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Probabilistic Seismic Hazard Analysis for Low Seismicity Region

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Introduction

Critical facilities and structures such as nuclear and thermal power plants and dams, as well as the siting of new industry, require design ground motion data which are as accurate, homogeneous and complete as possible, so that hidden tectonic features may be revealed and seismic hazard assessed. Seismic hazard analysis is usually performed to obtain a characterization of the earthquake ground motion and liquefaction at a particular site. However, main interest is in the estimation of ground motion hazard, since it causes the largest economic loss in most earthquakes. Thus, the seismic hazard studies are carried out for estimating ground motion parameters expected to occur at bedrock levels at a particular site during strong earthquakes. Design earthquake selection process involves consideration of the seismic hazard at the site and the general response characteristics of the structure being analyzed considering the local site effects. Seismic hazard is commonly used to describe the severity of ground motion at a particular site without consideration of the consequences. In most situations the seismic hazard is uncertain, and is posed by the possible occurrence of earthquakes at more than one location; likewise, the sizes, or magnitudes of potentially damaging earthquakes. It is to be noted that the distance and magnitude of the causative fault have more effect on the nature of strong motion expected at a specific site. The methodologies for earthquake hazard analysis during the last few decades were developed primarily to assess seismic hazards of tectonically active areas (Cornell 1968; Der Kiureghian and Ang 1977; Wesnousky et al. 1984; McGuire 1995; Main 1995; Peter Tsai 2000; Rebez and Slejko 2000).

Stable Continental Regions (SCRs) were generally thought to be free from the potential earthquake hazard, except for a few anomalous source regions. This was true prior to last few decades but recent damaging earthquakes (Killari 1993; Jabalpur 1997) in these areas of Indian continent have changed this concept and scientific community has started investigating seismic characteristics of these regions. Due to complex structures, associated numerous faults and fractures, the

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Peninsular India has been one of the most interesting regions to study for earthquake phenomena associated with the intraplate activities (Rao and Murthy 1970; Chandra 1977; Khattri 1992; Sreedhar 2007; Ornthammarath et al. 2008; Anbazhagan and Sitharam 2008). A slow and steady accumulation of strain energy in prominent tectonic pockets of the Peninsula has resulted in earthquakes of low to moderate magnitudes in the past. These pockets are basically part of intraplate, crossed by faults of various sizes where the elastic stresses build up and drop periodically. However, occurrence of earthquakes at locations which have been known to be seismically quiet during their recent geological history has not been fully addressed. In order to develop sensible earthquake mitigation strategies, it is essential that the earthquake hazard of a region be realistically estimated. In this paper, an effort has been made to evaluate seismic hazard for Chennai city using probabilistic seismic hazard assessment procedure. The Chennai city falls in the Stable Continental Region (SCR) of the Peninsular India. The Chennai city (11°45′ to 14°15′ N; 80°15′ to 78° 30′ E) is one of the oldest and seismically most stable landmasses of the Indian plate. Recent seismic history, however, shows that more than five damaging earthquakes with magnitudes greater than 5.0 (moment magnitude, M_w) have occurred in this region, highlighting the importance of seismic hazard assessment for the region.

The available regional geological and seismological information is utilized in the evaluation of seismic hazard for the Chennai city. Non-instrumental and instrumental seismicity data for the present study have been retrieved from the published catalogues compiled by National Earthquake Information Center (NEIC), International Seismological Society (ISC), Gauribidanur Seismic Array (GBA), India Meteorological Department (IMD), Rao and Rao (1984), Iyengar (1999), Jaiswal and Sinha (2007) and Sreedhar (2007). The earthquake catalogue completeness intervals have been evaluated using the Visual Cumulative method (Mulargia and Tinti 1985) and Stepp’s method (Stepp 1972). The seismicity parameters for hazard assessment have been estimated incorporating completeness criteria for various spans of the catalogue data. For probabilistic seismic hazard analysis (PSHA), zoneless approach incorporating the observed seismic activity and known geological characteristics of the region is used. The large-scale geological features are used for assigning the maximum possible earthquake potential. Due to the poorly known attenuation characteristics of the study region, four attenuation relationships have been used for the estimation of ground motion parameters. For the assessment of seismic hazard for Chennai city, the Gutenberg-Richter recurrence law has been used to characterize the seismicity of the region. All the probability calculations needed for the hazard evaluation of the study area are carried out using Cornell-McGuire approach. Uncertainties in the PSHA have been handled using attenuation relationships and upper bound maximum magnitude as the controlling parameters. Horizontal uniform response spectra have been computed for reference return periods of 72, 224, 475 and 975 years (i.e. 50%, 20%, 10% and 5% probability of exceedance in 50 years respectively). Hazard maps for the Chennai city have been developed using a convolution scheme based on weighting and incorporating uncertainties.

Low Seismicity Area - Chennai Region

An understanding of the regional tectonics, local geological history and seismicity of the area leads to identification of possible seismic sources of the region. Given the geological and seismological records of fast earthquake activity it is possible to assess the probability of occurrence of earthquakes for the tectonically active areas (Bolt 1999). The ground motion hazard is characterized by the probability of exceeding a given level of a ground motion parameter (e.g. peak ground acceleration, PGA) at least once in a number of years corresponding to the life time of a structure. In a specific sense, seismic hazard is the probability of experiencing a specified intensity at a particular site in some time period.

Preliminary analysis of the available data of past earthquakes and knowledge of the various tectonic features in the study region indicates that seismicity is low to medium for the Chennai region. Earthquake records of last few hundred years also suggest that seismic activity has been more localized in nature. It was mainly associated with marginal areas of the Peninsula like several other shields of the world. Central continental land mass was generally aseismic with a few prominent exceptions of intraplate earthquakes in the last decade.

Tectonic Elements of Coastal Belt

The close relationship of tectonic elements with earthquakes and seismicity in general has already been established (Gutenberg and Richter 1954; Bolt 1999). The distribution and frequency of earthquakes are controlled by active tectonic elements. Similar observations have also been made for the Indian subcontinent. Physiographic analysis divides the Indian subcontinent into three major units - the Peninsula, the Extra-Peninsula and the Indo-Gangetic Plain. The peninsular unit is triangular and lies to the south and is bounded on all three sides by geofractures (along the eastern and western coasts of India and the Narmada-Son lineament). Based on the tectonic features and the observed seismic activity in the peninsular shield of India, tentatively, the seven broad seismic zones can be identified: (i) Cambay graben (ii) Rann of Kutch (iii) Narmada-Son graben (iv) Panvel and Koyna (v) Kerala-Tamilnadu (vi) East coast, and (vii) Godavari graben (Figure 1). Thus the peninsular shield of India broadly seems to be active only in its marginal areas like several other shields of the world with a central aseismic continental mass. However, in the coastal Peninsular India, the Narmada-Son geofracture is parallel to the Satpura orogenic trend that runs approximately in the ENE-WSW direction. The development of the major tectonic elements has taken place along the western continental margin of India. Being the trailing margin of the advancing Indian subcontinent, a number of horsts, grabens and faults have developed along this continental margin (Figure 1). Of these different structural elements, the most prominent are the West Coast Fault and the Panvel flexure which is almost parallel to the coast. Both these tectonic elements trend nearly in a NNW-SSE direction, which is a typical Precambrian trend in Peninsular India. The break-up of the Indian subcontinent from Gondwanaland is regarded as also having developed along this Precambrian trend (Biswas 1982).

In contrast, the eastern part of the subcontinent, more so the eastern coast of India is less marked by any lineament or fault of tectonic significance. The development of deltas along the eastern coast of India and the associated coastal geomorphic features suggest the steady evolution of the coastal areas over a longer geologic time. The eastern margin of the subcontinent is marked by the Java-Sumatra trench of the subduction zone that trends approximately in a NS direction. The Andaman-Nicobar island complex constitutes a part of this trench. The northern extension of the Java-Sumatra trench merges through Burma into the Himalayan mountain belt. To the west of the Java trench, a nascent linear tectonic expression - the Ninety-East Ridge marks the floor of the Bay of Bengal. The coastal zone along the east coast of India is marked by a major lineament that trends approximately in NE-SW direction, encompassing the major trend of the Cuddapah orogeny of the Precambrian period. This lineament is either intersected or offset by rifts or grabens. The continental shelf of the east coast of India is quite broad, compared to that of the western coast. It is about 25 km wide and lying east of Chennai and progressively widens to about 200 km at the mouth of the Ganga river. This continental shelf appears to have been subjected to neotectonic activity that is responsible for generating faults mainly along the mouths of major rivers. Such major rivers as the Godavari, Krishna, Cauvery, etc. have given rise to submarine canyons on the continental shelf in front of their mouths. Offshore investigations have indicated the development of sedimentation faults, resulting into horsts and grabens. These structural elements, however, have limited extent in the context of the plate configuration and, therefore, are of less tectonic significance (Sukhtankar et al. 1993). Sukhtankar et al. (1993) concluded that the seismicity of the coastal areas of Peninsular India is moderately seismic to very low. However, the active Godavari graben and the eastern part of coastal Bangladesh are frequently experienced by low to moderate magnitude earthquakes. The major part of the coastal Bay of Bengal in India is characterised by low seismic intensity.

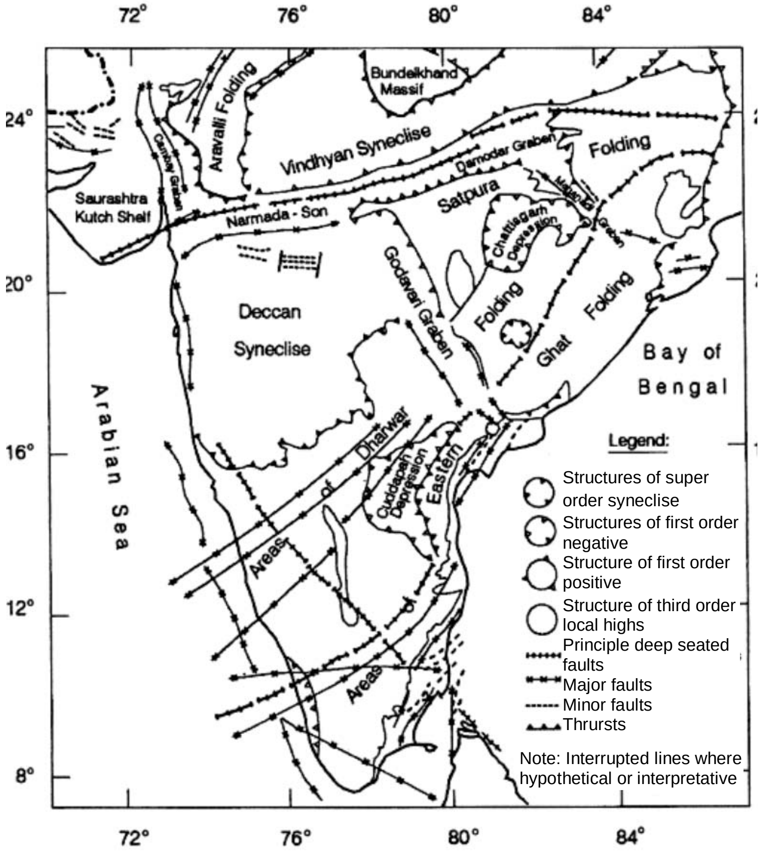

Fig. 1 Major Tectonic Features in the Peninsular India (Sukhtankar et al. 1993)

Seismic History of the Study Area

Discussion on causes of earthquakes had been a perennial topic in ancient Indian literature. All the current scientific approaches the world over depend on historical records for estimating the seismic hazard in a given region. Chennai and its adjoining regions have suffered earthquakes since ancient times. This has been highlighted in a series of papers by Iyengar (1999) and Iyengar et al. (1999). However, records of historical earthquakes start from 1720 A. D. only in the study area.

In seismic hazard assessment it is important to be able to obtain good estimates with quantified uncertainties of the magnitudes of earthquakes that are likely to be generated on known faults (Bolt 1999). Models for doing this have been developed where magnitude is estimated from the fault rupture parameters of length, width, displacement and area. Traditionally, empirical models have been based on measurements of lengths and displacements made by geologists on the observed surface traces of the ruptures. The magnitudes of the events associated with the rupture data are obtained either from instrumental data or from estimates of seismic moment. It is found that the relationships between magnitude and fault rupture parameters vary with the stress-state of the fault, such that different expressions are found for different fault mechanisms and for interplate and intraplate events. This information is used in demarcating the zones for evaluating seismicity parameters for the Chennai region in the study.

Earthquake Database

In order to understand the seismic characteristics of the study area, earthquake catalogues compiled by Rao and Rao (1984), Jaiswal and Sinha (2007), Sreedhar (2007) and Ornthammarath et al. (2008) for the Peninsular India were used. In all, a total of 623 earthquake data from the Gouribidanur Array (GBA) (Figure 2) and global sources from the year 1968 to 1991 have also been compiled. Although catalogues are available, they cover different time periods, incomplete at a given region, and are grossly deficient in several respects, particularly in magnitude, depth and location. For some events, especially those prior to 1960, epicentral locations, magnitudes and other pertinent earthquake characteristics are inaccurate or simply not available (Sreedhar 2007). The composite catalogue of the study area spanning from 1798 to 2008 A. D. with a total of 229 earthquake events is prepared. Seismic events with magnitude greater than 3.0 are only considered in the preparation of earthquake catalogue. A few historical earthquake data prior to 1968 and the recent seismicity of the region after the year 1991 have also been obtained from the NEIC. The foreshocks and aftershocks of the main events were removed by using dynamic windowing method suggested by Gardner and Knopoff (1974) and finally a new catalogue of 216 earthquake events was prepared (Sreedhar 2007). The catalogue data spanning over a period of 210 years (1798 – 2008 A. D.) was used for evaluating the seismicity of the Chennai region between 10°00′ to 16°00′ N and 81°00′ to 77° 00° E (within 300 km radial distance from the Chennai). Figure 3 depicts the distribution of seismic events having moment magnitude greater than 3.5 with rupture distance for the study area. In order to obtain a homogeneous magnitude scale for the whole catalogue, an attempt was made to find and use known relations to transform the different magnitude scales into the moment magnitude scale, M_{w}.

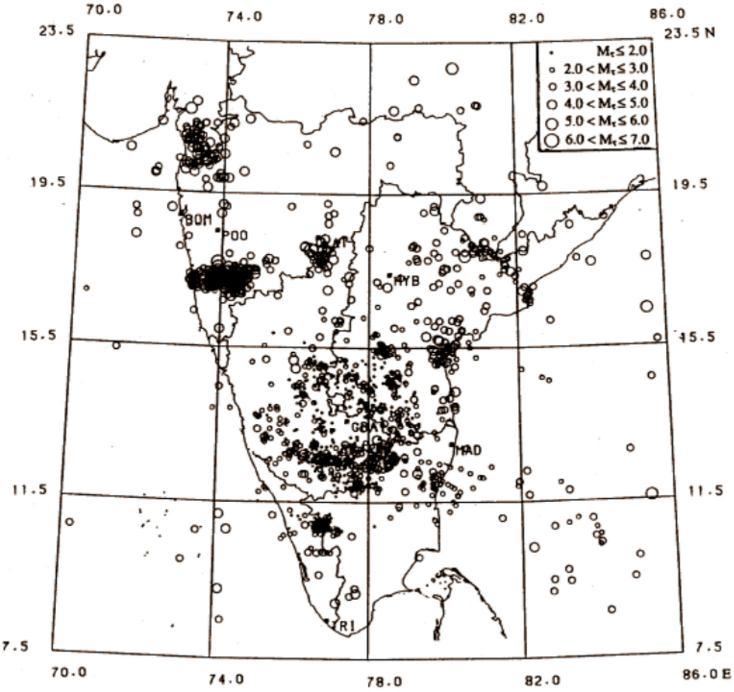

Fig. 2 Typical Seismicity of Peninsular India Based on GBA

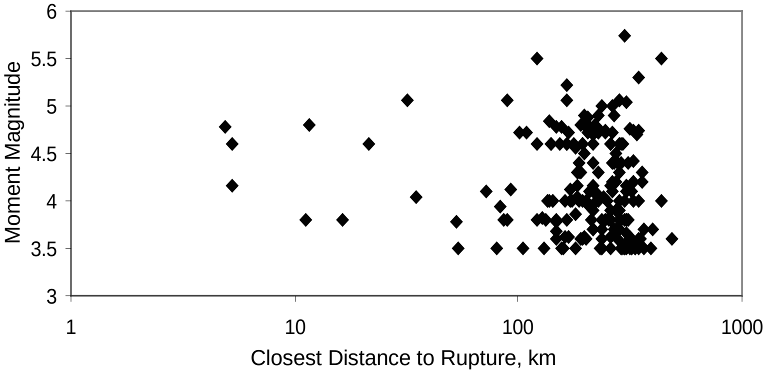

Fig. 3 Distribution of Seismic Events with Rupture Distance

Catalogue Completeness: Visual Cumulative Method

An important step in the processing of an earthquake catalogue is the definition of the time window in which the catalogue is complete. Catalogue incompleteness exists because, for historical earthquakes the recorded seismicity differs from the “true” seismicity. In early instrumental catalogues, incompleteness is seen across different ranges of magnitude. Completeness of the data base is a statistical property. For the recurrence relation to be meaningful, a sufficient number of samples should be available at all possible magnitude values. Since the number of samples in a catalogue refers to the number earthquakes in a given period of time T, completeness can be characterized in terms of a magnitude range and observation interval. No catalogue can be strictly considered complete for all magnitudes and time period. An analytical method for finding regional recurrence based on incomplete catalogue has been developed notably by Stepp in 1972 (Shankar and Sharma 1997; Menon et al. 2004; Kijko and Sellevoll 1989; 1992). Since the availability of data in the Chennai region is very less (after removing the foreshocks and aftershocks only 216 records for 210 years of magnitude $\geq$ 3 observed), an alternate method called Visual Cumulative method (CUVI) formulated by Mulargia and Tinti (1985) is adopted in the study to estimate the period of completeness of the catalogue. However, the catalogue completeness procedure of the Stepp's method is also explained briefly. The procedure to assess the completeness is given below (Mulargia and Tinti (1985):

Events are divided into magnitude classes, as incompleteness is known to be a function of magnitude. Either the subdivisions could be intervals (for instance ΔM_c = 0.5) or cumulative, containing all the events of magnitude exceeding the lower bound of chosen interval. An appropriate time interval depending on the coverage of the catalogue is adopted and for every magnitude class, a chart is constructed with time in years from the beginning of the catalogue as the abscissa and the cumulative number of events as the ordinate. The cumulative number of events in each magnitude class is computed by summing the number of events in a given interval with the number of events in the previous interval. The catalogue is considered to be complete from the time when the trend of the data stabilizes to approximate a straight line. The approach is based on the fact that the slope coincides with the seismicity and a straight line or a 'constant average slope' indicates a constant average rate of occurrence. It implies that from the identified period the data available in the catalogue are substantially complete. The completeness interval is the number of years from the beginning of the period to the last year of occurrence in the catalogue.

Some important aspects of the problem at hand emerge when the procedure is applied:

> An abrupt change of slope is noticed from the point the catalogue is considered to be complete. If the catalogue had been considered to be complete from a period before this point, then it would result in grossly underestimating the occurrence rate of events in the corresponding magnitude class.

> The completeness interval for the higher magnitude classes would be relatively difficult to determine. The graph would exhibit a stepped behaviour due to the fact that stronger events tend to be separated by relatively long time intervals and sometimes occur within a short period, both owing to the physical nature of earthquakes in a siesmogenic zone.

> For the highest class of magnitudes a certain degree of arbitrariness would be present in determining the period of completeness. Generally, the entire length of the catalogued years is considered with a degree of conservativeness, in order that large earthquakes in the early period of the catalogue are not ignored.

Figure 4 illustrates the results of the completeness analysis performed in this study for the entire earthquake catalogue.

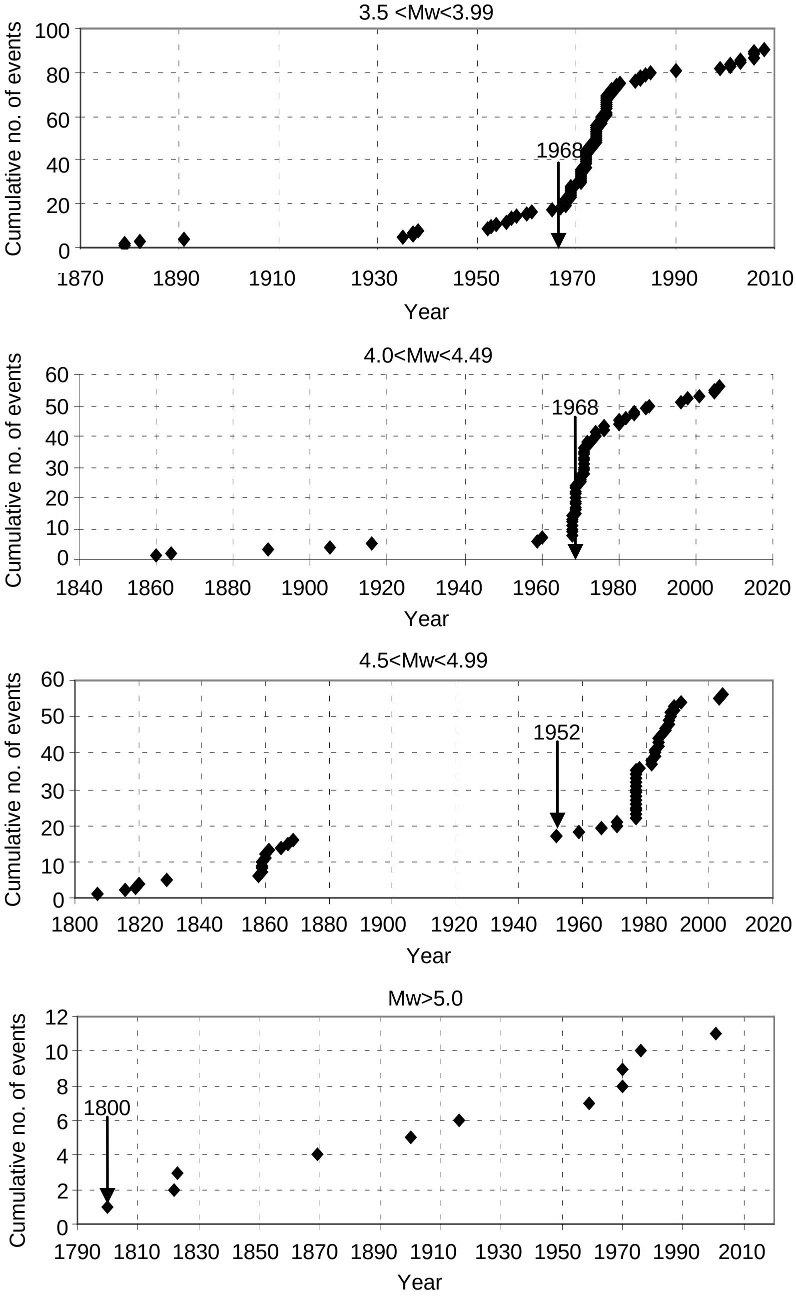

Fig. 4 CUVI Method for Determining Catalogue Completeness

Plots of the cumulative number of events versus the time from the beginning of the catalogue for four different classes of magnitudes are shown. For a given magnitudes class, the period of completeness is considered to begin at the earliest time when the slope of the fitting curve can be well approximated by a straight line. The whole catalogue can be considered complete over the entire period 1798 – 2008 A. D. for magnitudes exceeding 5.0. Table 1 shows the completeness intervals that have been computed for the seismic zone of the study area.

Table1 Completeness Interval for the Chennai Region

Magnitude interval (M_w)	Completeness interval	Years
3.5 – 3.99	1968 – 2008	40
4.0 – 4.49	1968 – 2008	40
4.5 – 4.99	1952 – 2008	56
$M_w \geq 5.0$	1800 – 2008	208

Seismic Source Zoning

The procedure for estimation of seismic potential using probabilistic seismic hazard assessment requires the determination of seismic source zones, and knowledge of their hazard parameters such as activity rate and Guttenberg-Richter parameter *b*. Such information is not readily available for large part of the Indian subcontinent and most Indian seismic catalogues are highly uncertain and incomplete. Most of the available earthquake catalogues usually contain two types of information: macroseismic observations of major seismic events that occurred over a period of few hundred years, and complete instrumental data for relatively short periods of time, say the last fifty years at the most. In the present study, use of complete part of the catalogue as well as extreme part of the data is used for estimation of the seismic hazard. A region of 300 km radius with its centre at IIT Madras, Chennai is selected as the seismogenic province, for establishing the level of ground shaking in the form of peak ground acceleration. Since Chennai is on the coastal belt, the semicircular part of the 300 km radius zone lies in the Bay of Bengal and is not included in the present study. Hence, for the seismic hazard assessment, only a half of the circle which falls in the western part (the continental part) of the Chennai is considered along with the faults as demarcated in Figure 5. Table 2 presents the details of the faults.

Table 2 Faults around 300 km Distance: Chennai

No.	Fault Name	No.	Fault Name
1	Palar River Fault	7	Swarnamukhi Fault
2	Neotectonic Fault	8	Fault Involving Basement
3	Tirukkavilur Pondicherry Fault	9	Tirumala Fault
4	Pamber River Fault	10	Papaghani Fault
5	Javadi Hills Fault	11	Fault Involving Cover
6	Amirdi Fault		

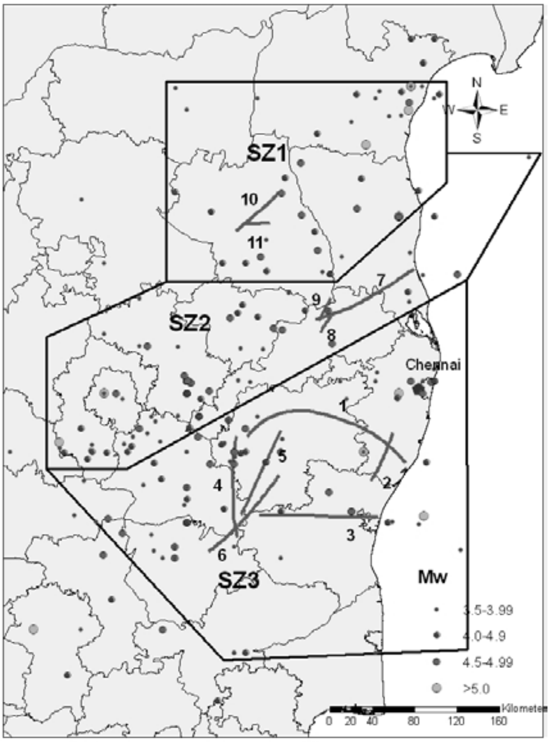

Fig. 5 Fault Locations around Chennai Region, 300 km Radial Distance

Maximum Earthquake Potential of the Fault

Since the size of fault is finite, the maximum possible magnitude (M_{max}) on it must be limited to a reasonable value. Generally M_{max} is found either based on geological characteristics like fault rupture length, fault rupture area and fault slip rate or based on the historical seismicity (Wells and Coppersmith 1994) of the area under study. In the absence of reliable data of the first kind, the historical data has been used to evaluate M_{max}. Gupta (2006) has provided the epicentral plot for the Peninsular India and the same is used in the identification of possible seismic sources in the study area. From the plot, M_{max} value of 6 is noted in the Chennai region. From the historical data also, the maximum observed magnitude is 6. Hence for the present study, M_{max} value of 6 is taken and accordingly the seismic hazard in the form of peak ground acceleration (PGA) is established for the Chennai city.

Regional Recurrence

On any given fault within any given region, earthquakes occur at irregular intervals in time, and one of the basic activities in engineering seismology has long been the search for meaningful patterns in the time sequences of earthquake occurrence (Bolt 1999). The longer the historical record, the better is the overall picture that can be obtained. Thus, it is important to consider the correlation between seismicity and tectonics in the region under consideration while carrying out hazard analysis. The seismic hazard at a particular region is a function of the siesmogenic activity of that region, which in turn has to be directly related to the recurrence (frequency-magnitude) relationship of the listed faults. This argument highlights that if the regional seismicity can be determined, the same can be accounted for in differing proportions by the faults identified in the present study. Thus, characterization and quantification of regional seismicity assumes a central role in site-specific seismic hazard studies. In the present case, this regional seismicity has to be understood for engineering purposes in terms of historical data, in the 300 km region around the Chennai city. As stated earlier, the historical period of 1798 - 2008 A. D. has been considered, during which there were 216 catalogued events of $M_w \geq 3$, in the controlling region.

The seismicity of a siesmogenic zone is quantified by the standard Gutenberg-Richter recurrence relationship which postulates the existence of a potential correlation between the mean annual rate of exceedance of an earthquake of specified magnitude (λ_M) and the magnitude (M) itself. This law of earthquake occurrence states that larger events are less frequent than that of smaller events and the difference in relative terms follows an exponential law. Regional seismicity of a siesmogenic zone is described by the parameters '*a'* and '*b'* of the Guttenberg-Richter relationship.

Frequency-Magnitude Recurrence Relationship

According to Gutenberg-Richter recurrence relationship, the yearly occurrence rate of earthquakes with magnitude greater than or equal to M in a particular source zone can be described by

$$\log_{10}(\lambda_M) = a - bM \tag{1}$$

Where λ_M is the mean annual rate of exceedance of magnitude M, a and b are the constants specific to the source zone, and these can be estimated by a least square regression analysis of the past seismicity data. The 10^a is mean yearly number of earthquakes of magnitude greater than or equal to zero and b describes the relative likelihood of large and small earthquakes. The source regions may be described as areas of distributed seismicity, so that λ_M relates to a unit area, and faults are represented as lines with their own activity rates treated according to what is known of them.

The source specific values of a and b are calculated by the following steps: The catalogue is grouped into magnitude ranges of say $\Delta M = 0.5$, in the time interval of 10 years. Here it is taken as $3.5 \leq M_w \leq 3.99$; $4.0 \leq M_w \leq 4.49$; $4.5 \leq M_w \leq 4.99$; $M_w \geq 5$. The average number of events per year in every magnitude range is determined. This exercise is carried out for all time window lengths. The earthquake distribution data by magnitude and time is given in Table 3. For a particular magnitude range, let $x_1, x_2, x_3, \ldots, x_R$ are the number of events per unit interval, obtained from the catalogue.

Table 3 Earthquake Distribution by Time and Magnitude

Time period	Time interval (Year)	Rate of occurrence of magnitude			
		3.5-3.99	4.0-4.49	4.5-4.99	>5.0
1998-2008	10	0.9000	0.5000	0.2000	0.3000
1988-2008	20	0.5000	0.3500	0.3500	0.1500
1978-2008	30	0.6000	0.4333	0.7000	0.1000
1968-2008	40	1.8000	1.2250	0.9250	0.1500
1958-2008	50	1.5400	1.0200	0.7800	0.1400
1948-2008	60	1.3667	0.8500	0.6667	0.1167
1938-2008	70	1.1857	0.7286	0.5714	0.1000
1928-2008	80	1.0750	0.6375	0.5000	0.0875
1918-2008	90	0.9556	0.5667	0.4444	0.0778
1908-2008	100	0.8600	0.5200	0.4000	0.0800
1898-2008	110	0.7818	0.4818	0.3636	0.0818
1888-2008	120	0.7250	0.4500	0.3333	0.0750
1878-2008	130	0.6923	0.4154	0.3077	0.0692
1868-2008	140	0.6429	0.3857	0.2929	0.0714
1858-2008	150	0.6000	0.3733	0.3400	0.0667
1848-2008	160	0.5625	0.3500	0.3188	0.0625
1838-2008	170	0.5294	0.3294	0.3000	0.0588
1828-2008	180	0.5000	0.3111	0.2889	0.0556
1818-2008	190	0.4737	0.2947	0.2842	0.0632
1808-2008	200	0.4500	0.2800	0.2750	0.0600
1798-2008	210	0.4286	0.2667	0.2667	0.0619

The unbiased estimate of the mean rate per unit time interval of this sample is

$$\chi = \frac{1}{R'}\sum_{i=1}^{R'} x_i \tag{2}$$

and its variance is

$$\sigma_{\chi}^{2} = \frac{\chi}{T} \tag{3}$$

where R′ is the number of intervals. Here the occurrence of earthquake is assumed to follow a Poisson distribution (Stepp 1972). The standard deviation values are presented in Table 4 and these values are plotted in log scale (Figure 6). The standard deviation shows stability in shorter time window for the smaller magnitude earthquakes and longer time window for the large magnitude earthquakes.

Table 4 Standard Deviation of Magnitude with Time Interval

Time interval	Standard deviation (σ_x) of M_w			
	3.5 – 3.99	4.0 – 4.49	4.5 – 4.99	≥ 5.0
10	0.3000	0.2236	0.1414	0.1732
20	0.1581	0.1323	0.1323	0.0866
30	0.1414	0.1202	0.1528	0.0577
40	0.2121	0.1750	0.1521	0.0612
50	0.1755	0.1428	0.1249	0.0529
60	0.1509	0.1190	0.1054	0.0441
70	0.1301	0.1020	0.0904	0.0378
80	0.1159	0.0893	0.0791	0.0331
90	0.1030	0.0793	0.0703	0.0294
100	0.0927	0.0721	0.0632	0.0283
110	0.0843	0.0662	0.0575	0.0273
120	0.0777	0.0612	0.0527	0.0250
130	0.0730	0.0565	0.0487	0.0231
140	0.0678	0.0525	0.0457	0.0226
150	0.0632	0.0499	0.0476	0.0211
160	0.0593	0.0468	0.0446	0.0198
170	0.0558	0.0440	0.0420	0.0186
180	0.0527	0.0416	0.0401	0.0176
190	0.0499	0.0394	0.0387	0.0182
200	0.0474	0.0374	0.0371	0.0173
210	0.0452	0.0356	0.0356	0.0172

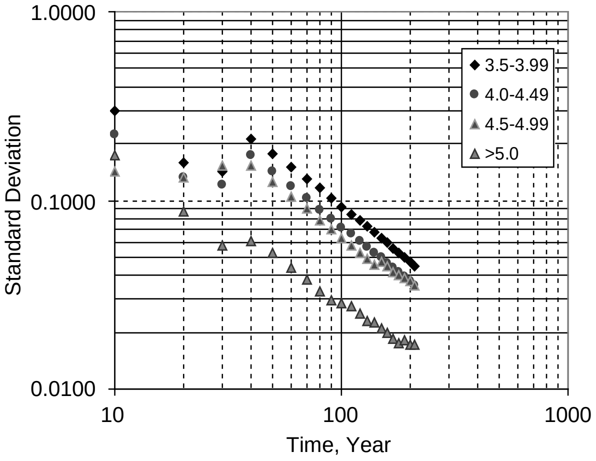

Fig. 6 Variation of Standard Deviation vs. Time Interval and Magnitude

Regression analysis has been carried out to obtain *a* and *b* values using SPSS software. The cumulative number of events are taken for computation of *a* and *b* values of the frequency-magnitude relationship (Figure 7). Finally these values are compared with the previous values given by the earlier investigators for the Peninsular India. Table 5 presents a comparison between the values obtained in this study with those of the earlier studies.

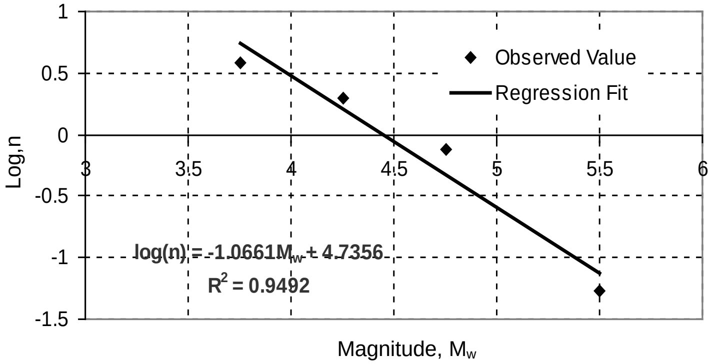

Fig. 7 Frequency-Magnitude Relationship for Earthquake Occurrence

Table 5 Comparison of *a* and *b* Values

Sl. No.	Author(s)	Value of a	Value of b	a/b	Data for a period
1	Avadh Ram and Rathor (1970)	5.30	0.81	6.54	70
2	Kaila et al. (1972)	3.25	0.70	4.64	14
3	Rao and Rao (1984)	4.40	0.85	5.17	170
4	Anbazhagan et al. (2009)	3.52	0.86	4.09	200
5	Present study	4.74	1.07	4.43	210

For the Chennai region, the magnitude-frequency relationship is given by the following expression:

$$\log_{10}(\lambda_M) = 4.74 - 1.07M_w \quad (4)$$

The Gutenberg–Richter parameters obtained are: *a* = 4.74 and *b* = 1.07. From Equation (4), the recurrence of earthquakes for Chennai city can be established. The cumulative distribution function (CDF) and probability density function (PDF) of magnitude for the Gutenberg–Richter law with upper and lower bounds can be expressed as

$$F_M(m) = P[M < m | m_0 \le m \le m_{\max}] = \frac{1 - \exp[-\beta(m - m_0)]}{1 - \exp[-\beta(m_{\max} - m_0)]} \quad (5)$$

$$f_M(m) = \frac{-\beta \exp\left[-\beta\left(m - m_0\right)\right]}{1 - \exp\left[-\beta\left(m_{\max} - m_0\right)\right]} \tag{6}$$

where m_0 and $m_{\max}$ are the lower and upper threshold magnitudes. For Chennai city, $m_{max} = 6.0$, $m_0 = 3.75$ and $\beta = 2.303\,b$. The CDF and PDF are plotted in Figures 8 and 9, respectively.

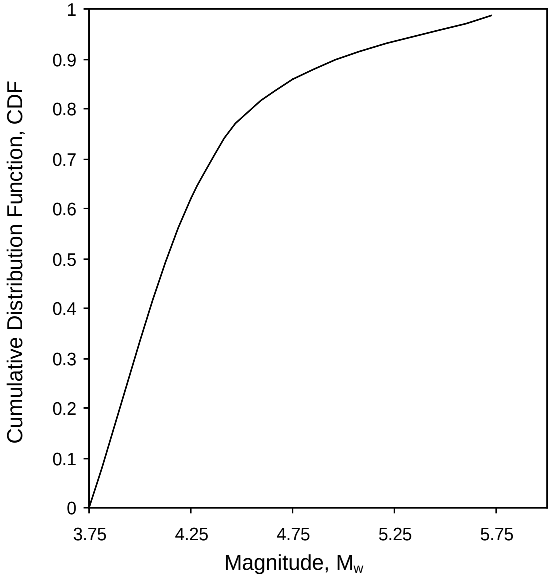

Fig. 8 CDF of Magnitude for the Gutenberg–Richter Law

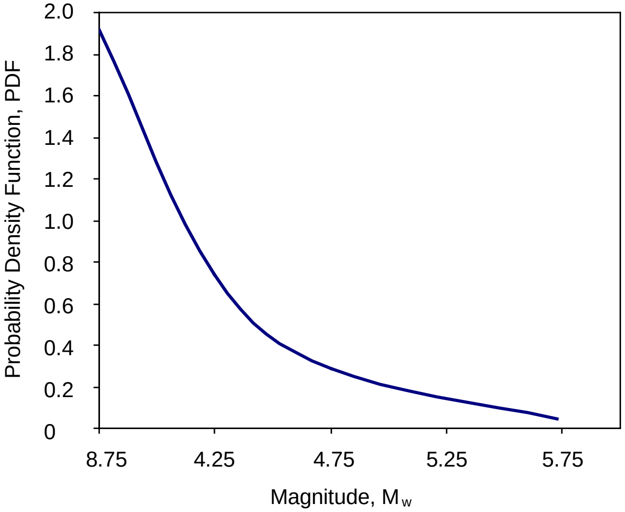

Fig. 9 PDF of Magnitude for the Gutenberg–Richter Law

PGA Attenuation Relationship for Peninsular India

It is required to know the attenuation characteristics of the various strong motion parameters with distance, earthquake magnitude and the geologic conditions. Specifically, the attenuation of strong ground motion with distance from the causative fault is a function of source characteristics, transmission path, geometrical spreading, absorption coefficient and local site conditions. In practice, however, the estimation of the ground motion parameter is almost always based on attenuation equations derived from regressions of observed motions against earthquake magnitude and distance from source to site. Because of their importance, these equations have received much attention and are updated when new data become available. Boore and Joyner (1982) reviewed the techniques used in establishing attenuation relationships for estimating ground motion parameters. The widely used seismic hazard models assume a general set of functions (Abrahamson and Silva 1997; Faccioli 2003). A general representation of attenuation relations, elaborating the independent physical parameters that influence ground motion estimation, has the following structure:

$$\log(y) = f_1(M, r, SD) + f_2(FT) + f_3(S) + \varepsilon \tag{7}$$

where y = Ground motion parameter, M = Magnitude, r = Source to site distance, SD = Source directivity factor, FT = Fault type factor, S = Site conditions factor, and ε = Random variable, introduced to account for the uncertainty of the prediction, usually assumed to have a normal distribution, with zero mean and standard deviation $\sigma_{\log y}$.

The term $f_1(M, r, SD)$ in Equation (7) is the basic form describing the dependence of the ground motion descriptor on magnitude, source-to-site distance and on the source rupture directivity (*SD*). The functional form of the predictive relationship is usually selected to reflect the mechanics of the ground motion process as closely as possible. Due to unavailability of well-established attenuation relation for the region, four models have been used in the present study and their appropriateness is evaluated. The schemes of expected ground motion parameters for the Chennai city were compiled and compared with the corresponding peak PGA values (Figure 10). Four attenuation relationships proposed for India and United States of America have been used to check the attenuation of PGA value at Chennai region with respect to distance. Figure 10 shows the comparison of estimated PGA for each of the attenuation relationships adopted with uniform focal depth of 17 km and M_w = 5. The focal depth of 10 km is also used by Bhatia et al. (2007) for computing seismic hazard for India and adjoining regions. Table 6 gives the corresponding peak values of PGA noted from Figure 10.

In order to study the variation of magnitude of PGA with distance, Boore et al. (1993) attenuation relationship has been used (Figure 11) and the PGA values are presented in Table 7. The maximum value of PGA of 0.12g is obtained for a moment magnitude of 6.

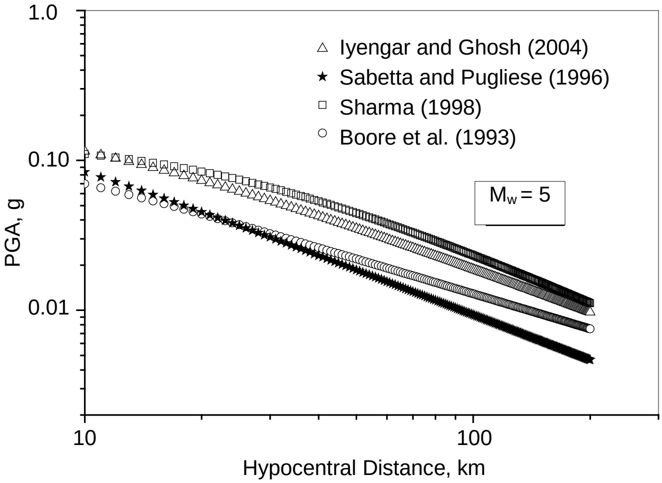

Fig. 10 Comparative Estimate of PGA for Different Attenuation Relationships

Table 6 Comparative Estimates of Maximum PGA

Sl. No.	Author(s)	Max. PGA (g)
1	Iyengar and Ghosh (2004)	0.115
2	Sabetta and Pugliese (1996)	0.11
3	Sharma (1998)	0.07
4	Boore et al. (1993)	0.083

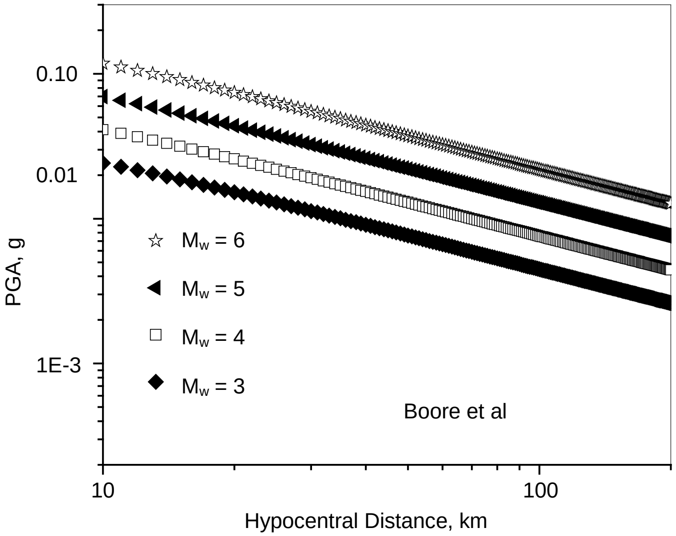

Fig. 11 Attenuation of PGA with Distance (Boore et al. 1993)

Table 7 Maximum PGA from Boore et al. (1993)- Attenuation Relationship

Boore et al. (1993)				
M_w	3	4	5	6
Max. PGA (g)	0.024	0.041	0.07	0.12

Probabilistic Seismic Hazard Analysis for Chennai City

The probabilistic seismic hazard analysis (PSHA) has been developed in the literature as an improvement over the deterministic procedures and is well established (Cornell 1968; Atkinson and Charlwood 1983; Bender 1984; Wesnousky et al. 1984; Youngs and Coppersmith 1985, Reiter 1990; McGuire and Arabasz 1990; McGuire 2001; Cramer 2003; Lapajne et al. 2003; Convertito et al. 2006). The technique of PSHA was developed originally by Cornell (1968) and coded into a FORTRAN program by McGuire (1976). The Cornell-McGuire approach incorporates the influence of all potential sources of earthquakes and their corresponding activity rates. In this methodology, the concept of a potential source of earthquakes plays a very important role. In any given study the approach should be chosen according to the nature of the project and also should be tailored to the seismicity of the region, including the quantity and quality of the seismicity data available.

In PSHA all the parameters associated with the seismic phenomena are considered explicitly and their uncertainties quantified. In low seismicity regions like Chennai, it is extremely difficult to introduce long-term behaviour because active faults cannot be identified in most cases; thus the Poisson process is more or less exclusively used. The foundations of PSHA were established by Cornell (1968), who recognized the need for seismic hazard to be based on a method which properly accounted for the essential uncertainties associated with earthquake phenomena. Since then, both the seismological and geological techniques applied to seismic hazard analysis have improved steadily, so that current practice is now able to utilize information from a variety of both the seismological and geological data sources with due considerations for uncertainties.

One of the main steps in PSHA consists of evaluating the effects of an earthquake occurring at a given distance from a site of interest in the form of hazard. The effects of all the earthquakes of different sizes, occurring at different locations in different earthquakes sources with different probability of exceeding are integrated into one curve that shows the probability of exceeding different levels of ground motion at the site during a specified period of time. The average exceedance rate can be expressed as

$$\lambda_{y^*} = \sum_{i=1}^{N} \alpha_i \int_{M_{\min}}^{M_{\max}} \int_{R=0}^{R=\infty} f_i(M) f_i(R) P(Y > y \mid m, r)\, dr\, dm \qquad (8)$$

where λ_{y^*} is the expected number of exceedance of ground motion level y^*, α_i is the mean rate of occurrence of earthquakes in the i^{th} source, $f_i(M)$ is the probability density distribution of magnitude within source *i*, $f_i(R)$ is the probability density distribution of epicentral distance between the various locations within source *i* and the site for which the hazard being estimated and $P(Y > y \mid m, r)$ is the probability that a given earthquake of magnitude *m* and epicentral distance *r* will exceed ground motion level *y*. The Poisson model could be invoked with careful consideration when predicting the ground motion from the seismic sources where seismic gaps prevail and the data on strain release is scarce. This model can be used to make some other useful approximations. As a result of there being no preferred occurrence of earthquake in any particular year, the return period (in years) of an event exceeding a particular ground motion level is the reciprocal of its annual probability of exceedance.

Methodology used for PSHA

CRISIS 2003 Ver. 3.0.1, a computer program for computing seismic hazard, developed by Ordaz et al. (2003) has been used in this study. The program uses two models (Poissonian and Characteristic) to consider the occurrence and distribution of earthquakes and the seismicity of the sources along with attenuation relationships to define the ground motion at the site. The sources can be modelled as point sources, line sources or area sources with the possibility of depth being defined for line and area sources. As many as 200 seismic sources can be defined simultaneously with 40 vertices for each source. Fifteen attenuation models can be defined simultaneously with a maximum of 15 spectral ordinates for each model (Ordaz et al. 2003). Uncertainty in the *'b'* value, maximum magnitude and attenuation relationship can also be accounted.

For an acceleration target *y**, the program calculates the annual rate of occurrence of acceleration higher than *y** (annual rate of going beyond). Equation (8) is numerically integrated to get the λ_{y^*} . The following information is required to run the CRISIS program. Coordinates of the site, the minimal magnitude M_{min} and rate of seismicity associated with each source area *i*: $\alpha_i = \alpha_i\ (M \geq M_{\min})$, the maximum magnitude M_{max}, slopes of the laws of recurrence β_i, polygons which delimit the source areas, the parameters which control the discretizations in magnitude (ΔM) and integration parameters [Minimum distance and triangle ratio (F_{min}), Minimum triangular size (R_{min}), parameter controlling spatial integration process (D_{max})], coefficients of the attenuation relationship, target accelerations and return period. The CRISIS calculates λ_{y^*}:

> by subdividing each source area in subfields in order to obtain the f_{Ri}

> by calculating the f_{Mi} starting from M_{min} and M_{max}.

> by calculating $P\,[Y > Y^* \mid m, r]$ starting from the relation of attenuation for all the combinations (*m, r*) [Equation (8)].

The program makes it possible to introduce uncertainties in the parameters of seismicity and in the maximum magnitude and it will take into account of all these uncertainties in the calculation. The CRISIS determines target accelerations for which the calculation of the annual rate is carried out using three parameters: minimum acceleration (A_{min}), maximum acceleration (A_{max}) and number of targets.

It also evaluates the annual rates of going beyond these targets and interpolates accelerations corresponding to the annual exceedance rates of interest. The targets are distributed in the interval ($A_{min} - A_{max}$) with a step which increases in a logarithmic manner with acceleration. It is important to choose the terminals judiciously, A_{min}, A_{max}, as well as the required number, so that the annual exceedance rates are correctly interpolated. In this study, the annual rates are calculated between 0.01 and 0.2 g. The calculation of the annual exceedance rates on this series of accelerations ensures a very precise interpolation for all the return periods.

Uniform Hazard Spectrum

The seismic hazard at a site is influenced by all the earthquakes with different magnitudes and distances, and PSHA is able to correctly reflect the actual knowledge of seismicity. Along with the bigger events, smaller events are also important in hazard estimation, due to their higher occurrence rates (Wheeler and Mueller 2001). The essence of PSHA lies in the uniform hazard spectrum (UHS), which is a convenient tool to compare the hazard representations of different sites (Trifunac 1990; Todorovska et al. 1995; Peruzza et al. 2000). The PSHA can be carried out in various ways depending on how one defines the model of seismicity. All earthquakes together contribute in the hazard calculations, if representative acclerograms are ultimately required as the output. The resulting UHS will often represent a ground motion that could only be caused by the simultaneous occurrence of two earthquakes (Bommer et al. 2000). By using the PSHA formulation, the spectral amplitudes of acceleration can be evaluated at all the natural periods for a constant probability of exceedance at a site. Such a response spectrum is commonly known as the UHS. For seismic hazard analysis, the entire region of Chennai lying between latitude 11° 45′ to 14° 15′ N and longitude 80° 15′ to 78° 30′ E is considered and the uniform hazard spectra are estimated for all the sites defined by the intersection points of the grid. For this purpose, the seismicity which is a function of (M_j, R_i) for the site is evaluated by fitting the Guttenberg-Richter recurrence relation to the past earthquake data within a 300 km radius zone. The UHS plots for different locations in the Chennai city are shown in Figures 12 and 13. The attenuation relationship proposed by Raghu Kanth and Iyengar (2007) is used in this study. Table 9 presents the peak values of UHS at various locations within the Chennai city. Figure 14 shows the UHS corresponding to 10% probability of exceedance in 50 years (Return period = 475) and also for 975, 224 and 72 years return periods, respectively at IIT Madras (IITM).

TABLE 9 Peak Values of UHS at Various Locations in Chennai City (Return Period = 475 Years)

Location	Period (s)	Peak spectral acceleration (g)
Koyambedu	0.015	0.119
Kathipara	0.015	0.109
Guindy	0.015	0.108
Chennai Central	0.015	0.104
IIT Madras	0.015	0.102

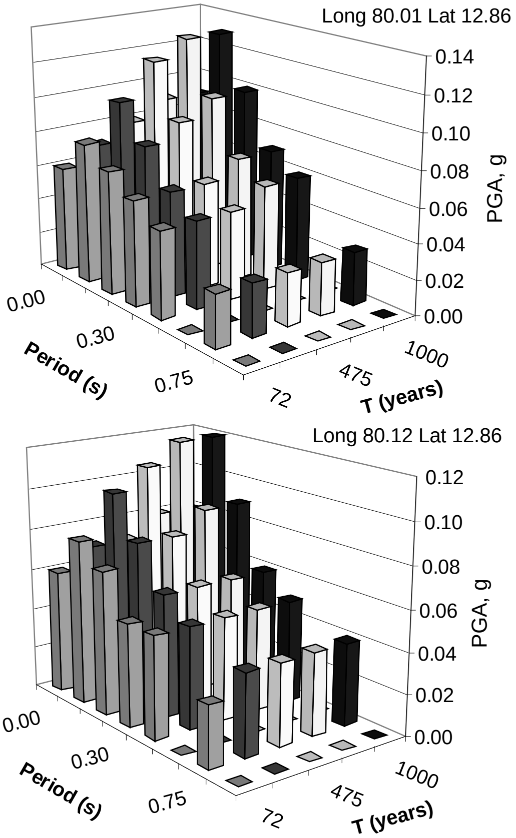

Fig. 12 UHS at Various Locations in Chennai City with Return Periods

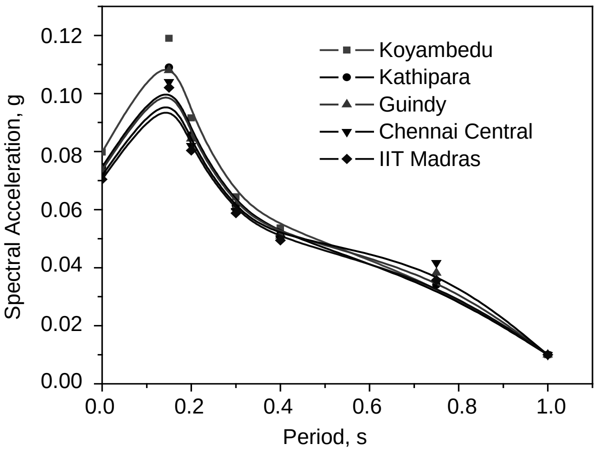

Fig. 13 UHS at Various Locations in Chennai City (Return Period = 475 Years)

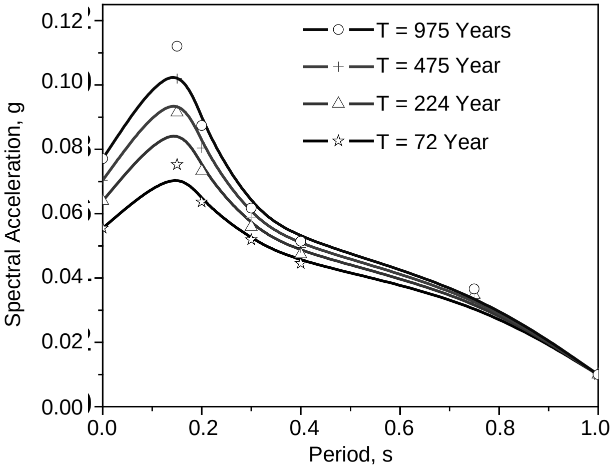

Fig. 14 Uniform Horizontal Hazard Spectra at IITM with Varying Return Periods (Structural Periods – 0 to 1 s)

The UHS plots obtained at IIT Madras using various attenuation relationships for 475 years return period (i.e. 10% probability of exceedance in 50 years) are shown in Figure 15. It can be concluded from the figure that the uniform hazard spectrum obtained from Das et al. (2006) relationship gives upper bound values whereas Raghu Kanth and Iyengar (2007) gives lower bound values.

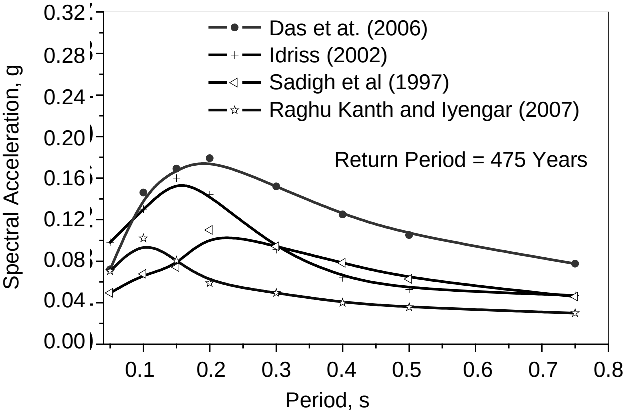

Fig. 15 UHS at IIT Madras with Different Attenuation Relationships

Hazard Maps

The seismic hazard map in the form of seismic hazard curve is developed for the Chennai city using Poisson process model to estimate probabilities of exceedance of a particular value of peak ground acceleration *y**, in a finite time period. For Poisson process, the probability of exceedance of *y*,* in a particular time period *T* years is given by

$$P\left[Y > y^*\right] = 1 - e^{-\lambda_{y^*} T} \tag{9}$$

The mean rate of annual exceedance of *y** can be expressed in terms of the time period and probability of exceeding *y** in that time period as

$$\lambda_y = \frac{\ln\left(1 - P\left[Y > y^*\right]\right)}{T} \tag{10}$$

It should be noted that as the exposure time *T* increases, the probability of exceeding a particular peak ground acceleration value (*y**) increases. Similarly, the value of ground motion parameter with a particular probability of exceedance increases with increasing exposure time. Equation (10) is used for finding λ_y for a particular probability of exceedance in a given period. The corresponding PGA is found from the hazard curve of the site. Figure 16 provides the contour plot of PGA values corresponding to return period of 72 years for the Chennai region.

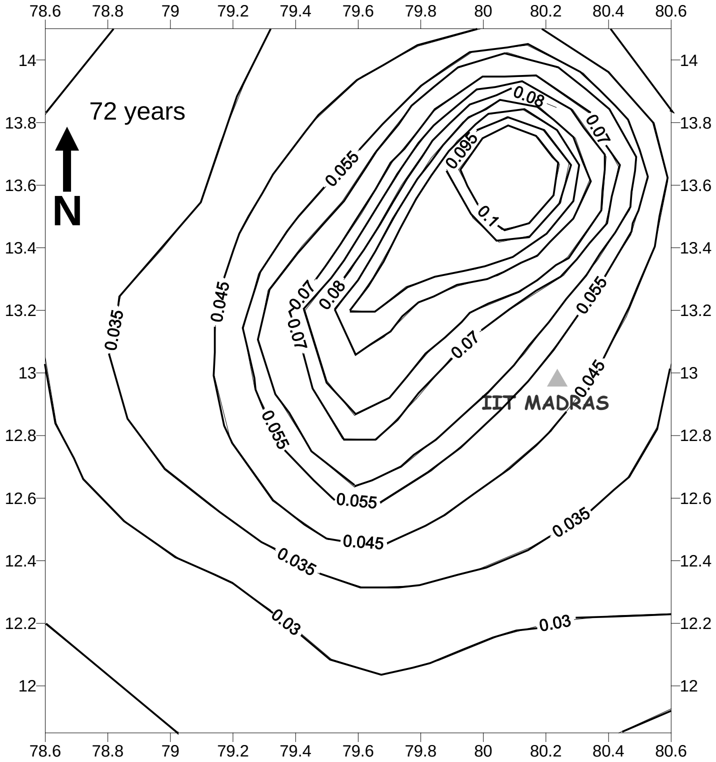

Fig. 16 Contours of Rock Level PGA for Chennai Region (Return Period = 72 Years)

Table 10 gives the horizontal peak ground acceleration values at IITMadras for return periods of 72, 224, 475 and 975 years. It is quite obvious from the table that as the return period increases the hazard level has also increased. For a short return period, i.e. 475 years (10% probability of exceedance in 50 years), short-distance and low to moderate earthquakes dominate the hazard at the IIT Madras.

Table 10: Peak Ground Accelerations and Corresponding Return Periods

Probability of exceedance	Return period (years)	Horizontal peak ground acceleration (g)
50% probability of exceedance in 50 years	72	0.10
20% probability of exceedance in 50 years	224	0.14
10% probability of exceedance in 50 years	475	0.18
5% probability of exceedance in 50 years	975	0.23

Summary and Conclusions

Seismic hazard studies are needed for the preparation of earthquake loading regulations, for determining the earthquake loadings for projects requiring special study, for areas where no codes exist, or for various earthquake risk management purposes. Probabilistic seismic hazard analysis (PSHA) for Chennai city is performed through the Cornell-McGuire approach by using a uniform earthquake distribution and a selected magnitude range. Based on the review of seismotectonic set-up and seismic history around Chennai, a controlling region of 300 km radius around the IIT Madras is considered for the PSHA. In order to check the completeness of the catalogue the occurrence rate for several magnitude thresholds is examined. Great care must be taken in using published earthquake catalogues for low seismicity areas such as Chennai region. Completeness thresholds have been determined by the standard method of visual inspection of time (CUVI method), defining the completeness level for a magnitude threshold since the time when the data begin to follow a linear relationship. Regional recurrence relations are obtained based on nearly 210 years of past data and the same is used in PSHA. The slope b of the magnitude-frequency relationship is a key seismicity parameter. A decrease in b over a period of time indicates an increase in the proportion of large events. This may be caused by a relative increase in the frequency of large events, or by a relative decrease in the frequency of small ones. For the Chennai city, the estimated values of a and b are 4.74 and 1.07, respectively, which are the important input parameters of the Gutenberg-Richter recurrence relationship.

Uncertainties in earthquake location, size and recurrence are quantified in PSHA for the Chennai city using the available information. The product of PSHA is a hazard curve for a particular site representing the values of a selected strong ground motion parameter having a fixed probability of exceedance in a specified period. The bounded Gutenberg-Richter recurrence law is found to give an acceptable ground shaking hazard for the Chennai city. Uniform hazard spectra and seismic hazard maps depicting bed rock level peak ground acceleration (PGA) contours for various return periods and for different locations in the city are provided. The PGA at IIT Madras corresponding to 10% probability of exceedance in a life span of 50 years or in other words a PGA corresponding to a return period of 475 years is 0.102g which is indicative of moderate seismicity. When performed properly, a good PSHA will be valid for a number of years and will not be discredited by new theories or data that result from the occurrence of a single earthquake. Uniform hazard spectra can be used to select the spectrum compatible acceleration time histories from the published data base of the actual ground motions. In choosing from amongst real earthquake records it will be desirable to match as nearly as possible the design conditions of magnitude, source distance, source depth, source mechanism, tectonic regime, (i.e. intraplate or interplate), and soil profile with those of the real earthquakes. It is to be noted that the engineering judgment must be applied to the interpretation of PSHA results. The selection of a methodology for analysis of seismic hazard should be adopted to the data available and its merits, and not based on the availability of a particular computer program or the philosophical inclination of the analyst.

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