Probabilistic Seismic Hazard Analysis for Rock Sites in the Chennai City

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ABSTRACT: Seismic hazard assessment of low seismicity regions of the world is now-a-days becoming more common. The seismic hazard assessment involves the quantitative estimation of ground motion characteristics at a particular site. The assessment of probabilistic seismic hazard is required for the establishment of zoning maps over large regions or in the context of seismic risk studies for sites that deserve special attention such as nuclear power plant sites. Probabilistic seismic hazard analysis (PSHA) implies an integration of all the potential magnitudes and source distances to estimate the mean frequencies of earthquake ground motions occurring at the site in any given time period i.e., the estimation of \( P(a \geq a^* \text{ in } t) \), the probability with which ground motion values of interest \((a^*)\) are expected to be exceeded at least once during a certain time interval of duration \(t\).

Specification of ground motion attenuation relating the ground motion parameters at a site to earthquake magnitude, source-to-site distance, and other variables such as style of faulting, site geology, etc. constitute major ingredients of the seismic hazard analysis. In this paper, an attempt is made to carry out seismic hazard analysis for rock sites in the Chennai city. As the seismicity data of the study area are scarce, appropriate assumptions are made in the completeness analysis of the records. A few locations in the Chennai city are selected and seismic hazard results are presented in the form of hazard curves, which indicate the annual probability of exceeding the peak horizontal ground acceleration in a specified period of time. Deaggregation is also performed and the resulting hazard curves are presented.


Introduction

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. However, the 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. 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.

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 of Killari (1993) and Jabalpur (1997) in these areas of the 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 Peninsular India has been one of the most interesting regions to study for earthquake phenomena associated with the intraplate activities (Chandra 1977; Khattri 1992; Sreedhar 2007; Ornthammarath et al. 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. In this paper, an effort has been made to evaluate seismic hazard for rock sites in the 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, Mw) have occurred in this region, highlighting the importance of seismic hazard assessment for the region.

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, the Gutenberg-Richter recurrence law has been used to characterize the seismicity of the region. Horizontal uniform response spectra have been computed for reference return periods of 72, 224, 475, 975 and 2475 years (i.e., 50%, 20%, 10%, 5% and 2% probability of exceedance in 50 years respectively). Hazard maps for the selected sites in the Chennai city have been developed using a convolution scheme based on weighting and incorporating uncertainties.

Earthquake Database

In order to understand the seismic characteristics of the study area, earthquake catalogues compiled by Rao and Rao (1984), Sreedhar (2007) and Ornthammarath et al. (2008) for the Peninsular India

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were used. In all, a total of 623 earthquake data from the Gouribidanur Array (GBA) and global sources from the year 1968 to 1991 have also been compiled. 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. 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. 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 1 depicts the distribution of seismic events having moment magnitude greater than 3.5 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. 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. 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), Visual Cumulative method (CUVI) formulated by Mulargia and Tinti (1985) is adopted in the study to estimate the period of completeness of the catalogue.

According to CUVI method events are divided into magnitude classes, as incompleteness is known to be a function of magnitude. 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 completeness interval is the number of years from the beginning of the period to the last year of occurrence in the catalogue.

**Figure 1** Distribution of Seismic Events with Rupture Distance

**Figure 2** CUVI Method for Determining Catalogue Completeness
beginning of the catalogue for four different classes of magnitudes are shown in the figure. 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 computed for the seismic zone of the study area.

<table>
<thead>
<tr>
<th>Magnitude interval $(M_w)$</th>
<th>Completeness interval</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 – 3.99</td>
<td>1968 – 2008</td>
<td>40</td>
</tr>
<tr>
<td>4.0 – 4.49</td>
<td>1968 – 2008</td>
<td>40</td>
</tr>
<tr>
<td>4.5 – 4.99</td>
<td>1952 – 2008</td>
<td>56</td>
</tr>
<tr>
<td>$M_w \geq 5.0$</td>
<td>1800 – 2008</td>
<td>208</td>
</tr>
</tbody>
</table>

**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 $b$. In this study, 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 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 3 (GSI, 2000). Table 2 presents the details of the faults.

**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

$$\log_{10}(\lambda_M) = a - b M$$

where $\lambda_M$ 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 specific values of ‘$a’ and ‘$b’ are calculated by grouping the catalogue into magnitude ranges of say $\Delta M = 0.5$, in the time interval of 10 years. The magnitude ranges considered are: $3.5 \leq M_w \leq 3.99$; $4.0 \leq M_w \leq 4.49$; $4.5 \leq M_w \leq 4.99$ and $M_w \geq 5.0$. The average number of events per year in every magnitude range is determined.
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 4). Finally these values are compared with the previous values given by the earlier investigators for the Peninsular India. Table 3 presents a comparison between the values obtained in this study with those of the earlier studies.

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

$$\log(n) = -1.0661M_w + 4.7356$$  \hfill (2)

### Table 3 Comparison of $a$ and $b$ Values

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Author(s)</th>
<th>Value of $a$</th>
<th>Value of $b$</th>
<th>$a/b$</th>
<th>Data for a period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Avadh Ram and Rather (1970)</td>
<td>5.30</td>
<td>0.81</td>
<td>6.54</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>Kaila et al. (1972)</td>
<td>3.25</td>
<td>0.70</td>
<td>4.64</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>Rao and Rao (1984)</td>
<td>4.40</td>
<td>0.85</td>
<td>5.17</td>
<td>170</td>
</tr>
<tr>
<td>4</td>
<td>Present study</td>
<td>4.74</td>
<td>1.07</td>
<td>4.43</td>
<td>210</td>
</tr>
</tbody>
</table>

### PGA Attenuation Relationship for Peninsular India

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. 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 5). 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 5 shows the comparison of estimated PGA for each of the attenuation relationships adopted with uniform focal depth of 17 km and $M_w = 5.7$. Table 4 gives the corresponding peak values of PGA noted from Figure 5.
Methodology used for PSHA

CRISIS 2007 Version 1.1, a computer program for computing seismic hazard, developed by Ordaz et al. (2007) has been used in this study. The frequency-intensity curves are generated by computing the annual probability of exceedance for a range of ground motion intensities. Figure 6 shows the mean hazard curves for both the horizontal and vertical components of ground motion at a particular site (80.2°E, 13.0°N).

Uniform Hazard Spectrum

The essence of PSHA lies in the uniform hazard spectrum (UHS), which is a convenient tool to compare the hazard representations of different sites (Todorovska et al. 1995; Peruzza et al. 2000). 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 the Chennai city. The UHS plots for different return periods in the Chennai city are developed. Figure 7 depicts these plots for a particular site using Abrahamson and Silva (1997) attenuation relationship. Table 5 presents the spectral acceleration values in ‘g’ for a return period of 475 years at IIT Madras.

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

$$P[Y > y^*] = 1 - e^{-\lambda_y T}$$

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

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

It should be noted that as the exposure time $T$ increases, the probability of exceeding a particular peak ground acceleration value ($y^*$) increases. Equation (4) is used for finding $\lambda_y$ for a particular probability of exceedance in a given period. The corresponding PGA is found from the hazard curve of the site. Figure 8 provides the contour plot of PGA values corresponding to return period of 475 years for the Chennai region. Table 6 gives the horizontal peak ground acceleration values at IIT Madras for return periods of 72, 224, 475, 975 and 2475 years.
Summary and Conclusions

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. 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. A decrease in $b$ over a period of time indicates an increase in the proportion of large events. For the Chennai city, the estimated values of $a$ and $b$ are 4.74 and 1.07, respectively. Uniform hazard spectra and seismic hazard maps depicting bed rock level peak ground acceleration (PGA) contours for various return periods 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 0.12g which is indicative of moderate seismicity. 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.

References


