Estimation of probabilistic seismic hazard for Aizawl city in North Eastern India (NEI)

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Abstract. It is common practice to describe seismic hazard in terms of Peak Ground Acceleration (PGA) and Spectral acceleration ($S_a$). Response spectrum representation of ground motion is directly applicable in structural response analysis. However, in India, engineers have been using a standard response spectral shape as recommended by the code IS-1893:2016 all over the country, modified only by a zonal factor representing the PGA of unknown probability of occurrence. This approach is silent about the various seismo-tectonic sources and non-uniform level of hazard at different parts of India. Thus, the expected or desired design life of structures cannot rationally harmonize with existing earthquake hazard and economical construction practices. Whereas, the underestimation of the hazard will lead to questionable safety margins, overestimation makes the projects uneconomical and hence social goal suffers in either case. It is in this context, Probabilistic Seismic Hazard Assessment (PSHA) that addresses engineering safety issues with quantifiable risk levels has become more popular. Now-a-days, seismic hazard maps are prepared in different countries for a given annual frequency of exceedance. With this in mind, probabilistic seismic hazard for Aizawl City has been prepared. In this study, we have estimated seismic hazard for different return period in Aizawl city. The active fault within 300 km radius of the city are considered for this study. The seismic hazard values estimated in this study will be useful for the structural designers of Aizawl city and its adjacent region to design various types of Engineering Structures.

1. Introduction
NEI is very highly active seismic region and is considered to be one of the six most active region in the world. The other five are Mexico, Taiwan, California, Japan and Turkey [1]. NEI is located in the seismic zone V in India. As per Indian Standard code of practice IS 1893: 2016, seismic zone V is considered to be the most severe seismic zone in India. The seismotectonic map of NEI is shown in Figure 1. The region include the Eastern Himalaya, Arakan-Yoma Belt including the folded belt of Tripura, Irrawaddy basin, Shillong Plateau where Dauki fault is located and the northern Bengal basin [2, 3].

Seismic hazard may be assess as a combination of probabilities determined from observations of various phenomena related to the occurrence of large earthquakes [4]. Kaila et al. [5] have calculated the seismic hazard values for India. They calculated the return period of an earthquake of magnitude equal to or greater than 6.0 for all the important cities in NERI. They calculated the return period for the earthquake of magnitude equal to or greater than 6.0 for Guwahati and Shillong cities as 124 and
122 years respectively. They also calculated the return period for the earthquake of magnitude equal to or greater than 6.0 for Imphal and Tezpur cities as 130 and 126 years respectively. Goswami and Sharma [6] studied about the probabilistic earthquake expectancy for NERI. They found that the average return period for an earthquake of magnitude 8.0 or greater for NERI are 25 and 30 years respectively. Their observation was based on the Gumbel’s theory of extreme events. They have calculated the average return period for the high magnitude earthquakes for all the six tectonic blocks in NERI which are presented here. They reported that the average return period for the earthquake of magnitude 8.6 for the Eastern Himalayan region is 50 years. The average return period for the earthquake of magnitude 7.4 for the Naga Hill region is 50 years. The average return period for the earthquake of magnitude 8.5 for the Shillong plateau region is 100 years. The average return period for the earthquake of magnitude 7.4 for the Surma valley region is 50 years. Khattri et al. [7] has reported the seismic hazard values for the 10% probability of exceedence in 50 years as 0.7g in the Eastern Himalayan region and 0.8g for the Assam valley region. These calculated seismic hazard values are based on the PGA attenuation curve of Algermission and Perkins developed for the United States in the year 1976. Khattri [8] reported the probabilistic seismic hazard value for the 10% probability of exceedance in 50 years (1981-2031) as 0.6g in Shillong region and these values vary for NERI from 0.3g to 0.75g. Parvez and Ram [9] have carried out the study of probabilistic earthquake hazard assessment in NERI. They estimated the probability of occurrence of earthquakes with magnitude greater than 7.0 during a specified interval of time on the basis of four probabilistic models namely Weibull, Gamma, Lognormal and Exponential for NERI. They have calculated the model parameters by the method of maximum likelihood estimates and method of moments. They estimated the cumulative probability of occurrence of high magnitude earthquakes (>7.0) for NERI for a period of 40 years from 1964 and it is ranging from 0.881 to 0.995 based on all the four model. They concluded that NERI would expect great earthquakes at any moment in the remaining years of the 20th century. Bhatia et al. [10] have prepared seismic hazard map for Indian region using the probabilistic seismic hazard approach of McGuire [11] based on the attenuation relation of Joyner and Boore [12]. They calculated the PGA value for NERI for the 10% probability of exceedance in 50 years. According to the seismic hazard map prepared by them, NERI can expect to have a Peak Ground Acceleration (g) of 0.24g to 0.48g. Sandip et al. [13] have calculated the probabilistic seismic hazard for NERI. They reported the expected horizontal pseudo spectral values for the 100 years return period at 0.04 second at the various important cities of NERI such as Guwahati, Shillong, Kohima, Imphal, Aizawl, Agartala and Silchar are 0.22g, 0.22g, 0.26g, 0.24g, 0.26g, 0.18g and 0.3g respectively. Their approach is free from the existence of various seismotectonic sources. They have calculated the probabilistic seismic hazard for NERI based on the attenuation model for the pseudo spectral velocity scaling using only 6 recorded earthquake data. They did not account for local site condition for calculating the seismic hazard values.

2. Methodology

The term seismic hazard is used to denote the probability of occurrence of an earthquake with magnitude larger than or equal to a particular value within a given time span in a specified region. Finding the specification of ground motion parameters for a particular site due to the existing seismic sources is one of the most important problems in engineering applications. This is achieved through the seismic hazard assessment (SHA). It involves the quantitative estimation of ground-shaking hazard at a particular site considering all the seismic sources within 300 km radius around the site. The systematic evaluation of the seismic hazard is absolutely necessary for evaluation of the seismic risk for a region. Specifically, it is often necessary to estimate the size of largest earthquake and the related hazard that might be generated by a particular fault or the earthquake source. It is rare, however that the largest possible earthquakes along an individual fault have occurred during the historical period. The future earthquake potential of a fault is commonly evaluated from the faults rupture parameters.
The fault rupture parameters are in turn related to the earthquake magnitude. So the hazard caused by the earthquake at a place depends on the size of the seismic source potential and the source to site distance. The calculation of forces and the others ground motion parameters at a particular site due to a future earthquake is the main objective in the field of earthquake engineering. This can be achieved at a site through the Probabilistic Seismic Hazard Assessment (PSHA) from the various existing seismic sources located within 300 km radius around the site. Seismic hazard may be analyzed deterministically from the minimum distance of the seismic sources or probabilistically in which uncertainties in earthquake size, location and time of occurrence are explicitly considered. Both the approaches overlap up to a large extent. PSHA is an improvement approach over its deterministic counterpart.

DSHA (Deterministic Seismic Hazard Assessment) ignores the randomness of the earthquake phenomenon except in the recurrence relationship. Actually two type of uncertainties called aleatory and epistemic are recognized for the earthquake process. Aleatory uncertainty reflects the inherent unpredictable nature of future events and cannot be removed by additional data. Epistemic uncertainty is due to the incomplete knowledge and data about the earthquake process which can be reduced by the collection of additional information. The DSHA ignores both the above uncertainty. The location of seismic source potentials and the rupture parameters are uncertain for the earthquake process and so the source to site distance is treated as random variable. Also, for any seismic source potential, the size of the future earthquakes is uncertain and it may create low to high magnitude earthquakes depending on its fault rupture length. Keeping this in view, the size of the future earthquakes magnitude may be treated as a random variable with an exponential density function. This uncertainty in the earthquake magnitude and the source to site distance is considered in the PSHA but this is ignored in the approach of DSHA by taking a fixed magnitude and distance value corresponding to a desired recurrence period such as 100 or 1000 years. As a result DSHA approach gives PGA values lower than the realistic values. An improvement to the seismic hazard assessment would be to incorporate all the possible uncertainties in the hazard estimation procedure. Cornell [14] pioneered the method of PSHA and has developed a method for evaluating the seismic risk at a particular project site. This method incorporate the influence of all potential sources of earthquake and the average seismic activity rate assigned to them. Using the point source model of the earthquake sources and the predictive
attenuation relationship, he has come up with a closed form of analytical solution to represent the hazard at site. These results are presented in term of PGA versus return period which are known as hazard curves. Cornell and Merz [15] improved the previous approach by introducing quadratic log frequency versus magnitude relationship and based on this they described the quantitative analysis of the seismic threat on the rock site of Boston city. They represented the annual risk associated with the project site in terms of probability that in any given year certain intensity value will be either equal or greater but these results are based on the selected point source model. NERI has suffered earthquakes since ancient time. But recording of these earthquakes are not available. However, recording of historical earthquakes starts from 1720 A.D. but in India, recording of strong motion data starts after 1966. So, prior to earthquake recording, the intensity of the earthquake size can be assigned based on the damage induced in the area. Numerous intensity scales developed in preinstrumental times to measure the earthquake induced damaged in the structures. The most common in use today are Modified Merceli Intensity (MMI) and MSK (Medvedev-Sponheur-Karnik) scale. Based on the damage induced in engineering structures, MMI scale is defined. The MMI can be converted to suitable PGA value using empirical relation, which can be used in engineering application. Trifunac and Brady [16] studied in details about the earthquake engineering aspects of strong ground motion data and they used the conversion formula from MMI to PGA as given below

\[
\log(\text{PGA}) = \left(\frac{\text{MMI}}{3}\right) - \frac{1}{2}
\]

Seismic intensity is the strength of an earthquake hazard at a specific location. The MMI scale can be converted to the earthquake magnitude as given by Kanai [17]. For Indian region, from the Koyna (1967) earthquake, Dharamsala (1985) earthquake, Uttarkashi (1991) earthquake, Chamoli (1999) earthquake, the relation between MMI and PGA can be written as [18].

\[
\log(\text{PGA}/g) = 0.65\text{MMI} - 6.66 \sigma(\ln\epsilon) = 0.72
\]

Knowing MMI, the approximate earthquake magnitude and PGA can be obtained

3. Ground motion model for NEI

Most of the recorded crustal earthquakes in NEI are located on the C type site and few of them are located in the firm stiff soil [19]. In this study, we have developed our model base on site specific recorded events in NEI, so the proposed model is valid for C type site. We used the ground motion model developed by Singh et al. [20] for NEI which is presented below.

\[
\ln(Y_{br}) = c_1 + c_2(M_w - 6) + c_3(M_w - 6)^2 - \ln R - c_4 R + \sigma_{br}
\]

where \(c_1, c_2, c_3\) and \(c_4\) are the regression coefficients. Here \(Y_{br}\) represents \(S_a\) at rock level, \(M_w\) is the moment magnitude and \(R\) is the hypocentral distance, respectively. The ground motion model will not differ if the site condition is different. The present ground motion model can be used for different site condition by multiplying the site amplification coefficients for a site class to the bedrock acceleration \((Y_{br})\). The hypocentral distance, \(R\) is calculated as

\[
R = \sqrt{R_e^2 + h^2}
\]

where \(R_e\) and \(h\) are the epicentral distance and focal depth, respectively.

4. Mathematical formulation of probabilistic seismic hazard

Structures are designed based on credible ground motion parameters and not for the earthquake magnitude. In this regard, all possible ground motion scenarios have to be considered to get the clear picture of design basis ground motion parameters. For this purpose, PSHA which estimates the probability of exceedance of various ground motion levels at a site is widely used in engineering practice. The details of PSHA are now available in many references including the textbook by Kramer [21]. The probability of exceeding a specified ground motion level \(y^*\) of \(Y\) (PGA) is calculated based on the conditional probability to a particular source to site distance with one possible
earthquake magnitude and then multiplied by the probability that the particular location will produce an earthquake of that particular magnitude. This step is then repeated for all possible distances and magnitudes with the probabilities of each and summed up all these steps to get the total annual probability of exceedance of a particular ground motion level as follows

$$P[Y > y^*] = \int_{m=m_0}^{M} \int_{r=r_{\text{min}}}^{r_{\text{max}}} P[Y > y^* | r, m] p_{Rm}(r | m) p_m(m) dm dr$$  \hspace{1cm} \text{(5)}$$

Where $P[Y > y^*]$ is the probability density function of the magnitude $m_0$ and $M_0$ are the threshold magnitude and maximum magnitude of the fault, $y^*$ is the particular level of ground motion parameters such as PGA/Sa. $P[Y > y^* | r, m]$ denotes the conditional probability that the chosen ground motion level exceeded for a given magnitude and distance. $r_{\text{min}}$ and $r_{\text{max}}$ are the minimum and maximum site distances from the fault. $p_{Rm}(r | m)$ is the conditional probability density function of hypocentral distance and magnitude. Equation (5) can be computed numerically by assuming that a fault is capable of generating earthquakes of discrete magnitudes $m_i$, separated by $\Delta m$ and only at some discrete source to site distances $r_j$, separated by $\Delta r$ which can be written as

$$P[Y > y^*] = \sum_{i=1}^{N_f} \sum_{j=1}^{N_r} P[Y > y^* | r_j, m_i] P[r_j | M = m_i] P[M = m_i]$$

$$\text{where } r_j = r_{\text{min}} + (j - \frac{1}{2}) \Delta r ; m_i = m_0 + (i - \frac{1}{2}) \Delta m ; N_r = \frac{r_{\text{max}} - r_{\text{min}}}{\Delta r} ; \text{ and } N_m = \frac{M_0 - m_0}{\Delta m}$$  \hspace{1cm} \text{(6)}$$

Since the seismic hazard at a particular node at a site is calculated considering all the seismic sources which are mainly faults within 300 km radius around the node. There can be several seismic sources within 300 km radius around the node. So, the mean annual rate of exceedance of at the site considering all the seismic sources within 300 km radius is given by

$$\mu_y = \frac{N_{\text{faults}}(m_0)}{N_f} \sum_{i=1}^{N_f} \sum_{j=1}^{N_r} P[Y > y^* | r_{i,j}, m_i] P[r_{i,j} | M = m_i] P[M = m_i]$$  \hspace{1cm} \text{(7)}$$

In the above equation, the average rate of threshold magnitude exceedance of magnitude $m_i$ of the $k$th fault is $N_{\text{faults}}(m_0)$. Now, considering the effects of all sources, the mean annual rate of exceedance is given by

$$\mu_y = \sum_{i=1}^{N_f} \sum_{j=1}^{N_r} \sum_{l=1}^{N_{\text{source}}} \lambda_{k_i}(m_l) P[| M = m_{k_{ij}} | \text{ and } P[r_{k_{ij}} | M = m_{k_{ij}}] P[M = m_{k_{ij}}]$$

$$\text{where } \sum_{i=1}^{N_0} P[m_k, m_l] - 1 \text{ and } \sum_{j=1}^{N_r} P[r_{k_{i,j}} | M = m_{k_{i,j}}] - 1$$  \hspace{1cm} \text{(8)}$$

Let for the $k$th source, $\lambda_k(m_i)$, be the frequency of occurrence of events of magnitude $m_i$, then

$$P[M = m_{k_{ij}}] \text{ can be expressed as } \frac{N_{\text{source}}(m_i)}{N_f} \text{ and replacing this value from equation (8), the final expression for the mean annual rate of exceedance at site is given by}$$

$$\mu_y = \sum_{i=1}^{N_f} \sum_{j=1}^{N_r} \lambda_{k_i}(m_i) \sum_{l=1}^{N_{\text{source}}} P[Y > y^* | r_{k_{i,j}, m_{k_{ij}}}] P[r_{k_{i,j} | M = m_{k_{i,j}}}]$$  \hspace{1cm} \text{(9)}$$

These probabilities are calculated for all the possible sources to site distances and magnitudes which may occur on each fault. The mean annual rate of exceedance of $y^*$ is obtained by summing up the
individual probabilities due to all faults. This is repeated for various ground motion values $y^*$ to obtain the seismic hazard curves. Assuming that the number of earthquakes occurring on a fault follows a stationary Poisson process, the probability of exceedance of $y^*$, in a particular time period $T$ years is given by

$$P(Y > y^* \text{ in } T \text{ years}) = 1 - \exp(-\mu_y T)$$

(10)

It is observed from the above expression that as the design life increases, the probability of exceeding a particular value also increases. As a result, the value of the design ground motion parameter also increases with increase in the time period $T$ years. The reciprocal of the annual probability of exceedance gives the return period for the corresponding ground motion value.

Seismic hazard curves can be obtained by computing the mean annual rate of exceedance $\mu_y$, for different specified ground motion level $y^*$. This curve at a site is obtained individually for all faults which are located within 300 km radius around the site. The seismic hazard curve at a site is finally obtained after summing up of all these individual hazard curves within 300 km radius.

5. Results and discussion

Probabilistic seismic hazard curves in the present study have been calculated based on the GMPE developed for the crustal earthquakes for NEI by Singh et al. (2016) at the bedrock level and using the equations (5), (9) and (10). The primary function from PSHA is a seismic hazard curve showing PGA against the mean annual rate of exceedance. In engineering analysis and design, one needs to know the ground motion due to all causative sources in a region of about 300 km radius around a given site. The probabilistic seismic hazard curves for Aizawl city has been prepared by considering all the seismotectonic sources within 300 km radius around this city for the 100, 500 and 2500 years return period. The seismic hazard curves for all the individual faults have been prepared for the city after summing up the hazard from all the contributing individual faults. In the present study, probabilistic seismic hazard curves at the bedrock level corresponding to shear wave velocity ($V_s$) greater than or equal to 3 km/sec have been prepared for Aizawl city, which are presented in Figure 2 and 3 respectively.

![Figure 2. Response Spectra of Aizawl city at bedrock level ($V_s \geq 3$ km/s)](image_url)
It is observed from Figure 2 that the peak acceleration occurred at 0.03 to 0.04 s for all the return periods considered in this study. From Figure 3, Naga fault and Shillong fault are the two most active zones for seismic events to produce more annual frequency of occurrence for Aizawl city.

6. Conclusion
In this paper, the results of probabilistic seismic hazard analysis (PSHA) of Aizawl city have been presented for different return period. PSHA is carried out from different earthquake sources over a distance of 300 km radius with respect to Aizawl city. The present model is based on hard rock level ($V_{S30}$ 2800 m/s), such that it can be converted into any type of NEHRP site class A to F. The conversion can be done using the suitable site coefficient from Singh et al. [20], which is applicable for North-Eastern India. The present PSHA will be helpful in the seismic designing of structures in Aizawl city and its vicinity.

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