Proceedings of IOE Graduate Conference, 2016
pp. 265–270

Probabilistic Seismic Hazard Analysis of Nepal

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Abstract

Probabilistic seismic hazard assessment of Nepal has been updated. Nepal has been divided into four area sources based upon density of historical earthquakes. At each sources, earthquake data has been collected from various sources. All data has been converted to moment magnitude, aftershocks and repeated events have been removed, and completeness analysis has been performed. Magnitude-frequency relationship has been developed. Entire area of Nepal has been divided into 1.2*0.6 degrees grid size. Earthquake densities are calculated based upon historical earthquakes using kernel estimation method which accounts the significance of both numbers of earthquakes and size. Considering various attenuation laws developed for subduction zone, peak ground acceleration and spectral acceleration for return period 475 years are calculated at 64 sites.

Keywords

Nepal – PSHA – Peak ground acceleration – Spectral acceleration – Kernel estimation method

1. Introduction

Nepal lies towards the southern collisional boundary of the Indian and the Eurasian Plate, converging at 19 mm per year (Jouanne et al. 2004). Within the narrow width of Nepal (Fig. 1), three fault systems, Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT), pass east to west throughout the length of Nepal. Along the sides of these three greater fault systems and in the Tibetan Himalayan region, ninety two small faults have been identified [1]. This indicates high rate of deformation and seismicity in the region. Four great earthquakes, in 2015 with M7.8, in 1833 with M7.7 (Bilham 1995), in 1934 with M8.1 (Rana 1934) and in 1505 with M8.2 (Ambraseys and Jackson 2003) have been observed in Nepal Himalayas, which has resulted in tremendous loss of life and property.

Recently on 25th April 2015, a strong earthquake with the moment magnitude measured by USGS, M7.8 hit Barpak-Gorkha of Nepal at 11:56 Nepal standard time (NST). On May 12, another large earthquake of magnitude M7.31 occurred with epicenter east-northeast of Kathmandu. 8790 people were killed, more than 23,500 were injured and 8,00,000 houses damaged.

The range of devastation we had to go through clearly defines the requirement of proper hazard assessment. PSHA is the first step to mitigate seismic risk as it gives a probabilistic description (a frequency of exceedance) of earthquake characteristics. Then only earthquake damage can be estimated, seismic hazard can be translated to seismic risk and rational decisions can be made on seismic safety [2]. Thus, in this study, PSHA has been carried out based on latest knowledge of seismicity.

2. Seismic Hazard Assessment

2.1 Earthquake Catalogue

Nepal is in 26.5-30.5N latitude and 80-89E longitude. All the historical earthquake data within the 300 km radius around the area enclosed by 26.5-30.5N latitude and 80-89E longitude was collected. The earthquake catalogue was formed merging the data from U.S. Geological Survey, National earthquake Information Centre (NEIC), Rana 1935, BECA 1993, Pant 2000, Ambraseys and Douglas 2004.

Earthquake Magnitude Conversion: The earthquakes data in catalogue have been reported in intensity and magnitude scales. Moment magnitude is preferred over other scales being a measure of earthquake size that can be related to physical parameters of an earthquake such as the amount of fault slip and the energy radiated by seismic waves, does not saturate because of seismograph limitations [2]. To make uniformity, all data were converted to moment magnitude using various relationships (McGuire 2004, Scordilis 2006, Johnston, Kanamori, Ambraseys and Douglas 2004).

2.2 Removal of dependent events and repeated entries

Aftershocks are earthquake events which are connected with parent event. After a large earthquake, numerous aftershocks occur at near space and time. Catalog of main shocks can be used in estimating seismic risk by virtue of statistical model when aftershocks are removed from total event listing. The windowing technique was applied to identify aftershocks. Each event was checked if it occurred inside the extent of aftershock zone it time T for every event occurring in previous points of time, and removed if found so. [3]

Since various sources were referred during the formation of the catalogue, many events were reported more than once. Most of them were removed during removal of aftershocks as they lied inside the time-location window used in the process. Few duplicate windows retained were checked for and removed manually.

2.3 Delineation of Seismic Source Zones and Source Models

Earthquake data is plotted (Figure 1) with the faults. The usual practice for seismic hazard analysis is to allocate the earthquakes to the nearest faults considering they are the sources, rearrange the data into various magnitude groups and year intervals, develop recurrence relationships, calculate mean rate of exceedences. If only the historical earthquake is considered, on the one hand, it is difficult to allocate them in the fault being close to multiple faults and on the other hand, some of the faults are empty, and some hold only few numbers of data which is insufficient to define the recurrence relationship for individual faults. Besides there are two categories of faults- greater fault systems and smaller faults.

Areal sources are used rather than linear sources to develop recurrence relationships. In this method, a source zone is considered region of uniform seismicity and historical seismicity is used to determine the rates. All points inside it are assumed equally likely to denote an earthquake focus. Methods of drawing seismic sources can be based on historical seismicity, crustal geology, tectonic processes and uniform hazard. Historical earthquakes indicate regions where crustal strain energy has been sufficiently high to cause earthquakes and where faults have been available to release that energy [2].

Higher concentration exists in the narrow zone along MCT, MBT than Tibetan Himalayan and lowest concentration is in the southern alluvium. Area south of MFT have very low rate of seismicity. Four area sources have been considered (figure 1) Separate catalog of independent events were formed for each area source.

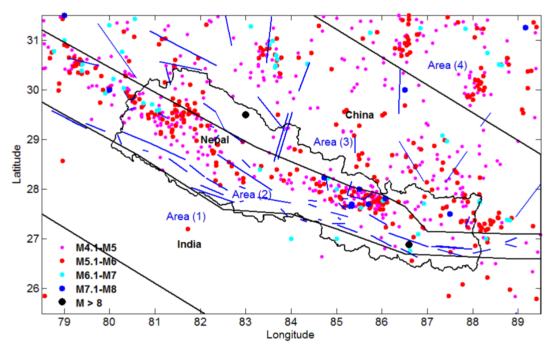

Figure 1: Historical earthquakes (points), faults (blue line) and boundaries of four source zones (black line)

2.4 Completeness Analysis

Earthquake data are not uniformly distributed, only few records are available in early periods and numbers of records have been increasing towards end. Short samples in which small magnitude events are completely reported may not represent long term seismicity of larger magnitude events due to lack of data. Likewise, longer year samples lead to serious underestimates of mean rate of occurrence of lower magnitude earthquakes. It is necessary to obtain the interval of complete reporting in each intensity class over which that class is homogeneous. A separate mean rate of occurrence can then be determined from above interval for each intensity class. In order to do completeness analysis [4] of data, events have been grouped into small interval of time and each magnitude ranges have been judged separately. Earthquakes are assumed to follow poissonian distribution. If $k_1, k_2, k_3, \ldots, k_n$, are the number of quakes per unit time interval, then unbiased estimate of the mean rate of earthquakes per unit time interval of the sample exceeding each magnitude is given by equation 1.

$$rate_M = \frac{1}{n}\sum_{i=1}^{n} k_i \quad (1)$$

Its variance is

$$\sigma^2 = \frac{rate}{n} \quad (2)$$

Where, n is number of unit time intervals. For stability, σ behaves as inverse of square root of sample length. Subinterval with constant mean rate of occurrence is period of complete reporting.

2.5 Evaluation of Seismicity Parameters

Earthquake recurrence can be expressed by equation [5]

$$\log \lambda = a - bm \quad (3)$$

where, λ is mean annual rate of exceedance of magnitude m, 10^a is mean yearly number of earthquakes of magnitude greater than or equal to zero, b is a constant describing relative likelihood of large and small magnitude earthquakes.

2.6 Attenuation of ground motions

The estimation of seismic hazard depends upon the attenuation relationship. An attenuation law is usually an empirical relationship that defines the transfer of ground motion from the source to a particular site as a function of magnitude of earthquake, source to site distance and geologic characteristics of the site or tectonic environment, faulting mechanism and medium of earthquake propagation.

$$\log(y) = f(\text{magnitude, style of faulting, distance, nsite characteristics}) + \varepsilon\sigma \quad (4)$$

Where ε is the residual ground motion measured as the difference relative to the median motion and expressed as a number of standard deviation (Boomer and Abrahamson, 2006).

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 relationship can be categorized into four groups: shallow crustal earthquakes in active regions, shallow crustal earthquakes in stable regions, subduction zones and extensional tectonic regimes. As Nepal lies in subduction zone, attenuation laws is selected from the ones developed for subduction zones (Molas and Yamazaki 1995, Young et al. 1997, Gregor et al 2002, Atkinson and Boore 2003, Atkinson and Boore 2008, Kanno et al 2006, Zhao et al. 2006 etc.). Molas and Yamazaki 1995[6], Young et al. 1997[7] and Atkinson and Boore 2003[8] have been found appropriate for the study.

2.7 Seismic Hazard Curve

The last step of PSHA is combining all uncertainties to obtain the probability that the ground motion parameter will be exceeded during the particular time period. The seismic hazard curve for individual source zone is obtained at first and combined to get the hazard for the particular site. The probability that the particular value of ground motion parameter y* exceeds Y is calculated for one possible earthquake at one possible source location and then multiplied by the probability that the particular magnitude earthquake would occur at the particular location. This process is repeated for all possible magnitudes and locations with the probabilities of each summed.

The probability that a ground motion parameter Y will exceed a particular value y* can be computed as:

$$P[Y > y^*] = \int\int P[Y > y^*|m,r] f_M(m) f_R(r) dm\, dr \quad (5)$$

Where,$P[Y > y^*|m,r]$ is obtained from predictive relationship, $f_M(m)$= probability density function of magnitude, $f_R(r)$= probability density function of distance.

If the site has capacity to develop N_s potential earthquakes with threshold magnitude of exceedence, $\upsilon_{iM} = exp(\alpha - \beta M_{min})$, the total average rate of exceedence for the region will be calculated by considering possible ranges of magnitudes and distances as,

$$\lambda_{y*} = \sum_{i=1}^{N_s} \sum_{j=1}^{N_r} \sum_{k=1}^{N_m} \upsilon_{i_{Mmin}} \rho_i P[Y > y^* | m, r] \\ P[M = m] P[R = r] \Delta m \Delta r \quad (6)$$

The probability density function for Gutenberg Richter law with lower and upper bound magnitude is given by (McGuire and Arabasz, 1990),

$$f_M(m) = \frac{\beta exp[-\beta(m - m_{min})]}{1 - exp[-\beta(m_{max}) - m_{min})]} \quad (7)$$

2.8 Earthquake densities

Density is obtained using Kernel estimation method.

Kernel density model: Earthquake density is simply number of earthquakes per unit area. However, size of earthquake makes major influence in terms of effects. Effect of a single big event would be far greater than thousands of smaller events. Thus, activity rate based upon size of earthquake is calculated using Kernel estimation method [9].

The mean activity rate $\lambda(m,x)$, at a cell is taken as a kernel estimation sum considering the contribution of N events inversely weighted by its effective return period which satisfies the condition (equation 8) can be obtained from equations 9 to 12.

$$r \leq h(m_j) \quad (8)$$

$$\lambda(m,x)_i = \sum_{j=1}^{N} \frac{K(m_j, r_j)}{T(r_j)} \quad (9)$$

$$K(m,r)_j = \left[\frac{D}{2\pi h(m_j)}\right] \left[\frac{h(m_j)}{r_j}\right]^{2-D} \quad (10)$$

$$h(m_j) = Hexp(Cm_j) \quad (11)$$

$$\rho_i = \frac{\lambda(m,x)_i}{\sum_{i=1}^{N_s} \lambda(m,x)_i} \quad (12)$$

Where, $K(m,x)$ is kernel function, $T(r)$ is return period of the event located at distance from r, $h(m)$ is kernel band width scaling parameter shorter for smaller magnitude and vice vice-versa, which may be regarded as fault length and D is fractal dimension, is taken as 1.7. H and C are constants equal to 1.45 and 0.64.

2.9 Temporal uncertainty

The temporal uncertainty of an earthquake is most commonly described by a Poisson model[10]. The probability of occurrence of at least one event in a period of t years is given by

$$P[N \geq 1] = 1 - e^{-\lambda t} \quad (13)$$

The seismic hazard curve can easily be combined with the Poisson model to estimate probabilities of exceedance in finite time intervals. Probability of exceedence of y* in a time period t is

$$P[Y \geq Y^*] = 1 - e^{-\lambda_{y*} t} \quad (14)$$

where, the return period of y* is defined as

$$R_{y*}(y^*) = \frac{1}{\lambda[Y \geq y^*]} = \frac{-t}{ln(1 - P([Y \geq y^*])} \quad (15)$$

3. Results and Discussion

Data upto 2016-9-18 have been used to prepare the earthquake catalogue. 828 data were found to be main shocks, which were used to form separate catalogues for four area sources. Now, time of complete reporting is calculated for each magnitude range. Frequency of events corresponding to above calculate time is used to develop recurrence relationship of each source area.

For all four source zones, logλ at the complete reporting is plotted against corresponding magnitude m. Fitting a straight line, recurrence relation is obtained for each sources.

For Area 1,
log(λ)=5.18-1.27M with Mmax=6.6 in 1833
For Area 2,
log(λ)=5.04-0.91M with Mmax=8.1 in 1934
For Area 3,
log(λ)=6.30-1.16M with Mmax=8.2 in 1505
For Area 4,
log(λ)=5.86-1.18M with Mmax=7.2 in 1934

Table 1: Time of complete reporting

Magnitude		4.5	5	5.5	6	6.5	7	7.5	8
Time of compete reporting	Area 1	30	40	115	200	200	-	-	-
	Area 2	30	40	70	80	100	120	120	429
	Area 3	30	40	70	80	100	278	368	643
	Area 4	30	40	70	80	100	110	-	-

The slope (represented by b value) is almost unity in the areas 2 and 3 whereas it is higher in areas 1 and 4. This means sufficient data are available in areas 2 and 3 and in areas 1 and 4, either earthquake data is missing or number of larger magnitude earthquakes is less compared to smaller magnitude ones due to tectonic reasons. Mmax shown is the maximum size of earthquake that occurred in past at each source zone.

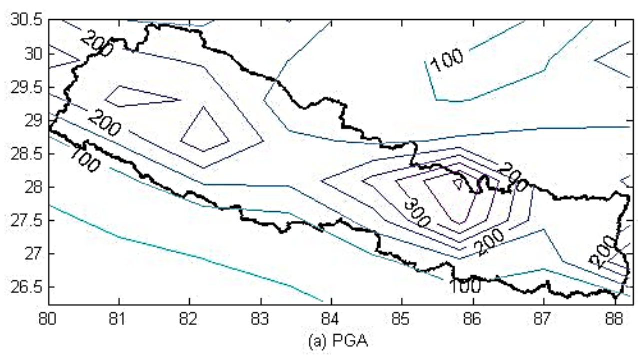

Figure 2: PGA in gals at return period 475 years on hard soil (5 percent damping)

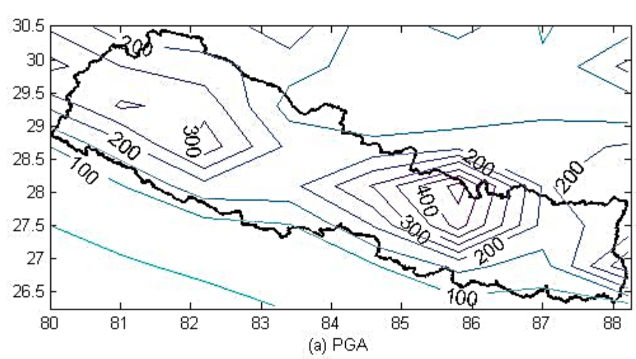

Figure 3: PGA in gals at return period 475 years on medium soil (5 percent damping)

Higher concentration of earthquake data exists in the narrow zone along MCT, MBT than Tibetan Himalayan and lowest concentration is in the southern alluvium. PGA and SA for different periods have been calculated for 475 years return period taking mean of three attenuation relationships (Molas and Yamazaki 1995, Young et al. 1997 and Atkinson and Boore 2003). Value of acceleration are higher where concentration of historical earthquakes are higher.

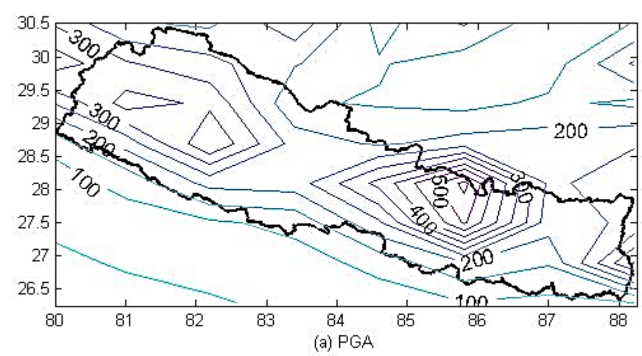

Figure 4: PGA in gals at return period 475 years on soft soil (5 percent damping)

4. Conclusions

Probabilistic seismic hazard analysis has been carried out to access peak ground acceleration and spectral acceleration for return period 475 years using most recent earthquake information of Nepal. Maximum PGA for the return period for hard soil is 300 gal, for medium soil is 400 gal and for soft soil is 500 gal. Seismic hazard maps have been developed for three soil types. Calculated hazard is more along the narrow zone along MCT and MBT. Higher hazard exists in central region and far western region, where the concentration of historical earthquakes is higher.

Acknowledgments

The authors are indebted to all the people who have directly or indirectly helped for the research work.

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