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Probabilistic Seismic Hazard Analysis of Nepal considering Uniform Density Model

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Abstract
Probabilistic seismic hazard analysis for Nepal has been carried out in terms of peak ground acceleration. A detailed earthquake catalogue within the rectangular area bounded by the coordinates (N253000,E783000), (N313000,E893000)from 1255 up to 2015 A.D and new seismic and seismo tectonic map have been prepared. Five hundred twenty eight numbers of areal sources has been proposed and historical earthquakes are plotted in the map of Nepal for identifying and characterizing the seismic sources. The completeness of the data has been checked by using Stepp's procedure. Seismicity in four regions of study area has evaluated by defining 'a' and 'b' parameters of Gutenberg Richter recurrence relationship. The uniform density model has been adopted to get the hazard in terms of contour map for peak ground acceleration for hard, medium and soft subsoil conditions for different probability of exceedence in 50 years period. The average seismic hazard curve for Nepal for hard, medium and soft subsoil condition has been plotted for the period of 50 years.

Keywords
PSHA – Uniform density model – Attenuation relationship

1. Introduction

Nepal is highly susceptible to earthquake related hazards like ground shaking, structural damage and destruction, liquefaction, landslide, flood, lifeline damage and obstruction etc. Such hazard is responsible for huge loss of life and properties. Recent Gorkha earthquake on 25th April 2015 of magnitude 7.8M with another strong aftershock of magnitude 7.3M caused about 9000 deaths, 22000 injuries with loss of billions of dollars is one of the clear example of devastation during the hazard. To mitigate such hazard, there is not any other alternative left for professionals rather than making the structures earthquake resistant.

For the design of seismic resistant structures, it is essential to do site specific seismic hazard analysis and to quantify the site specific ground motion parameters. This necessitates the probabilistic seismic hazard analysis for the whole country. So an attempt has been made to carry out probabilistic seismic hazard analysis of the country and the result is presented in the form of contour map for PGA and spectral accelerations for hard, medium and soft soil site conditions for four various probabilities of exceedence in fifty years.

2. Seismicity and Geology of Nepal

The active tectonic action since a million of year's time in the subduction zone had been resulting for the formation of series of Himalayas from west to east in northern of Nepal. The three faults namely Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT) exists in a narrow width along with many other smaller faults about ninety two in numbers [1]. Along with the faults extended over the country the geography is too complex. The northern part of Nepal lies on rocky strata with high hills and mountains which are believed as the product of tectonic action. The southern part contains loose, soft alluvial soil deposits transporting from the higher Himalayas. The non uniformity in soil type and the complex geology results different level of shaking and destruction during the earthquake.

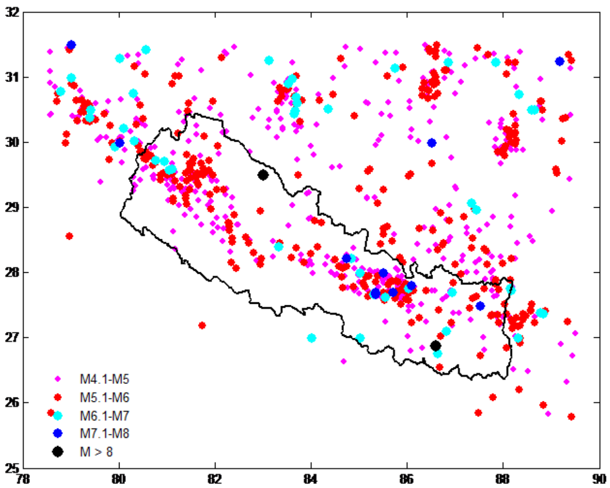

Figure 1: Earthquake density in study area

3. Earthquake Catalogue

Earthquake catalogue was obtained by merging data from historical and recorded data. To achieve uniformity in the data, all the magnitudes or intensities are converted to moment magnitude using various relationships [2] and scaling relationship for Himalayan region . The earthquake record contains large number of aftershocks which if not removed leads the earthquake data to be a non Poissoinian. This makes the statistical analysis more complicated. Hence the aftershocks are removed based on windowing algorithm [3]. For this the aftershocks are identified based on its distance from epicenter of main shock and time difference in occurrence with main shock. The catalogue after the aftershock removal follows Poissoinian distribution. There are total 1228 records available among them 827 events are found to be the main events.

4. Completeness Analysis

As the analysis has been done by discretizing the area of Nepal in small zones and by taking the available past records of earthquake, it is necessary to characterize the seismicity of each of zone. It is very difficult to allocate the location of earthquake occurrence and more than this it is difficult to specify which earthquake belongs to which fault. The recorded earthquake data has non uniformity in its number due to the difficulty in availability of data of old times. Hence it is necessary to do the completeness analysis for the best fit of frequency formula [4].

For the earthquakes events are grouped into small intervals of time and each magnitude range (0.5M) is judged separately. If $k_1, k_2, k_3, \ldots.., k_n$ are the number of earthquakes per unit time interval, then an unbiased estimate of the mean rate per unit time interval of the sample is

$$\lambda_m = \frac{1}{n}\sum_{n=1}^{n} k_i \tag{1}$$

The variance of the sample is given by,

$$\sigma^2_{\lambda_m} = \frac{\lambda_m}{n} \tag{2}$$

Where, n= number of unit time intervals If we assume number of unit time intervals as 1 year then standard deviation of the estimate of the mean

$$\sigma_{\lambda_m} = \frac{\sqrt{\lambda_m}}{\sqrt{T}} \tag{3}$$

Where, T = sample length Thus, assuming stationarity, we expect that $\sigma_\lambda m$ behaves as $\frac{1}{\sqrt{T}}$ in the subinterval of the sample in which the mean rate of occurrence $\frac{N}{T}$ in each magnitude class constant. Where, N = cumulative number of earthquakes in the time interval T The completeness analysis as done above gives the best fit for the magnitude frequency relation. In this case the magnitude frequency relationship for all the four areas of Nepal is obtained.

5. Probabilistic Seismic Hazard Analysis (PSHA)

Because of the uncertainty in location, size and shaking intensity of future earthquakes, it is necessary to quantify the uncertainties and combine those to produce the explicit description of distribution of future shaking that may occur at the site. Because of the complication to find out the worst level of shaking at a particular site which may not be occurred due to single earthquake it is not practicable to do the deterministic analysis hence we should go for probability based analysis.

5.1 Spatial Uncertainty

Due to uncertainty in location and nature (geometry) of the source it is very much difficult to define the source zone. In this study, the area is divided into 528 numbers of smaller areal elements of size 0.5° along longitude and 0.25° along latitude. All the sources are assumed to be equally capable of producing earthquake and the occurrence will be in the center of each areal cell.

5.2 Magnitude Uncertainty

To address the uncertainty in magnitude produced by each source zone various recurrence relationships specifying the average rate at which an earthquake of some size will be exceeded is to be developed. Thus obtained magnitude frequency relationship may accommodate the maximum size earthquake. The recurrence relation as per Gutenberg and Richter is,

$$\log \lambda_m = a - bM \tag{4}$$

Where, λ_m = mean annual rate of exceedence of magnitude M
10^a = mean yearly number of earthquakes of magnitude greater than or equal to zero
b = relative likelihood of large and small earthquakes

As b value increases the number of larger magnitude earthquake decreases compared to those of smaller magnitude earthquakes.

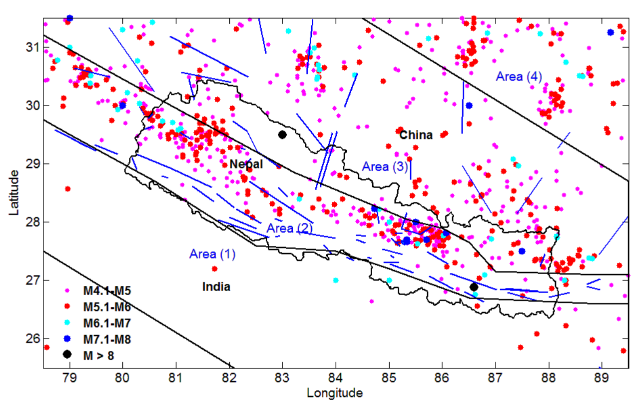

Figure 2: Delineation of seismic source zones

The standard Gutenberg-Richter law predicts the non-zero mean rate of exceedences for magnitudes up to infinity. We are concerned with the earthquake greater than magnitude M4.5 since greater size earthquake produces maximum level of shaking generally. So bounded recurrence relation law is used to express the certain maximum magnitude Mmax associated with each source zone the value of which is greater than minimum magnitude Mmin . The probability density function for Gutenberg Richter law with lower and upper bound magnitude is given by

$$f_M(m) = \frac{\beta \exp[-\beta(m - m_{min})]}{1 - \exp[-\beta(m_{max} - m_{min)}]} \tag{5}$$

Where, $\beta = 2.303b$
The areal seismicity in this study is presented in table 1.

Table 1: Seismicity distribution in the area

Area	a	b	M_{max}(year)
1	5.18	-1.27	6.6 (1833)
2	5.04	-0.91	8.1 (1934)
3	6.3	-1.16	8.2 (1505)
4	5.86	-1.18	7.2 (1934)

5.3 Temporal uncertainty

The temporal uncertainty of an earthquake is suitably modeled by using Poissoin's model. For a Poissoin's process, the probability of a random variable N representing the number of occurrences of a particular event during a given time interval is given by

$$p[N = n] = \frac{\mu^n e^{-\mu}}{n!} \tag{6}$$

Where, μ = average number of occurrences of the event at the given time interval So for seismic hazard assessment purposes,

$$p[N = n] = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \tag{7}$$

Where, λ = average rate of occurrence of the event
t =time period (years)
$p[N = n] = p[N = 1] + p[N = 2] + ... + p[N = \infty]$ The probability of occurrence of at least one event in time period t is given by $1 - e^{\lambda t}$
Then at least one exceedence of particular magnitude in a period of years t is written as

$$p[N \geq 1] = 1 - e^{\lambda t} \tag{8}$$

Similarly, probability of exceedence of particular parameter y* in a time period t is given by

$$p[Y \geq y^*] = 1 - e^{\lambda_y t} \tag{9}$$

Where, the return period of y^* is defined as:

$$R_{y^*}(y^*) = \frac{1}{\lambda[Y \geq y^*]} = \frac{-t}{ln(1-p([Y \geq y^*])} \quad (10)$$

Example:
For the 10% probability of exceedence in 50 years, the return period is calculated from equation 10.

$$R_{y^*}(y^*) = \frac{-50}{\ln(1-0.1)} = 475 \text{ years}$$

If the similar procedure is adopted the return periods for various probability of exceedence in 50 years time period can be obtained as in table 2.

Table 2: Return periods for 50 years at different probability of exceedance

Probability of exceedence (%)	time (years)	return period (years)
2	50	2475
5	50	975
10	50	475
40	50	98

5.4 Attenuation of ground motion

The seismic hazard at any area depends upon the attenuation characteristics of that site, which is the function of magnitude of earthquake, source to site distance and geologic characteristics of the site or tectonic environment. Proper implementation of most modern ground motion attenuation relationship requires that the seismic sources are characterized by the details of the fault – rupture model. There are the various attenuation relationships developed by researchers at different site condition. These attenuation relationships can be categorized into four groups, shallow crustal earthquakes in active regions, shallow crustal earthquakes in stable regions, earthquakes in subduction zones and earthquakes in extensional tectonic regimes. As Nepal lies in the subduction zone, the attenuation laws developed for subduction zone is used to to develop the peak ground acceleration (PGA) and spectral acceleration (SA). So, three attenuation relationships developed for subduction zone have been used here and mean of them is used to calculate PGA [5, 6, 7].

1. Young's et. al. 1997

$$\begin{aligned}\ln(Y) = 0.2418 + 1.414M + C_1 + C_2(10-M)^3 \\ + C_3 \ln(r_r up + 1.7818e^{0.554M}) \\ + 0.00607H + 0.3846Z_T \quad (11)\end{aligned}$$

Standard deviation = $C_4 + C_5M$
Where,
Y = spectral acceleration
M = Moment magnitude
r_{rup} = source to site distance (km)
H = focal depth (km)
$C_{k,k=1to10}$ = coefficients determined by regression analysis
Z_T = source type, (0 for interface and 1 for intra slab)

2. Kanno et. al. 2006

$$\ln(pre) = a_1M_w + b_1X - \log(X + d_1 10^{0.5M_w}) + c_1 \quad (12)$$

Where,
$pre = in\ cm/s^2$
a_1, b_1, c_1, d_1 = the constants having values 0.56, -0.0031, 0.26, 0.0055 respectively

3. Zhao et. al. 2006

$$\begin{aligned}\log_{10} PGA = A_1M_w + A_2 \log_{10} \sqrt{r^2 + d^2} + A_3h_c \\ + A_4 + A_5\delta_R + A_6\delta_A + A_7\delta_I \quad (13)\end{aligned}$$

Where,
PGA = Peak ground acceleration (m/s^2)
The terms containing δ depends on soil types.
The terms containing A are constants.

6. Seismic Hazard Curve

The plot of mean annual rate of exceedence versus peak ground acceleration gives the seismic hazard curve. The seismic hazard curve for individual source zone is obtained at first and they are combined to get the hazard for the particular site. . The probability of exceedence of certain ground motion is estimated by assuming probability distribution of ground motion. The probability of exceedence of certain ground motion parameter Y than the particular value y* is calculated for one possible earthquake at one possible source location is multiplied by the probability that the particular magnitude earthquake will occur at the particular location. This process is repeated for all possible magnitudes and locations with the probabilities of each summed.

For a given earthquake occurrence, the probability that a ground motion parameter Y will exceed particular value y* can be computed by using total probability theorem. i.e.,

$$p[Y > y^*] = p[Y > y^*|X|p[X] = \int p[Y > y^*|X|f_x(X)dx \tag{14}$$

Where, X = a vector of random variable that influences Y. In most cases quantities in term X are limited to the magnitude M and distance R. Assuming M and R are independent, the probability of exceedence can be written as

$$p[Y > y^*] = \int\int p[Y > y^*|m,r]f_M(m)f_R(r)dm\,dr \tag{15}$$

Where,
$P[Y > y^*|m,r]$ = obtained from predictive relationship
$f_M(m)$ = probability density function of magnitude
$f_R(r)$ = probability density function of distance
If the site of interest in a region of Ns potential earthquake sources each of which has an average rate of threshold magnitude exceedence,
$\nu_{iM} = exp(\alpha - \beta M_m in)$, the total average rate of exceedence for the region will be given by

$$\lambda_{y^*} = \sum_{i=1}^{N_s} \int\int p[Y > y^*|m,r]f_M(m)f_R(r)dm\,dr \tag{16}$$

Since the individual terms of equation 16 are difficult to obtain analytically by integration, the possible magnitudes and distances and divided into N_M and N_R segments respectively. Then mean rate of exceedence can be obtained by

$$\lambda_{y^*} = \sum_{i=1}^{N_S}\sum_{j=1}^{N_M}\sum_{k=1}^{N_R}[\nu_i p[Y > y^*|m_j,r_k]f_M(m_j)f_R(r_k)\Delta m\Delta r] \tag{17}$$

Where,
$m_j = m_{min} + (j-0.5)(m_{max} - m_{min})/N_M$
$r_k = r_{min} + (k-0.5)(r_{max} - r_{min})/N_R$
$\Delta m = (m_{max} - m_{min})/N_M$
$\Delta r = (r_{max} - r_{min})/N_R$
This is equivalent to assuming that each source is capable of generating only NM different earthquakes of magnitude, mj, at only NR different source to site distances, r_k. Equation 17 is then equivalent to

$$\lambda_{y^*} = \sum_{i=1}^{N_S}\sum_{j=1}^{N_M}\sum_{k=1}^{N_R}[\nu_i p[Y > y^*|m_j,r_k]f_M(m_j)f_R(r_k) \\ P[M = m_j]P[R = r_k] \tag{18}$$

7. Uniform Density Model

As it is explained in previous sections, seismic hazard from faults cannot be estimated as it is done in conventional methods. If there is the lack of recognizable earthquake faults and seismically active geologic structure in any area then uniform density model is adopted. In such model the earthquake densities are equally distributed in all areas weather there is earthquake or not. Maximum magnitudes for these area sources are typically assessed from an extrapolation of historical seismicity of the region, from compelling worldwide analogs of the regional tectonic setting from regional paleoseismologic data and interpretations (if available), or simply from the judgments of experts. Uniform density model forgets faulting and assumes uniform geology and gives the equal weightage to all the area capable of producing earthquake.

8. Results and discussions

Following the above mentioned theory and procedures and by using code in Matlab, obtained results are presented here.

The curve with highest slope of area 1 indicates that there is lacking of major earthquake in this region and the flattest slope in area 2 indicates there is the major earthquake in the region. When the database is complete, the rate will be nearly constant.

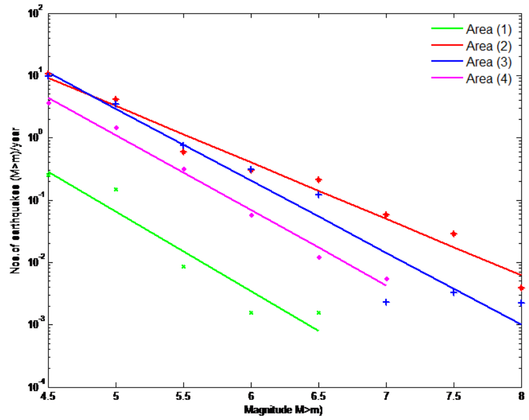

Figure 3: Magnitude frequency relationship

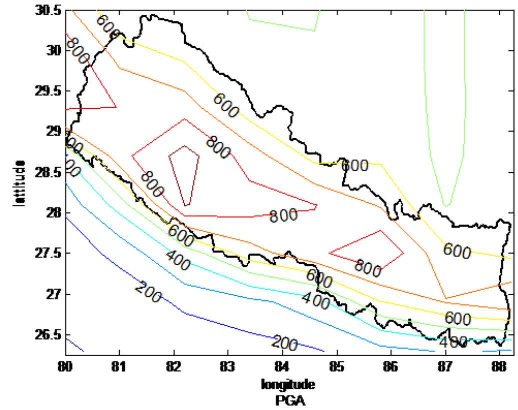

Figure 6: PGA with return period of 975 years on soft soil (5% damping)

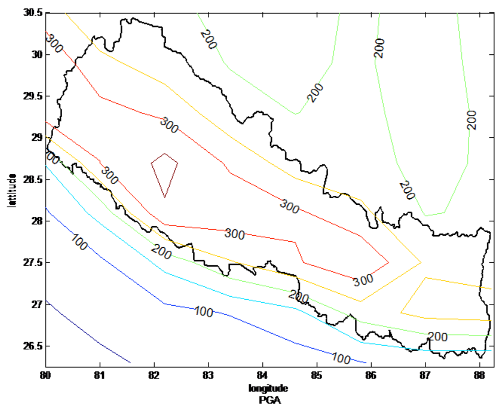

Figure 4: PGA with return period of 100 years on soft soil (5% damping)

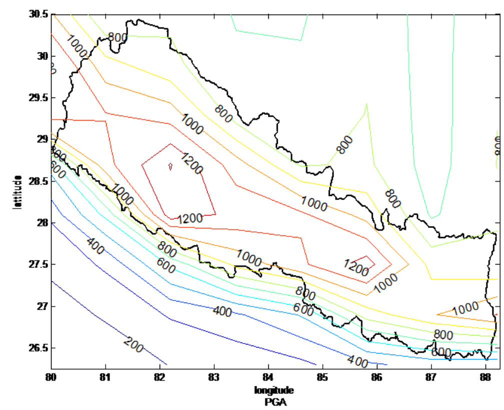

Figure 7: PGA with return period of 2475 years on soft soil (5% damping)

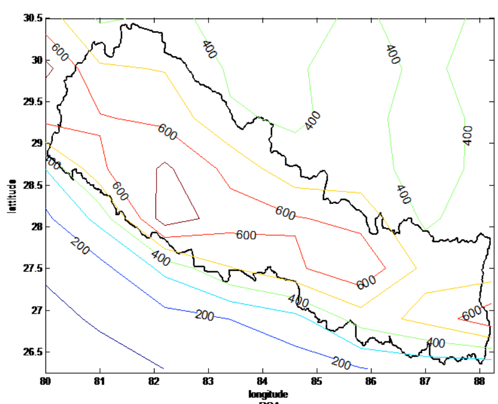

Figure 5: PGA with return period of 475 years on soft soil (5% damping)

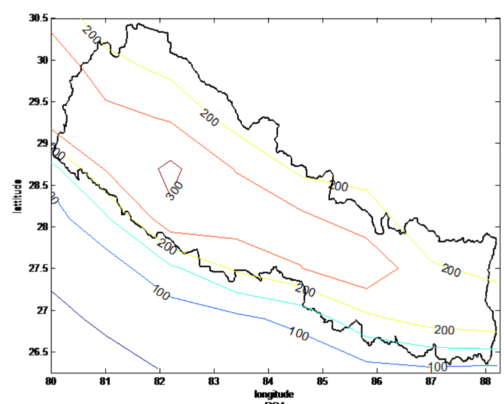

Figure 8: PGA with return period of 100 years on medium soil (5% damping)

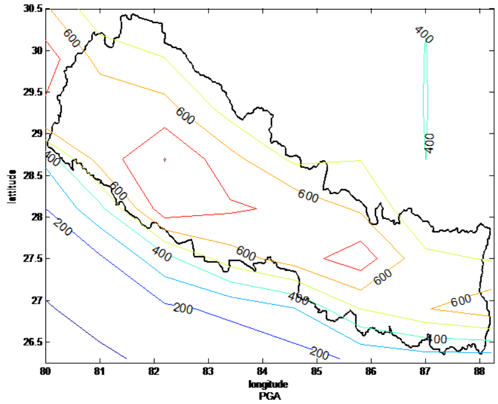

Figure 9: PGA with return period of 475 years on medium soil (5% damping)

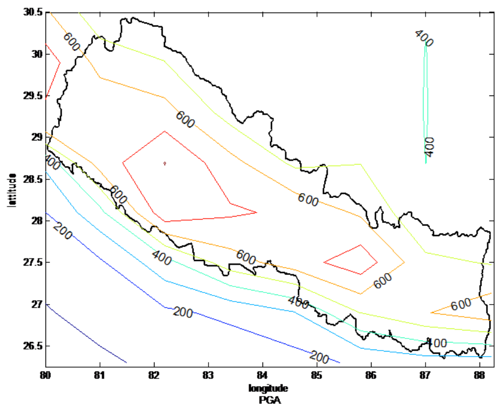

Figure 10: PGA with return period of 975 years on medium soil (5% damping)

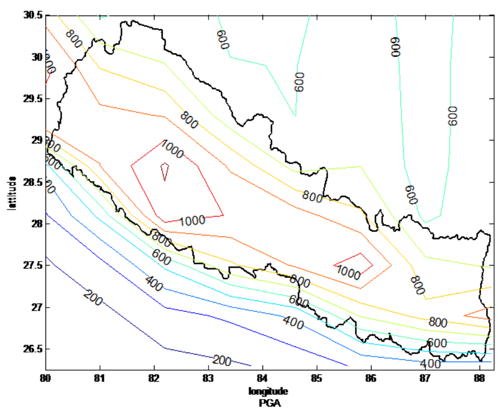

Figure 11: PGA with return period of 2475 years on medium soil (5% damping)

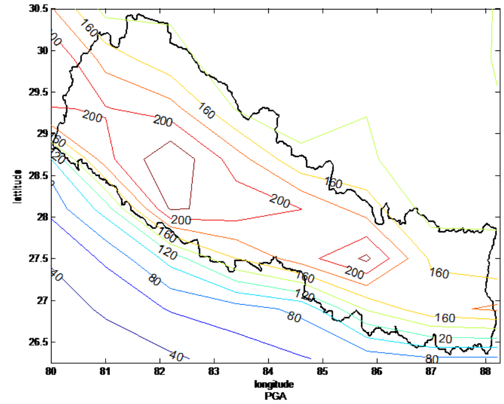

Figure 12: PGA with return period of 100years on hard soil (5% damping)

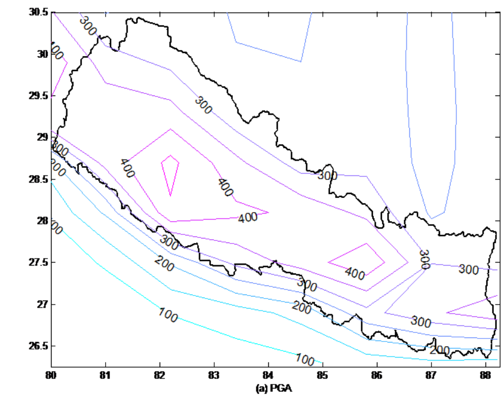

Figure 13: PGA with return period of 475 years on hard soil (5% damping)

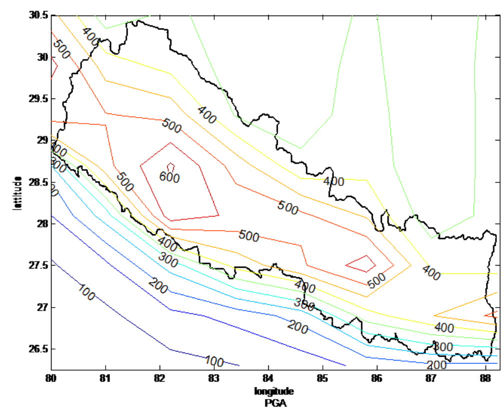

Figure 14: PGA with return period of 975 years on hard soil (5% damping)

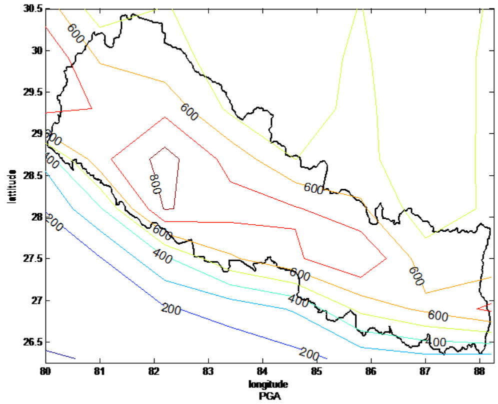

Figure 15: PGA with return period of 2475 years on hard soil (5% damping)

9. Conclusion

i. The magnitude frequency relationship for study area in four source zones is obtained in figure 3. The 'a' value for Nepal is found nearly equal to 5 and 'b' value is 1.

ii. Peak ground acceleration for hard, medium and soft soil sites for 2%, 5%, 10% and 40% probability of exceedence in 50 years is as shown in table 3.

iii. The PGA value we are adopting for design purpose in Nepal is underestimating the hazard.

Table 3: PGA for four return periods in three soil types

Soil type	PGA(g) at percentage Probability of exceedence in 50 years			
	2 %	5%	10%	40%
Hard Soil	0.84	0.61	0.46	0.24
Medium Soil	1.11	0.80	0.61	0.31
Soft Soil	1.31	0.94	0.76	0.36

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