# PSHA OF HIMALAYAN REGION USING ZONING, ZONE-FREE AND MOMENT SLIP APPROACHES

**Josodhir Das[1], Madan Mohan Rout[2], Kamal Kamal[3]**

[1]Associate Professor, Department of Earthquake Engineering, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India. josoeqiitr@gmail.com, jddasfeq@iitr.ac.in
[2]Scientist-C, Institute of Seismological Research, Gandhinagar, Gujarat, India. madaniitr@gmail.com
[3]Professor, Department of Earth sciences, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India, kamalfes@iitr.ac.in

## Abstract

The Himalayan arc occurring at the northern most part of the Indian continent is a part of an extensive Alpine-Himalayan convergent tectonic belt and remains very active seismically. Very strong to moderately strong earthquakes have already occurred in this mountainous belt. In view of its active seismic status and continued developmental activities in mountainous states it is imperative to update knowledge of seismic hazard incorporating latest knowledge on earthquake occurrence and attenuation process. This work is presented with the aim to deliver PSHA information for northwest and central Himalayan region employing different approaches. Adopted procedures include improved magnitude conversion techniques, updated attenuation relations and implementation of different hazard computation approaches. Out of three methods applied, the first one is known as Cornell's (1968) zoning, the second is Woo's (1996) zone free and the third is Bungum's (2007) moment slip method. The seismic activity rate was estimated employing different techniques as suggested by Cornell (1968), Bungum (2007) and Woo (1996). Standard probabilistic empirical relations are employed for seismic hazard assessment. Peak ground accelerations have been computed at the center of all the grid points for return periods of 475 and 2475 years (i.e., 10% and 2% probability of exceedance in 50 years) employing new generation ground motion equations.

In zoning method, seismogenic zones were delineated on the basis of earthquake clusters and nature of tectonic features combined and the boundary of zones are drawn following the natural break in seismicity and tectonic features. In case of zone free method kernel density estimation of seismic activity rate has been adopted. In the third method the mean annual rate of earthquake occurrence calculated from the moment slip rate. It is understood that the zoning approach is considerably governed by the annual rate of exceedance for the seismogenic zones and the estimated maximum ground motions occurred in the westernmost part of Nepal, in the north-eastern part of Himachal Pradesh and a small part of Tibet and Kashmir valley region (0.545g to 0.597g) for 2475 return period. Zone free method predicted maximum ground motion in two areas falling in Kashmir valley and eastern part of Uttarakhand and westernmost part of Nepal. Ground motion ranges from 0.547g to 0.609g for 2475 return period. Anisotropic parameter of the kernel used in this study controls shape of predicted hazard zones as the hazard zone took an elongated shape following the Himalayan structural features and geometrical structure of seismicity. The adopted moment slip approach predicted higher order of ground motion ranging from 0.687g to 0.749g for 2475 years return period in the westernmost part of Nepal. Higher ground motion estimated because there are uncertainties in calculation of fault length which tend to increase the maximum magnitude.

The bed rock level ground motion for MCE and DBE conditions as predicted in this work appears to be meaningful in view of expected earthquake potential of the Himalayan tectonic belt.

***Keywords:*** *Himalaya; PSHA; Seismogenic-zones; Zone free; moment slip*

## 1. Introduction

The Himalayan region remains to be one of the most seismically active regions of the world owing to continued collision of the India with the Eurasian plate. In view of ongoing seismic activities the region has been assigned as seismic zones IV and V in the seismic hazard zonation map of India (BIS, 2016). In the last two centuries, the Himalayan region has experienced many great earthquakes (M≥8), notably among these are the Shillong Earthquake of 1897 (M=8.7), the Kangra earthquake of 1905 (M=8.0), the Bihar-Nepal earthquake of 1934 (M=8.3) and the Assam earthquake of 1950 (M=8.5). It is important to carry out seismic hazard analysis of the region because of its high level of natural seismicity and the presence of tectonically significant tectonic features. This study involves probabilistic seismic hazard assessment of NW and central Himalaya using the zoning, zone free and momento slip approaches.

For seismic hazard assessment under zoning approach, the first step is to identify the seismogenic zones and then the seismicity parameters for all seismogenic zones Cornell (1968) and Reiter (1990). We delineate 22 seismogenic zones considering the tectonics, seismicity and focal mechanism. The zone free kernel estimation computes activity rate density method developed by Woo (1996). Under this method no delineation of seismogenic zones are required and hence it is zone free technique. This approach is a smoothing method and uses the concept on fractal distribution of earthquakes in space and this method is an alternative to the classical zoning method proposed by Cornell (1968). The alternative approach aimed at circumventing the drawbacks associated to Cornell's approach, smoothingof historical seismicity is done to avoid the judgment involved in drawing seismogenic zones (Frankel, 1995; Woo, 1996). Woo (1996) proposed a zone-free method solely based on the use of the earthquake catalog which includes historical, instrumental, foreshocks and aftershocks data. No declustering of earthquake catalog is required in this case. Proxy seismogenic sources are created from the epicentral locations of the events are smoothed following the fractal distribution in space (Kagan and Jackson, 2000). Woo's kernel estimation method can be considered an alternative approach to outwit the ambiguities associated with the definition of seismogenic zones. Under moment slip rate method by Bungum (2007), seismicity is derived from the slip rate based on the model. If slip rates of individual faults are available from different sources, it is possible to calculate the seismicity for an area sources from the moment slip rate. Once seismic activity rate is obtained from the two approaches, the ground motion prediction equations (GMPE) are to be employed and different GMPEs have been used to calculate the probabilistic seismic hazard map of NW and Central Himalayan region.

Several authors have attempted to estimate PSHA for Indian subcontinent and for different parts of the country (e.g., Khattri et al., 1984; Bhatia et al., 1999; Mahajan et al., 2010; Nath and Thingbaizam 2012; Patil et al., 2014). Bhatia et al. (1999) estimated expected PGA for the Himalayan region between 0.10g and 0.30g with 10% probability of exceedance in 50 years. These values were obtained under Global Seismic Hazard Assessment Programme (GSHAP). Recently National Disaster Management Authority (NDMA), Government of India presented various probabilistic seismic hazard maps showing the ground motion parameters for different return periods for the whole country. PSHA base on zone free approach may be found in the work of Menon et al. (2010) for the Indian State of Tamil Nadu, Bozzoni et al. (2011) for the Eastern Caribbean region and Zuccolo et al. (2013) for Italy.

## 2. Seismotectonics of the NW and Central Himalaya

The NW and central Himalayas and its adjoining region are associated with the up-thrusted rock blocks resting on the Indian plate resulting into development of two regionally northerly dipping convergent zones; the MCT and MBT. The MBT is a series of thrusts that separates the lesser Himalaya from the sub-Himalaya belt (Valdiya, 1980). The MCT at the base of the central crystalline zone dips northward separating the Higher Himalaya from the Lesser Himalayas (Gansser, 1977). On the north side of the MCT, three prominent tectonic features viz. Bangong-Nujiang Suture (BNS), Indus suture Zone (ISZ) and Karakoram Fault (KKF) cut across the region. The Indus Suture Zone marks the boundary between the Indian and Tibetian plates. The very extensive Karakoram fault (KKF) is the most prominent tectonic feature present in the region. One of the most important transverse faults in the Western Himalaya is the Sundernagar fault (SNF) also called as Manali Fault which is dextral in nature and traverses extending from Higher Himalaya to Frontal Belt. To the east of SNF another important transverse feature Kaurik Fault System (KFS). The KFS of higher Himalaya is characterised by normal faulting exhibiting splays and might have ruptured recently during Kinnaur earthquake of 1975 (GSI, 2000). Among longitudinal faults, the E-W trending Alaknanda Fault (AF) is one of the most conspicuous one. The cause of high seismicity in the Himalaya, convergence tectonics and upthrusting of the Himalayan rocks along the detachment surface was explained by Seeber and Armbruster (1981) based on the information of large earthquakes in terms of a steady state model. This model suggests that the detachment surface under thrusting Himalayan front is the locale of the recent seismicity. Figure 1 shows the tectonics features of the NW and central Himalayan region.

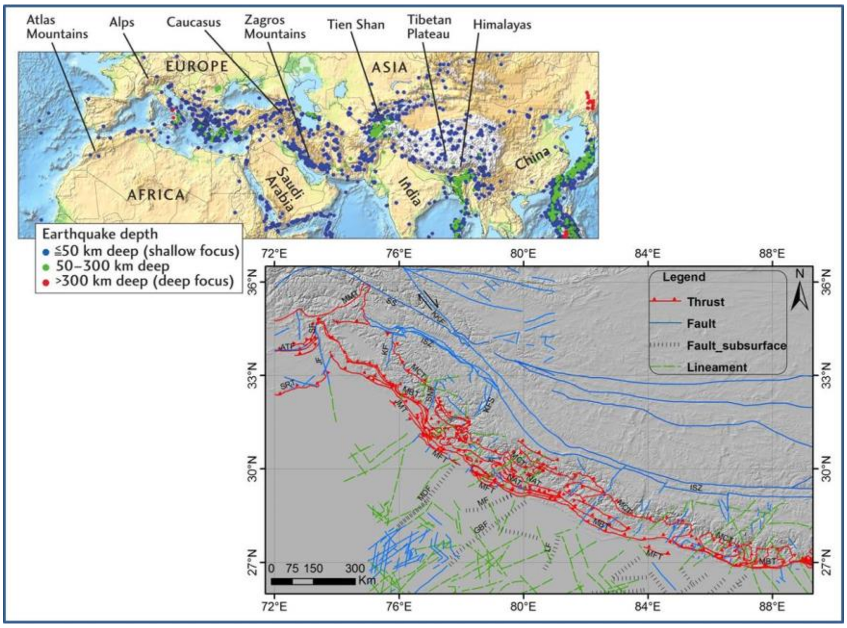


**Figure-1** Tectonics features present in and around NW and central Himalayas. MMT-Main Mantle Thrust, MCT- Main Central Thrust, MBT- Main Boundary Thrust, KKF- Karakoram Fault, ISZ- Indus Suture Zone, KFS- Kaurik Fault System, NAT- North Almora Thrust, KF- Kishtwar Fault, SNF- Sunder Nagar Fault, MDF- Mahendragarh-Dehradun fault, MF- Moradabad Fault, GBF- Great Boundary Fault. MFT-Main Frontal Thrust. (Tectonic features are adopted from GSI, 2000).

The region has experienced several earthquakes of moderate-to-large magnitudes in last two centuries. Among these, Kangra Earthquake of 1905 (M≈8.0), Bihar-Nepal earthquake in 1934 (M≈8.3), Kashmir Earthquake of 2005 ($M_W$=7.6) and Nepal earthquake in 2015 ($M_W$=7.9) are large ones. However, quite a few significant earthquakes have also occurred in the Himalayan belt before 19$^{th}$ century. These are the 1555 (M≈7.6) earthquake of Srinagar (J & K), 1720 and 1803 (M≈7.5, 8.1) earthquakes of Uttarakhand, 1833 (M≈7.7) earthquake of Nepal, 1916 (M≈7.3) earthquake of Uttarakhand, 1936 (M≈7.0) earthquake of west Nepal (Bilham and Ambraseys, 2005). The other important strong to moderate earthquakes are 1945 Chamba Earthquake (M≈6.5), 1975 Kinnaur Earthquake (M≈6.5), 1980 Dharchula Earthquake ($m_b$=6.0), 1980 Jammu-Kathua earthquake ($m_b$=5.5), 1986 Dharamshala Earthquake ($m_b$=5.5), 1988 Bihar-Nepal earthquake ($m_b$=6.6), 1991 Uttarkashi Earthquake ($m_b$=6.4), 1999 Chamoli Earthquake ($m_b$=6.8), 2005Kashmir Earthquake ($M_W$=7.6) and 2011 Sikkim Earthquake ($M_W$=6.9). Most of the earthquakes in this region are of shallow focus (0-40 km depth) and few having depth in the range between 41 km to 255 km.

## 3. Zoning approach

### 3.1 Delineation of seismogenic zones

For the purpose of delineation of seismogenic zones, spatial occurrences of earthquakes and various tectonic features have been carefully scrutinized. The adjoining parts occurring south of Himalayan mountain belt as well as areas of trans-Himalayas and southern Tibet also assume tectonic significance having earthquake potentials in view of its vicinity to the main Himalayan orogenic belt. Considering above facts adjoining regions of the main Himalayan belt has also been considered to include as seismic zones in this study. Based upon the seismicity, tectonics and earthquake dynamic processes, the region has been divided into 22 seismogenic zones. The delineated siesmogenic zones along with seismicity and tectonic features are shown in figure 2. The earthquake data set are obtained from various agencies viz., International Seismological Center (ISC), U.K catalog of seismic events from 1720-1972, National Earthquake Information Center (NEIC), USGS, USA catalog of seismic events from 1973-2011 and India Meteorological Department (IMD) catalog of seismic events from 1552-2011. In addition to global catalogs, some local catalogs prepared by Oldham (1883) and Iyengar et al. (1999) are also considered. The preparation of a homogenous earthquake catalog for a seismic region needs regressed relations for conversion of different magnitudes types, e.g. mb, Ms, to the unified moment magnitude Mw. In particular, the regional relations suggested by Das et al., 2012 and 2013 for Himalayan region for conversion of intensity and body wave magnitude to moment magnitude has been employed. Declustering i.e. removal of dependant events represented by foreshocks and aftershocks from the earthquake catalogue has been done following Gardner and Knopoff (1974) approach considering a specified time-space windows. Declustering eliminated 25% events from the catalog.

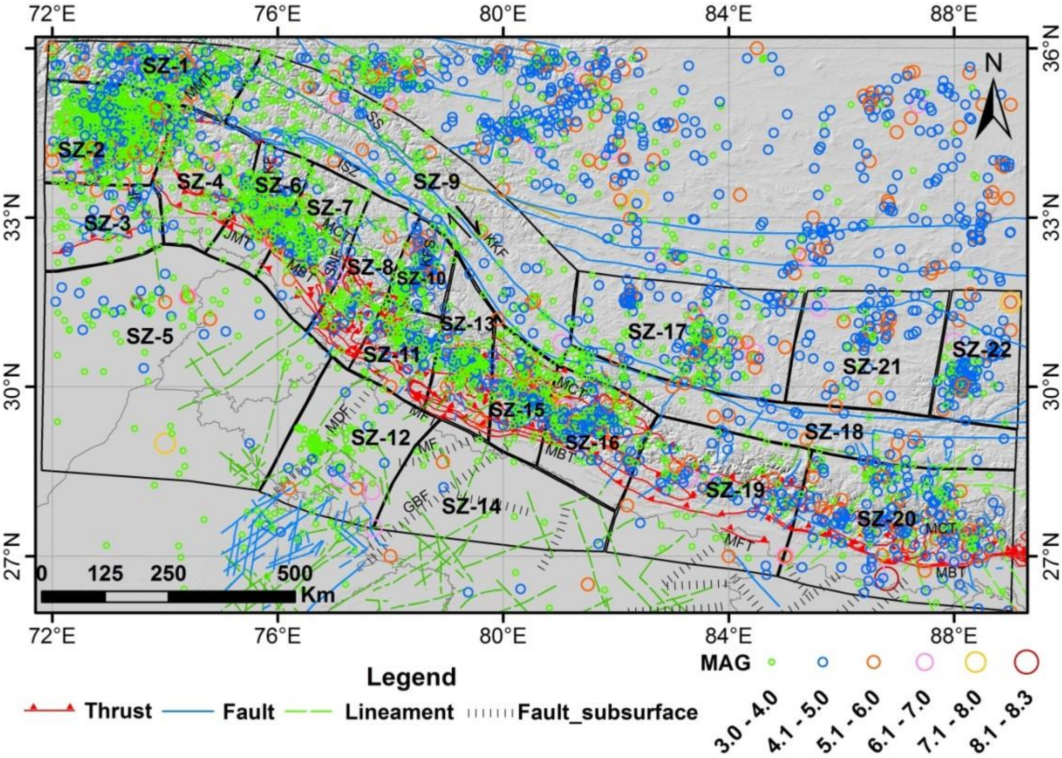


Figure-2 Demarcation of seismogenic zones based on geology, tectonics and seismicity.

3.2 Estimation of seismic hazard parameters and maximum magnitude ($\boldsymbol{m_{max}}$)

Magnitudes of completeness ($M_c$), Gutenberg-Richter (G-R) recurrence parameters ('b' and 'a') values have been estimated for each seismogenic zone from the homogenized earthquake catalog. The seismic hazard parameters are computed using Entire Magnitude Range Method (EMR) and Maximum Curvature method, though it slightly underestimate the magnitude of completeness (Woessner and Wiemer, 2005). Maximum magnitude is defined as the upper limit of magnitude for a given seismogenic zone or entire region. As $m_{max}$ reflects maximum potential of strain released in the scenario earthquake hence it plays vital role in probabilistic seismic hazard assessment. For $m_{max}$ estimation empirical formula suggested by Kijko (2004) is used. Both historical and instrumental seismicity data has been incorporated to determine $\boldsymbol{m_{max}}$ .



 

## 4. Zone Free Approach

4.1 Kernel estimation for seismicity

Kernel estimation method in seismic activity rate estimation is also known as zone-free method since they implement a kernel function for spatial smoothing of seismicity data. Kernel Density Estimation (KDE) is an important smoothing technique which estimates the probability density function of a random variable with a non-parametric approach. For this discriminant analysis, goodness-of-fit testing, hazard rate estimation, intensity function estimation and regression methods are used. In zone-free method, a grid of point sources (nodes) is considered around the site of interest. The activity rates for each magnitude interval are determined according to a magnitude-dependent smoothing procedure and this smoothing procedure is applied to the epicenters of earthquake catalog. These activity rates are calculated from the density and proximity of earthquake events spreading within that magnitude range. Woo's (1996) method uses concepts from fractal geometry, and it describes a seismicity is spatially non-uniformly distributed. In kernel methods, contribution of each earthquake to the seismicity of the regionis smeared over a distance through a magnitude dependent relation described by a kernel function K. In Woo's (1996) approach, the kernel function is described by a multivariate probability density function expressed by the following equation (Vere-Jones 1992):

$$K = \frac{n-1}{\pi H^2}\left[1 + \left(\frac{r}{H}\right)^2\right]^{-n}$$

where 'r' is known as the epicentral distance and 'n' is called as "kernel fractal scaling index," which increases with the proximity of epicenters. Its value lies in the range 1.5 and 2; 'H' is the bandwidth for normalizing epicentral distances and is also a function of magnitude.

By summing over all events of the earthquake catalog, the cumulative activity rate density, 'λ', is computed for each magnitude bin, from the minimum magnitude of engineering interest to the maximum magnitude of the catalog, and for each point source of the mesh. Once the activity rate of each magnitude class has been calculated for each point source in the mesh, a GMPE is employed and the hazard is computed by summing over each point source as in the standard Cornell's method.

Kernel bandwidth for every magnitude bin is determined using nearest neighborhood method by force fitting power law (Woo, 1996) and is given by equation, $H = ce^{dM}$ where 'c' and 'd' are two constants to be determined on the basis of the location of the epicenters of the earthquake catalog and M is the moment magnitude. Using the earthquake epicenters within the study area, the kernel parameters are estimated according to the procedure proposed by Molina et al. (2001). Estimated bandwidth parameters are, c=0.45 and d=0.83. In this study, we used Visual Cumulative (VC) method (Tinti and Mulargia, 1985) to check the completeness period (effective observational time period).

## 5. Moment slip rate method

The earthquake process can be measured in the form of rock deformation or rate of developed strain. The strain rate varies from about $10^{-6}$ per year in the seismically active areas and low up to $10^{-13}$ per year in continental regions which is relatively stable. The fault activity rate is derived through recoding the earthquake occurrence over a period of time using frequency-magnitude relations. This becomes difficult especially if the frequency of earthquake occurrence is considerably low but if the region has potential threat, then in such cases the seismicity can be derived from the slip rate based on the model by Bungum (2007).

The geological slip rate is related to the occurrence rate of the earthquake (N), which can be derived from the geomorphologic, paleoseismic study and GPS measurements. It has been found by GPS measurements that Indian and Tibetan (part of Eurasian plate) tectonic plates are undergoing convergence with the rate of about 20±3 mm/yr (Bilham, 2001) in Nepal, in the western Himalaya the rate is of 14±1 mm/yr (Banerjee and Burgmann, 2002), in eastern Nepal the slip rate is 17±1.5 mm/yr (Lave et al., 2005). England and Molnar (1997) suggested that there is an increase in rate of convergence from 10 ± 2 mm/yr in the western



 

Himalaya in the region west of 74°, to 17 ± 8 mm/yr in northwest part of India between 74°–78°E and as high as 25±10 mm/yr east of 88° E.

5.1 Estimation of fault activity rate from slip rates

The earthquake occurrence rate or mean annual rate of exceedance is related to the geological slip rates. If slip rates of individual faults are available from different sources, it is possible to calculate the seismicity for an area sources from the moment slip rate. The cumulative occurrence relationship is stated as below (Chinnery and North, 1975).

$$N(M) = 10^{(a1-bM)} H(M_{max} - M)$$

In the above equation H (.) means Heaviside step function. The nature of truncation indicates that the model is saturated in larger earthquake magnitudes. Considering all of the faults slip is due to the earthquake, then the total rate of moment release (i.e. moment per year), $M_0^T$ is a function of the slip rate (annual movement) occurred at the fault and expressed as $M_0^T = \mu S A$ (Brune, 1968). Here S means annual slip or slip rate. Anderson and Luco (1983) have derived a relationship for the estimation of the number of earthquakes N above the magnitude of lower bound (usually around 4–5) on a fault.

$$N_1(M) = \left(\frac{\bar{d}-\bar{b}}{\bar{d}}\right)\left(\frac{S}{\beta}\right) e^{\bar{b}(M_{max}-M)} e^{-\left(\left(\bar{d}/2\right)M_{max}\right)}$$

Where $\bar{b} = b(\ln(10))$, $\bar{d} = d(\ln(10))$, $\beta = \sqrt{(\alpha M_0(0))/(\mu W)}$, α=D/L and $M_0$ (0) means seismic moment for $M_s$=0

## 6. Ground motion prediction equations

Generally, region specific attenuation relationships are preferred for estimation of ground motion, however in absence of these, global relations can be used with similar conditions. As Himalaya is characterised by shallow crustal earthquakes, the ground motion prediction equations are selected according to the suitability parameters. Several attenuation relationships have been developed considering worldwide database for the shallow crustal earthquakes which mainly includes Zhao et al. (2006), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), Akkar and Bommer (2010) have been used to estimate PGA.

## 7. Seismic hazard estimation

The methodology developed by Cornell (1968) for PSHA is applied for the estimation of seismic hazard in terms of PGA for 10% and 2% probability of exceedance in 50 years. In this method, the annual rate of ground motion exceeding a specified value is computed to account for different return periods of the hazard. The probability of exceeding a particular value of a ground motion parameter z, 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 that particular location (Kramer, 2003). The process is repeated for all possible magnitudes and locations. The probability of exccedance is given as

$$E(z) = \sum_{i=1}^{N} \alpha_i \int_{m_0}^{m_u} \int_{r_0}^{r_0} f_i(m) f_i(r) P(Z\rangle z|m,r) dr dm$$

E(z) is the expected number of exceedances of ground motion level z during a specified period of time t, $\alpha_i$ is the mean rate of occurrence of earthquakes between lower and upper bound magnitudes ($m_o$ and $m_u$) in the i th source, $f_i$(m) is the probability density distribution of magnitude (recurrence relationship) within source I, $f_i$ (r) is the probability density distribution of site to source distances, P(Z⟩ z∣m, r) is the probability that a given earthquake of magnitude m and distance (epicentral) r will exceed ground motion level z.



 

## 8. Result

The study area is divided into small grids of size 0.2°×0.2° and PGA has been computed at the centre of all the grid points for return period of 475 years and 2475 years (i.e., 10% and 2% probability of exceedance in 50 years) and ground motion distribution is shown in the form of zones.

Zoning method: For 10% probability of exceedance in 50 years (return period of 475 years), the PGA values vary from 0.10g to 0.35g for NW and central Himalayan region. However, for 2% probability of exceedance in 50 years (return period of 2500 years), the PGA varies from 0.17g to 0.59g (Figures 3a & b). Highest PGA is observed in the western part of Nepal and varies from 0.52g to 0.59g. PGA value of 0.47g to 0.52g is observed around Kaurik fault system.

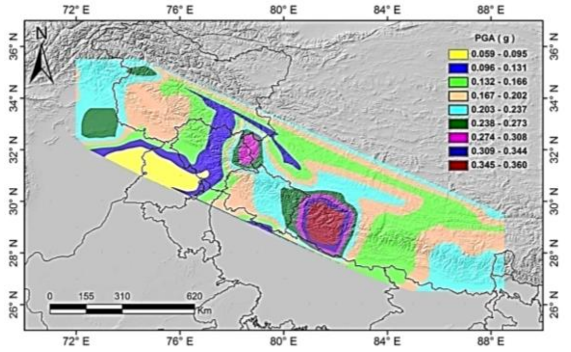


Figure 3a-Mean peak ground acceleration for 10% probability of exceedance in 50 years

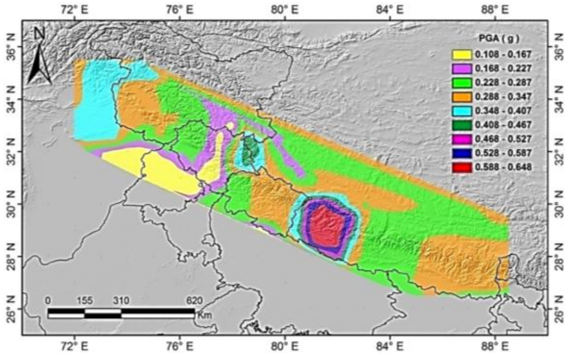


Figure 3b-Mean peak acceleration for 2% probability of exceedance in 50 years

Zone free method: For 10% probability of exceedance in 50 years (return period of 475 years), the PGA values vary from 0.02g to 0.30g for Northwest and Central Himalayan region (Figure 4a). However, for 2% probability of exceedance in 50 years (return period of 2475 years), the PGA varies from 0.10g to 0.55g (Figure 4a & b). Westernmost part of Nepal and eastern part of Uttarakhand exhibit higher level of ground motions.

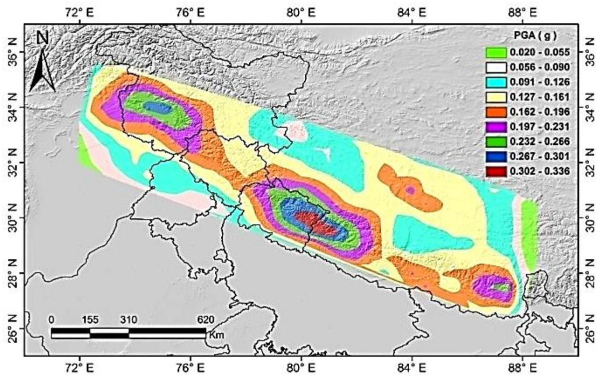


Figure 4a-Mean peak ground acceleration for 10% probability of exceedance in 50 years

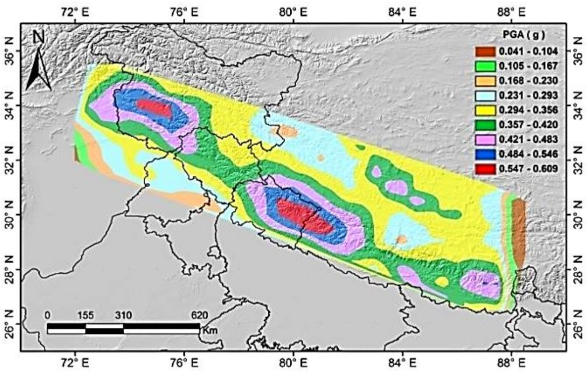


Figure 4b-Mean peak ground acceleration for 2% probability of exceedance in 50 years.

Moment slip rate method: For 10% probability of exceedance in 50 years (return period of 475 years), the PGA values vary from 0.1g to 0.41g (Figure 5a). However, for 2% probability of exceedance in 50 years (return period of 2475 years), the PGA varies from 0.24g to 0.69g (Figure 5a & b).



 

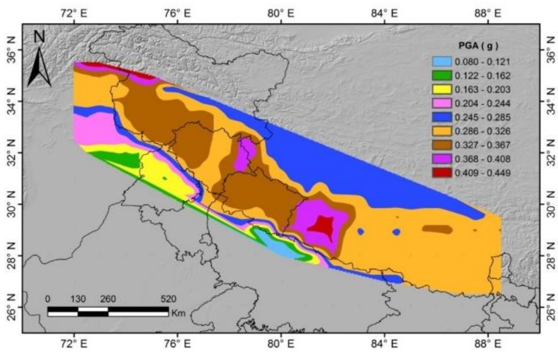


Figure 5a-Mean peak ground acceleration for 10% probability of exceedance in 50 years.

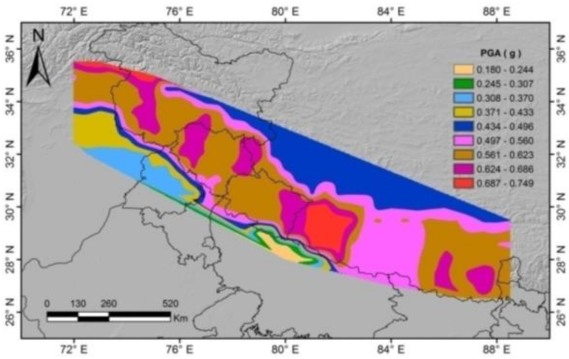


Figure 5b-Mean peak ground acceleration for 2% probability of exceedance in 50 years.

PGA at 10% probability of exceedance in 50 yr from different studies in the northwest and central Himalaya are shown in Table 1. All the above investigations are either based on inappropriately homogenized earthquake catalog or heterogeneous catalogs with old attenuation equations. In this study, an improved homogenization technique for magnitude conversion has been used with updated attenuation equations for estimation of strong ground motion.

Table-1 Estimated peak ground acceleration for Himalayan region with 10% probability of exceedance in 50 yrs (return period 475 years) from different studies

| Research byAuthor/Agency | Min PGA(g) | Max PGA(g) |
|---|---|---|
| Khattri et al., (1984) | 0.40 | 0.70 |
| Bhatia et al., (1999) | 0.05 | 0.40 |
| Mahajan et al., (2010) | 0.02 | 0.75 |
| NDMA, Govt. of India, (2011) | 0.06 | 0.20 |
| Nath and Thingbaijam (2011) | 0.12 | 0.60 |
| This study | | |
| Zoning method | 0.10 | 0.35 |
| Zone free method | 0.06 | 0.30 |
| Moment slip method | 0.12 | 0.41 |

PSHA results for similar convergent tectonic belts viz., Iran and Turkey are as follows. Seismic hazard assessment of Iran by Tavakoli and Ghafory-Ashtiany (1999) estimated an average PGA of 0.45g for a return period of 475 years. Ground acceleration values in rock varies between 0.20g and 0.40g with an exceedance probability of 10% in a 50-year return period for the city of Ankara, Turkey (Ozmen and Basbugerkan, 2014). Erdik et al. (1999) calculated the PGA value of 0.2g to 0.7g for Turkey and its surrounding region but for most part of the study area the ground motion value varies from 0.2g to 0.6g. Ground motion estimated for northern Italy covering mountainous region range from 0.125g to 0.150g whereas for whole Italy the ground motion has a range from 0.050g to 0.400g.



 

## 9. Conclusion

The present study aimed to improve the hazard assessment with incorporation of improved magnitude conversion techniques and updated attenuation relations. For 10% probability of exceedance in 50 years (return period of 475 years), the PGA values vary from 0.06g to 0.41g and 2% probability of exceedance in 50 years (return period of 2500 years), the PGA varies from 0.10g to 0.69g as estimated using the three approaches. The present results are higher than the suggested ground motion for Zone-V, which is 0.36g, of seismic zonation map of India.

Zoning method predicted maximum ground motion in the westernmost part of Nepal, in the north-eastern part of Himachal Pradesh (0.52g to 0.59g) for 2475 return period. Second maximum predicted ground motion area falls on the easternmost part of Nepal. The ground motion parameters increases with the increase in annual rate of exceedance for the seismogenic zones and predicted maximum ground motion is governed by the size of zones. Zone free method predicted maximum ground motion in two areas falling in Kashmir valley and eastern part of Uttarakhand and westernmost part of Nepal. Ground motion ranges from 0.10g to 0.55g for 2475 return period. Anisotropic parameter (delta) of the kernel revealed a degree of correlation between the tectonic feature trend and shape of predicted hazard zones. Whereas, moment slip rate method estimates higher level of ground motion (0.24g to 0.69g for 2475 years return period) which may be attributed to the lack in proper data set.

The ground motion conditions as estimated in this work is justifiable in view of expected earthquake potential of the Himalayan tectonic belt.

## References

1. Akkar S, Bommer J J (2010): Empirical equations for the prediction of PGA, PGV, and spectral accelerations in Europe, the Mediterranean region, and the Middle East. *Seismological Research Letters*, 81, 195-206.
2. Anderson J G, Luco J J (1983): Consequences of slip rate constants on earthquake occurrence relations. *Bull. Seism. Soc. Am.*, 73, 471-496.
3. Banerjee P, Burgmann R (2002): Convergence across the northwest Himalaya from GPS measurements. *Geophysical Research Letters*, 29(13), 30(1)-30(4).
4. Bhatia S C, Kumar R M, Gupta H K (1999): A probabilistic seismic hazard map of India and adjoining regions. *Ann. Geofis*., 42(6), 1153-1164.
5. Bilham R (2001): Slow tilt reversal of the Lesser Himalaya between 1862 and 1992 at 78oE, and bounds to the southeast rupture of rupture of the 1905 Kangra earthquake. *Geophysical Journal International*, 144, 713-728.
6. BIS (2016): Earthquake hazard zoning map of India. Criterial for Earthquake resistant Desing of Structures, IS 1893 (Part 1) General Provisions and Buildings, Sixth Revision, Bureau of Indian Standards, New Delhi, www.bis.gov.in, p44.
7. Boore D M, Atkinson G M (2008): Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01s and 10.0s. *Earthquake Spectra*, 24, 99-138.
8. Bozzoni F, Corigliano M, Lai C G, Salazar W, Scandella L, Zuccolo E, Latchman J, Lynch L, Robertson R (2011): Probabilistic seismic hazard assessment at the Eastern Caribbean Islands, *Bull. Seismol. Soc. Am.*, 101(5), 2499-2521.
9. Brune J N (1968): Seismic moment, seismicity, and rate of slip along major fault zones. *J. Geophys. Res.*, 73, 777-784.
10. Bungum H (2007): Numerical modelling of fault activities. *Computer and Geoscience*, 33, 808-820.
11. Campbell K W, Bozorgnia Y (2008): NGA Ground motion model for geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10s. *Earthquake Spectra*, 24(1), 139-171.
12. Chinnery M A, North R G (1975): The frequency of very large earthquakes. *Science*, 190, 1197-1198.



 

13. Chiou B S J, Youngs R R (2008): Empirical Ground Motion Model for the Average Horizontal Component of Peak Acceleration and Pseudo-Spectral Acceleration for Spectral Periods of 0.01 to 10 Seconds. *Earthquake Spectra*, 24(S1), 173-216.
14. Cornell C A (1968): Engineering seismic risk analysis. *Bull Seismol Soc Am*, 58**,** 1583-1606.
15. Das R, Wason H R, Sharma M L (2012a): Magnitude conversion to unified moment magnitude using orthogonal regression relation. *Journal of Asian Earth Sciences*, 50(2), 44-51.
16.Das R, Wason H R, Sharma M L (2013): General Orthogonal Regression relation between body and moment magnitudes. *Seismological Research Letters*, 84(2), 219-224.
17. England P C, Molnar P (1997): The field of crustal velocity in Asia calculated from Quaternary rates of slip on faults. *Geophy J. Int.*, 130, 551-582.
18. Erdik M, Biro Y A, Onur T, Sesetyan K, Birgoren G (1999): Assessment of earthquake hazard in Turkey and neighboring. Annals of Geophysics, 46, 1125-1138.
19. Frankel A (1995): Mapping seismic hazard in the Central and Eastern United States. *Seism. Res. Lett.*, 66(4), 8-21.
20. Gansser A (1977): The great Suture Zone between Himalaya and Tibet. *A Preliminary note Acc Sci Terre Himalayas CNRS*, 268, 181-192.
21. Gardner J K, Knopoff L (1974): Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? *Bull Seismol Soc Am*, 64, 1363-1367.
22. Kagan Y Y, Jackson D D (2000): Probabilistic forecasting of earthquakes. *Geophys. J. Int.*, 143, 438-453.
23.GSI (2000): Seismotectonic Atlas of India and Its Environs. Geological Survey of India.
24.Iyengar R N, Sharma D and Siddiqui J M (1999): Earthquake history of India in medieval times. *Ind J Hist Sci*, 34(3),181-237.
25.Khattri K N, Rogers A M, Perkins D M, Algermissen S T (1984): A seismic hazard map of India and adjacent area. *Tectonophysics*, 108, 93-134.
26. Kijko A (2004): Estimation of the maximum earthquake 681 magnitude, Mmax. *Pure Appl. Geophys*, 161, 1655-1681.
27. Kramer S L (2003): Seismic hazard analysis, Chapter 4, Geotechnical Earthquake Engineering, Prentice Hall International Series, Pearson Education, Delhi, 106-142.
28. Lave J, Yule D, Sapkota S, Basan K, Madden C, Attal M, Pandey R (2005): Evidence for a Great Medieval Earthquake (1100 A.D.) in the Central Himalayas, Nepal. *Science*, 307, 1302-1305.
29. Mahajan A K, Thakur V C, Sharma M L, Chauhan M (2010): Probabilistic Seismic Hazard map of NW Himalaya and its adjoining area, India. *Nat Hazards*, 53, 443-457.
30. Menon A, Ornthammarath T, Corigliano M, Lai C G (2010): Probabilistic seismic hazard macrozonation of Tamil Nadu in Southern India, *Bull. Seismol. Soc. Am.*, 100(3), 1320-1341.
31. Molina S, Lindholm C D, Bungum H (2001): Probabilistic seismic hazard analysis: zoning free versus zoning methodology. *Bollettino di Geofisica*, selected papers from the 27th ESC, Lisbon, 42, 19-39.
32. Nath S K, Thingbaijam K K S (2011): Peak ground motion predictions in India: An appraisal for rock sites. *Journal of Seismology,*15**,** 295-315.
33. Nath S K, Thingbaijam K K S (2012): Probabilistic seismic hazard assessment of India. *Seismological research letters*, 83, 135-149.
34. NDMA (2011): Development of probabilistic seismic hazard map of India; 2011 Technical Report, National Disaster Management Authority (NDMA), Government of India, New Delhi.
35. Oldham T (1883): A catalog of Indian earthquakes from the earliest times to the end of 1869 AD. *Mem. Geol. Surv India*, XIX Part-3.
36. Ordaz M, Martinelli F, Aguilar A, Arboleda J, Meletti C, D'Amico V (2015): Crisis 2015: Program for computing seismic hazard, Ver. 4.1, Instituto de Ingeniería at UNAM, México.
37. Ozmen B, BaşbugErkan B B (2014): Probabilistic earthquake hazard assessment for Ankara and its environs. *Turkish J Earth Sci.*, 23, 462-474.



 

38.Patil N S, Das J D, Kumar A, Rout M M, Das R (2014): Probabilistic seismic hazard assessment of Himachal Pradesh and adjoining regions, *Journal of Earth System Science*, 123(1), 49-62.
39. Reiter L (1990): Earthquake hazard analysis:Issues and insights. Columbia University Press, USA. p254.
40. Seeber L, Armbruster J G (1981): Great detachment earthquakes along the Himalayan arc and the long term forecasting in earthquake prediction- An international review, edited by D.E. Simpson and Richards P.G., Maurice Ewing Series 4. *The American Geophysical Union*, 259-277.
41. Tavakoli B, Ghafory-Ashtiany M (1999): Seismic hazard assessment of Iran. Annali di Geofisica, 42, 1013-1021.
42. Tinti S, Mulargia F (1985): Completeness analysis of a seismic catalog. *Ann Geophys*, 3, 407-414.
43.Valdiya K S (1980): Geology of Kumaun Lesser Himalaya. *Wadia Institute of Himalayan Geology*, Dehradun, 290-291.
44. Vere-Jones D (1992): Statistical methods for the description and display of earthquake catalogs. In: Walden AT, Guttorp P (eds) Statistics in the environmental and earth sciences. Edward Arnold, London, 220-246.
45.Wiemer S and Wyss M (2001): ZMAP: A Tool for Analyses of Seismicity Patterns. A cookbook, p-57
46. Woessner J and Wiemer S (2005): Assessing the Quality of Earthquakes Catalogs: Estimating the Magnitude of Completeness and Its Uncertainty. *Bull Seismol Soc Am*., 95(2), 684-698.
47. Woo G (1996): Kernel estimation methods for seismic hazard area source modeling. *Bull. Seismol. Soc. Am*., 86, 353-362.
48. Zhao J X, Zhang J, Asano A, Ohno Y, Oouchi T, Takahashi T, Ogawa H, Irikura K, Thio H K, Somerville P G, FukushimaY, FukushimaY (2006): Attenuation Relations of Strong Ground Motion in Japan Using Site Classification Based on Predominant Period. *Bulletin of the Seismological Society of America*, 96 (3), 898-913.



 