their geometry and value of $m_{\max,i}$ are derived from the geological and seismological information of the region/area around the site, and past earthquake data. One value of minimum earthquake magnitude, $m_{\min}$ is generally assigned to all sources from practical consideration of hazardous effect of minimum earthquake that can affect the facility under consideration.

Activity rate of each source, α_i, is determined from the earthquake recurrence relationship of the region/source/fault based on Gutenberg-Richter relationship,

$$\log_{10} n(m) = a - bm \qquad (2.15)$$

Where *n(m)* is the number of earthquakes with magnitude *m* or greater per unit time, and *'a'* and *'b'* are constants representing the seismic activity of the region/source/fault.

The alternate form of Guttenberg-Richter relationship is,

$$n(m) = v_0 e^{-\beta m} \qquad (2.16)$$

In which, $v_0 = 10^a$ and $\beta = b \ln 10$.

The activity rate is the rate of earthquake corresponding to m_{min} and is given by,

$$\alpha = v_0 e^{-\beta m_{min}} \qquad (2.17)$$

α_i is calculated from α

The probability distribution of earthquake magnitude $f_i(m)$, is related to β, m_{min} and $m_{max,i}$ and generally follows the probability distribution function:

$$f_i(m) = \frac{\beta\, e^{[-\beta(m-m_{min})]}}{\left[1 - e^{[-\beta(m_{max,i} - m_{min})]}\right]} \qquad (2.18)$$

For estimation of α as well as $f_i(m)$, the recurrence relation for the sources, i.e., 'a' and 'b' values needs to be determined from the earthquake database of the region under consideration.
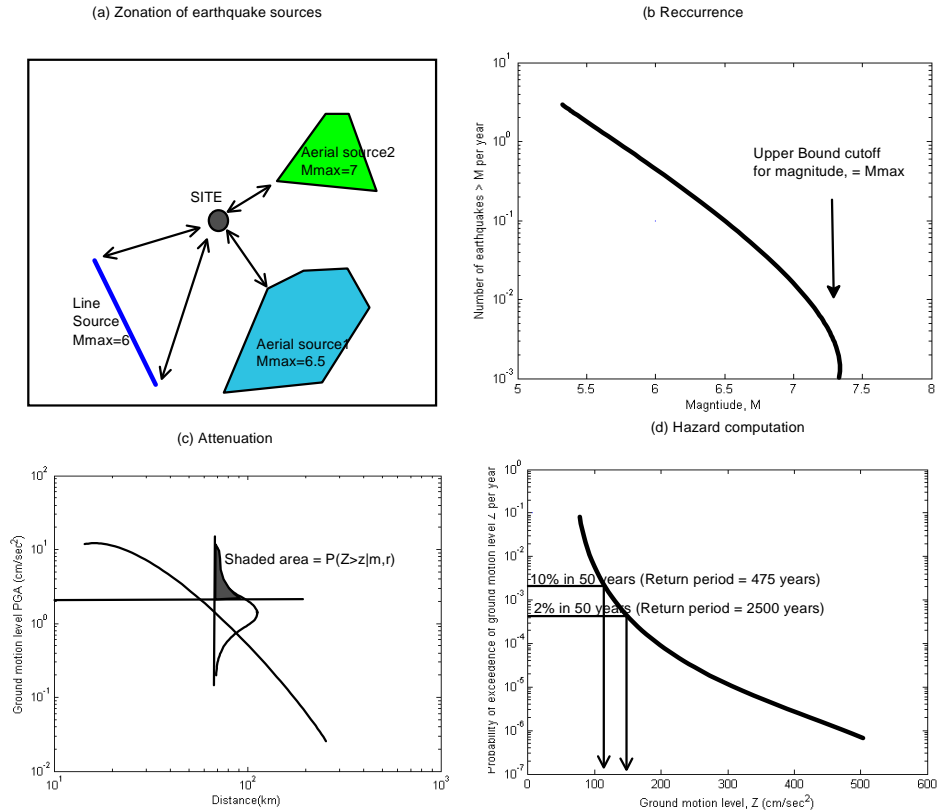

Figure 2.18: Various steps associated with probabilistic seismic hazard analysis.

Probability of exceedance of acceleration, *P(Z>z/m,r),* due to an earthquake of magnitude *m* originated in a source at a distance *'r'* is derived from the distribution function of *Z* which has the form of log-normal distribution. The mean value $\mu(lnZ)$ and standard deviation $\sigma(lnZ)$ are determined from the attenuation relation.

Distance measure is an important parameter for attenuation relationship. Various distance measures *'r'* used in the attenuation relationships are: (a) epicenter distance (R_e), (b) hypo-central distance (R_{hypo}), (c) distance to zone of energy release (R_z), (d) closest distance to rupture (R_{rup}), (e) closest distance to surface projection of rupture (r_{jb}). For the sites located at a distance of several times source dimensions (say, length of fault) from earthquake source, there is little difference between the results obtained using different distance measures. This may not be true in case of shorter distances; e.g., the case of near source earthquakes. It is further noted that the type of distance measures that should be considered is very much dependent on the attenuation relation.

The probability that earthquake occurs at a distance *'r'* from the site is calculated from the distribution function of distance measure, $f_i(r)$. The function, $f_i(r)$ depends on the geometry of the source and location of the site with respect to the source and also the distance measure used in attenuation formula. As analytical expressions for $f_i(r)$ are available only for simple source geometries, PSHA with complex source geometries usually adopts numerical methods for the evaluation of $f_i(r)$ (Kramer, S.L., 2007).

In summary, primary input to evaluate seismic hazard from equation (2.14) are source configuration, m_{max}, m_{min}, 'a' and 'b' values to determine α_i and β, attenuation relationships and *r*. Sources of major data/information required to develop the input parameters of this eqn. are geology and seismology, historical earthquake data, maximum earthquake potential of sources, and attenuation relationship as well as distance. The data/information should be as site specific as possible for rational application of PSHA technique to assess seismic hazard of the site.

One of the major advantages in this method is the possibility for incorporation of uncertainties. Uncertainties are introduced by lack of data and/or lack of knowledge, inadequate modeling, etc. These uncertainties can be taken into account by developing alternate scenarios and models.

2.11.3.   Uniform Hazard Spectrum

For generation of a uniform hazard spectrum, the only change with respect to the procedures brought out in sec. 2.11.2 is in the attenuation relation used for evaluation. Unlike the attenuation relation used for PGAs, the coefficients vary for each spectral period/frequency selected for derivation of hazard curve.

The general steps for generation of a uniform hazard spectrum are as follows:

1. Select a suitable attenuation relation which in addition to PGA, is also available for prediction of response spectral ordinates.

2. Undertake the investigations on seismotectonics and identify the tectonic sources and the maximum potential, as discussed in sec. 2.11.1

3. Generate the hazard curve for PGA using the procedures covered in sec. 2.11.2

4. For a spectral time period T_i, replace the coefficients attenuation relation so that the corresponding spectral ordinates are obtained.

5. Generate the hazard curve, say corresponding to period T_1

6. Repeat the procedure for each spectral periods so that the hazard curves for corresponding periods are generated, Figure 2.19.

7. For the chosen frequency of exceedence or return period, select the abscissa of each hazard curve. i.e., from the hazard curve corresponding to time period T_1, calculate Sa_1, from the hazard curve corresponding to time period T_2, calculate Sa_2, etc.

    All these values have same probability of exceedence (hence the term uniform hazard) but correspond to different time periods of a response spectrum,.

8. Generate the uniform hazard spectrum by plotting the ordinates (T_1, Sa_1), (T_2, Sa_2), (T_3, Sa_3), (T_4, Sa_4), etc., Figure 2.20.
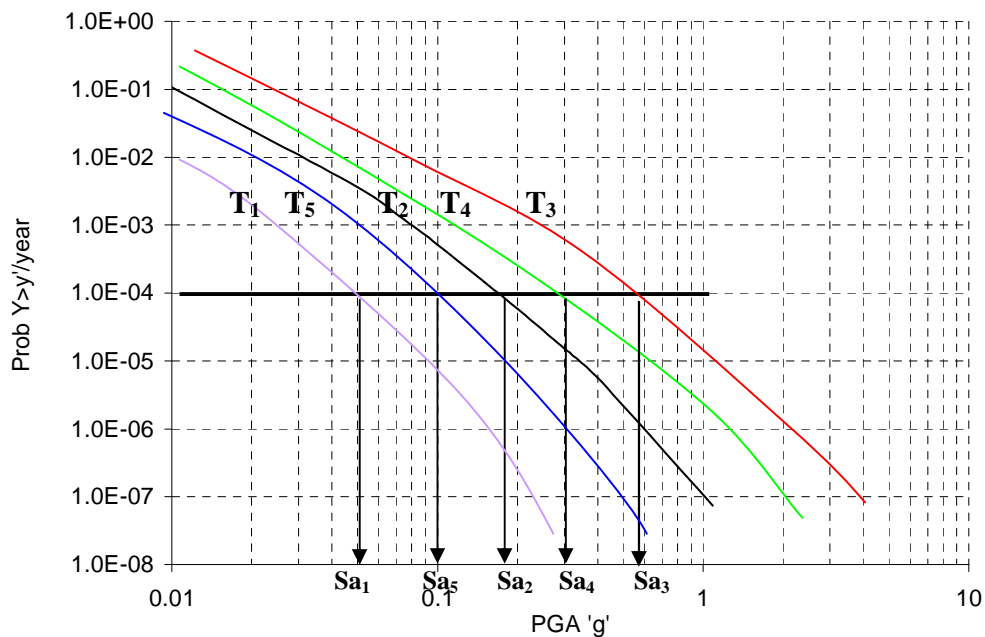

Figure 2.19 Hazard curves corresponding to different spectral periods and extraction of ordinates of a uniform hazard spectrum.
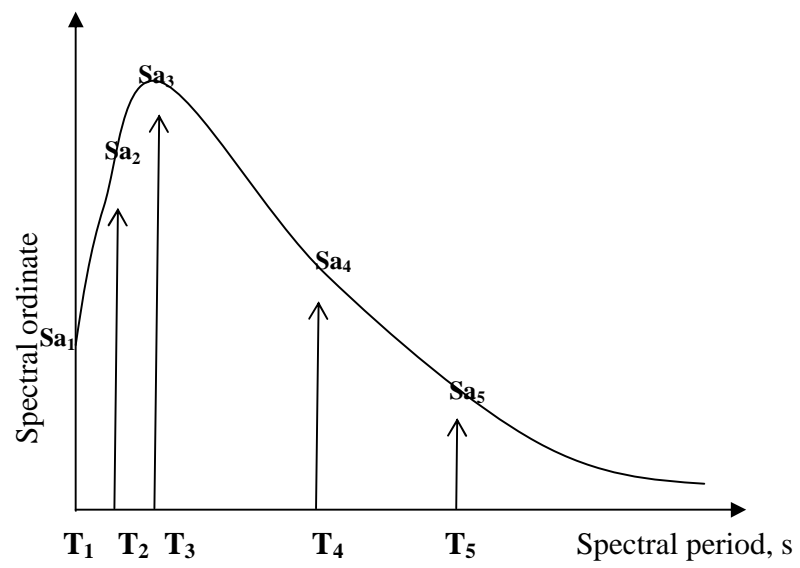
Figure 2.20 A uniform hazard spectrum generated from Figure 2.14.

2.12 Tutorial Problems

1. What is a response spectrum?

2. What is a Fourier spectrum?

3. What is a DVA spectrum?

4. Enumerate the different peak amplitude parameters for a earthquake ground motion.

5. What is an attenuation relationship?

6. What are the parameters that attenuation relations use as input?

7. What is seismic hazard analysis?

8. What is Gutenberg-Richter relationship?

9. Estimate the variation in mean peak ground acceleration with respect to distance for the attenuation relation proposed by Boore (1997) for a magnitude 7 event with reverse type mechanism. Use the values of closest distance to surface projection of rupture as 10km, 30km and 70km. Assume a Vs of 760m/s.

2.13 Answers to Tutorial Problems

1. A plot showing the maximum response induced by ground motion in single degree of freedom oscillators of different fundamental periods having same damping is known as response spectrum. The maximum response could be spectral acceleration, spectral velocity or spectral displacement.

2. The plot of Fourier amplitude of input time history vs time period or frequency is known as Fourier spectrum. The Fourier amplitude spectrum provides inputs on the frequency content of the motion and helps to identify the predominant frequency of motion.

3. The response spectra can be plotted with any of the three parameters (acceleration, velocity and displacement) as mentioned above as ordinate and period/frequency as abscissa. Since these parameters are interconnected, all three parameters can also be represented in a single graph known as tripartite plot or Displacement velocity acceleration (DVA) spectrum.

4. The parameters are
   - Peak ground acceleration
   - Peak velocity
   - Peak displacement

5. The acceleration produced by the earthquake is a function of earthquake magnitude and distance from the source. The attenuation of ground motion is represented by attenuation relationships. Generally, these empirical relationships generated from observed data.

6. The magnitude of the earthquake and distance from source are the main inputs used in attenuation relations. In addition, recent attenuation relationships also include functions to account for non linear dependence of attenuation on distance (usually a log (R) function), site conditions (soft soil, stiff soil, rock, etc), source type and location of measurement (reverse/strike slip/normal, hanging wall side or foot wall side), etc.

7. Seismic hazard analysis is the process by which the site specific design basis ground motion (DBGM) parameters are arrived at. For estimating the DBGM parameters of a site, the earthquake sources (e.g. faults) around the site needs to be identified and maximum potential earthquake of each source need to be

estimated. This is achieved by conducting a detailed investigation of geological and seismological environment of the site.

The Gutenberg-Richter relationship expresses the relation between the number of earthquakes occurring at any particular region and the magnitude of earthquake, for a given time period. This is of the form

$$\log_{10} n(m) = a - bm$$

Where *n(m)* is the number of earthquakes with magnitude *m* or greater per unit time, and *'a'* and *'b'* are constants representing the seismic activity of the region/source/fault.

8.

The relationship was first proposed by Charles Francis Richter and Beno Gutenberg. The variation in b-values range from 0.5 to 1.5 depending on the tectonic environment of the region. The constant b is typically equal to 1.0 in seismically active regions. In this case, for every magnitude 5.0 event there will be 10 magnitude 4.0 events and 100 magnitude 3.0 events.

9.

Attenuation relation by by Boore.et.al(1997), is given by

$$\ln Y = b_1 + 0.527(M - 6) - 0.778 \ln r - 0.371 \ln \frac{V_S}{1396}$$

Where

$$b_1 = \begin{cases} -0.313 \text{ for strike} - \text{slip faults} \\ -0.117 \text{ for reverse} - \text{slip faults} \\ -0.242 \text{ if mechanism is not specified} \end{cases}$$

r is the closest distance to surface projection of rupture
and V_S is the average shear wave velocity which depends on the site class.
The standard deviation of the predicted acceleration is given as $\sigma_{\ln Y} = 0.520$.

b_1 for reverse fault = -0.117

For 10 km distance, ln Y = -0.117 +0.527(6.5-6)-0.778 ln(10) -0.371 ln(760/1396)

i.e., **Y = 0.241 g**

For 30 km distance, ln Y = -0.117 +0.527(6.5-6)-0.778 ln(30) -0.371 ln(760/1396)

i.e., **Y = 0.103 g**

For 70 km distance, ln Y = -0.117 +0.527(6.5-6)-0.778 ln(70) -0.371 ln(760/1396)

i.e., **Y = 0.053 g**