17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

PROBABILISTIC SEISMIC HAZARD ASSESSMENT OF NEPAL FOR REVISION OF NATIONAL BUILDING CODE(NBC)-105

D. Chamlagain[(1)], G. P. Niroula[(2)], P.N. Maskey[(3)], M.K. Bista[(4)], M.R. Tamrakar[(5)], B.K. Gautam[(6)], S. Ojha[(7)], R. P. Dhakal[(8)], I.P. Acharya[(9)]

[(1)]Assistant Professor, Department of Geology, Tri-Chandra M. Campus, Tribhuvan University, deepakchamlagain73@gmail.com
[(2)]Lecturer, Kathford International College of Engineering and Management, Tribhuvan University, Nepal, govind.niroula@gmail.com
[(3)]Professor, Institute of Engineering, Tribhuvan University, Nepal, pnmaskey@live.com
[(4)]Consultant Engineer, National Reconstruction Authority, Nepal, mbistey@gmail.com
[(5)]Consultant Engineer, National Reconstruction Authority, Nepal, minesh.tamrakar@gmail.com
[(6)]Consultant Engineer, National Reconstruction Authority, Nepal, me@engineerbipin.com.np
[(7)]Consultant Engineer, National Reconstruction Authority, Nepal, swopnilojha@gmail.com
[(8)]Professor, University of Canterbury, New Zealand,rajesh.dhakal@canterbury.ac.nz
[(9)]Associate Professor, Institute of Engineering, Tribhuvan University, Nepal, indragb@gmail.com

Abstract

Being located in seismically active Himalayan mountain belt, Nepal has been the locus of many devastating earthquakes. The Mw 8.4 Bihar-Nepal earthquake of 1934 AD was the biggest earthquake disaster in Nepal that had highlighted the need of a building seismic design code for safer construction. Though the necessity was realised earlier, Nepal developed its first National Building Code (NBC-105) only in 1994 after the 1988 Mw 6.9Udayapur earthquake in eastern Nepal. In April 2015, central Nepal witnessed the Mw 7.8 Gorkha earthquake, which had epicentre at Barpak village of Gorkha district, about 75 km west of Kathmandu. The ground mtions recorded at soft soil sites in Kathmandu Valley clearly show strong site effect resulting in high energy in long period, i.e. at 3s to 5s. A comparative study has revealed that, at least in Kathmandu Valley, the observed ground motions exceeded the seismic design demand proposed by NBC-105 for some period ranges. Unsurprisingly, the earthquake caused extensive damage to buildings and infrastructures in 14 districts(mostly towards east of the epicentre due to further ruptured directivity effect) and killed 8,970 people. This earthquake also triggered revision of the existing national building code (known as NBC-105)by the Government of Nepal.A key feature of the revision of NBC-105 has been re-assessment of national seismic hazard by adopting a probabilistic approach.

Since the development of NBC-105 in 1994, a large number of studies have been carried on seismo-tectonics, active fault, paleoseismology, seismicity, geodesy etc, which have significantly increased the level of knowledge on seismic sources in the central Himalayas. In addition, after the 2015 Gorkha earthquake, much knowledge is gained on the geometry of the main seismogenic fault, the Main Himalayan Thrust (MHT) also called the Main Frontal Thrust (MFT) at the surface of the Himalayan front. Based on recent researches, in contrast to seismic sources adopted in 1994, a fault source (MHT) and area sources, i.e. northern garbens in Tibet, strike-slip event dominant sources in eastern and western Nepal and a source south of MHT are considered for seismic hazard analysis. As there is no specific Ground Motion Prediction Equation (GMPE) for the Himalayas, based on seismo-tectonics, GMPEs are adopted including Next Generation Attenuation laws. More than two GMPES are used for each source using the logic tree approach. Seismic hazard is computed for 2%, and 10% probability of exceedence in 50 year. In contrast to hazard map of 1994, the zones of relatively higher Peak Ground Acceleration (PGA) i.e. 0.36g to 0.46g are, for 10% probability of exceedence in 50 year, concentrated just above the locked portion of MHT throughout the country. The PGA values gradually decrease towards the north and south of MFT. This pattern of PGA distribution is consistent with the coupling nature of the MHT in the Himalayas.

Keywords: Seismic Hazard Assessment; Main Himalayan Thrust (MHT); National Building Code-105; Nepal

1. Introduction

Nepal is centrally located in the seismically active Himalayan mountain belt. Over the last century, the Himalayan arc has been struck by four major earthquakes with magnitude ca. 8.5, e.g. 1897 (Shilong earthquake) 1905 (Kangra earthquake) 1934 (Bihar-Nepal earthquake) 1950 (Assam earthquake) [1] and many other moderate size events. These events killed thousands of people in the region perishing hard-won economy of the Himalayan region. On 25th April, 2015 the Mw 7.8 Gorkha earthquake with epicentre at Barpak village of Gorkha district hit central Nepal killing 8,970 people and damaging around one million houses at different levels [2]. The ground motion characteristics of the Gorkha earthquake was different to that of the other Himalayan earthquakes. The peak ground acceleration (PGA) measured at bed rock in Kirtipur is higher (0.241g) than the PGA at soil site in Kantipath (0.155g) measured inside the Kathmandu Valley The long period ground motion was amplified at higher period (around 3-5 s) [3]. The seismic sequence was arrested in between Barpak and border between Sindhupalchok and Dolakha districts after the major aftershock of 12th May, 2015 with magnitude Mw 7.3. The main shock of the Gorkha seismic sequence had shown distinct rupture directivity effects as a result the intensity of damage was observed increasing towards away from the epicentre.

During the Gorkha earthquake, it was understood that there was strong modification of the ground motion resulting into strong shaking at long period causing severe damage to tall buildings in the Kathmandu Valley. The design spectra of National Building Code (NBC-105) along with the response spectra developed from the measured ground motion data of the Gorkha earthquake clearly show that at least in Kathmandu Valley the observed ground motion parameters exceeded the code parameters demanding the revision of existing building code (Fig. 1.). Based on the performance of the buildings during the 2015 Gorkha earthquake, It has been realized that the existing NBC may not be able to withstand seismic loading during the impending devastating earthquake of similar or greater size in the region. In addition, there are many new data on seismicity, seismogenic fault, characterization of its geometry and geodetic data, which has provided an ample opportunity to prepare a probabilistic seismic hazard map. In this context, National Reconstruction Authority, Government of Nepal has taken initiative for the revision of the existing building code, NBC-105. In this contribution, a new probabilistic seismic hazard map adopted for revision of NBC-105 is presented.

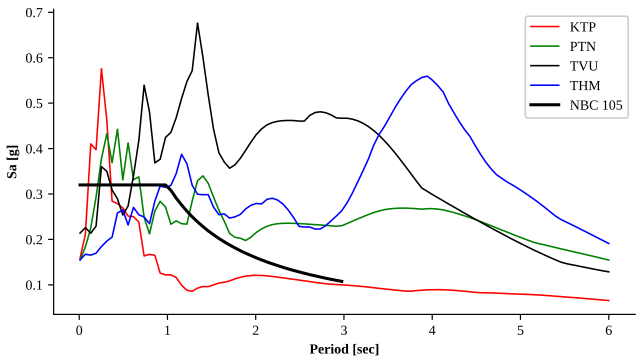

Fig. 1. Comparison of the National Building Code (NBC 1994) design spectra with the response spectra (at 5% damping) of the main shock of the Gorkha earthquake measured at rock site, Kirtipur(KTP) and at soil site (PTN, THM, and TVU) (Data source: [3]).

2. Seimo-tectonics and Seismicity of Nepal

2.1. Seismo-tectonics

The major tectonic framework of Nepal Himalaya to the south of South Tibetan Detachment System (STDS) is controlled mainly by three major thrust faults, e.g. from north to south the Main Central Thrust (MCT)

Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) (Fig. 2). These thrust faults with a north to south propagation direction are running the entire length of Nepal Himalaya and are generally inferred to be the splay thrusts of the Main Himalayan Thrust (MHT), which marks the underthrusting of the Indian Plate (Fig. 2) [4 and 5]. The geometry of the MHT is characterized by mid-crustal ramp, which is connected by southern and northern flat. The southern flat is locked during the inter-seismic period causing an accumulation of elastic stress, which is usually released during microseismic events in Nepal Himalaya. The major (great) earthquakes are generally occurred along the southern flat and hinge of the ramp just front of the Higher Himalaya and deformation is propagated along the MFT, a southern expression of MHT.

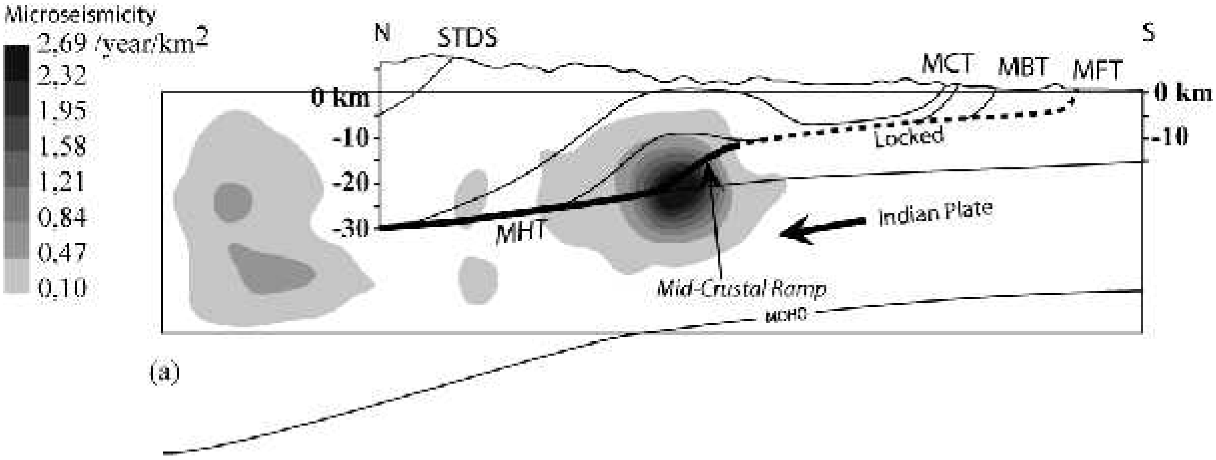

Fig. 2. The geological cross-section of Nepal Himalaya with microseismicity [5].

2.2. Seismicity

In Nepal Himalaya, the historical accounts of the earthquake since thirteen century has revealed that Nepal has been shaken by ten major destructive earthquakes [6]. The reported damage patterns have indicated that these events were most likely sourced within the Himalayas. The first reported historical great earthquake was of 1255 [6, 7]. The destruction was massive particularly in the Kathmandu Valley. About one-third of the population was killed and mortally wounded King Abhaya Malla died eight days after the earthquake. Another large earthquake hit central Nepal in 1344 causing massive damage mostly in Kathmandu Valley and again took the life of the King. Further, the damaging event of the earthquake occurred in central Nepal in 1833 and was preceded by two strong foreshocks [8, 9, 10]. Though little is known, this earthquake followed the event of 1808 that damaged few houses in Bhaktapur (eastern part of Kathmandu valley). After 33 years, an earthquake of magnitude of Mw-macro 7.2±0.2 was occurred in 1866. Since then first instrument great earthquake of magnitude Mw 8.4 badly hit Nepal in 1934 [11]. The damage of the earthquake was extreme in eastern half of Nepal to northern part of India and killed more than 10,000 people.

Intense microseismicity and moderate earthquake events throughout Nepal Himalaya cluster along the foothills of the Higher Himalaya [5]. It makes an E-W trending zone as shown in Figure 3. In western Nepal it lies between 80.5^{o} E and 82.5^{o}E whereas in central Nepal it is bounded between longitudes 82.5^{o}E and 86.5^{o}E. The eastern Nepal cluster is characterized by higher level of events between 86.5^{o}E and 88.5^{o}E. In central Nepal the cluster has a rounded form and is located in the vicinity of the flat-ramp transition of the MHT (Fig. 3 and 4). The cluster in western Nepal shows an elongated form and is nearly horizontal. These clusters reflect stress accumulation in the interseimic period, during which the MHT beneath the Higher Himalaya remains locked and mid-crustal ramp acts as a geometrical asperity [5]. Beside these, there are number of moderate size earthquakes in the recent time. The Udayapur earthquake of 1988 was the moderate event at depth of about 50 km that killed 721 people in eastern Nepal. Recent Gorkha earthquake of 2015 was the biggest earthquake disaster after the 1934 event that originated at the depth of 15 km just above the hinge of the mid-crustal ramp, which killed about 9000 people in central Nepal.

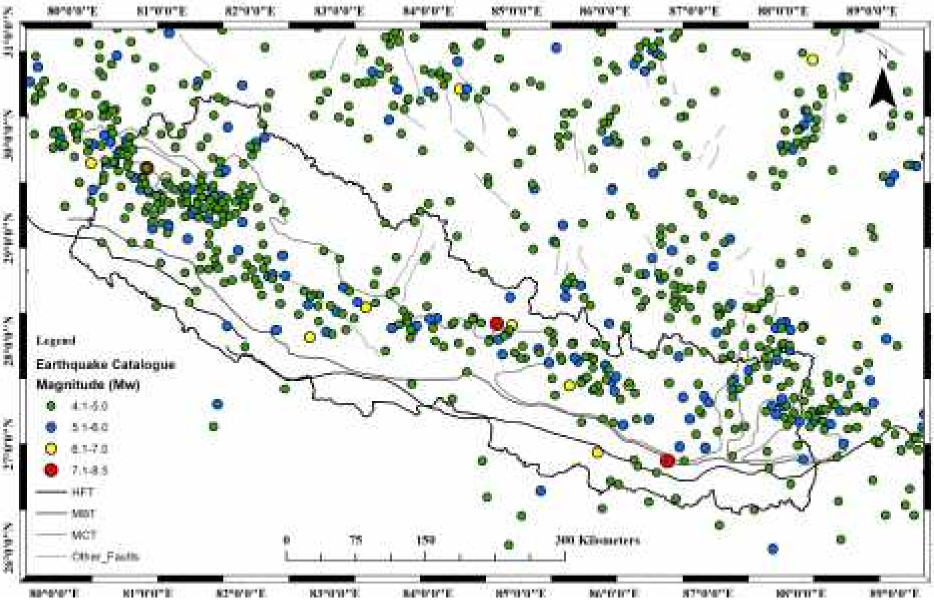

Fig. 3. Major fault line and de-clustered earthquake distribution (1100-2017 AD) map considered for the hazard computation (source: ISC).

3. Probabilistic Seismic Hazard Assessment (PSHA)

A methodology developed by Cornell [12] for PSHA is used to provide a framework in which uncertainties in size, location and rate of recurrence of earthquakes can be considered to provide a probabilistic understanding of seismic hazard. In the following sections, details of earthquake catalogue, source characterization, recurrence parameter and ground motion prediction equations are described.

3.1. Earthquake catalogue

Nepal has very short history of earthquake monitoring through its limited seismic stations network. Therefore, for hazard mapping catalog of International Seismological Centre (ISC) is used as this incorporates wide sources of data e.g. USGS, IRIS and other sources (Fig. 3). This catalog also consists of data acquired by National Seismological Centre (NSC) and historical data archived from chronicles and paleoseimological studies throughout the Himalayas. NSC catalog provides better data for Nepal, however, the region beyond Nepalese territory, the ISC catalog can primarily be used for better constrained data. Thus integrated database have been prepared and used for this study. As the catalog consists earthquake events of different magnitude scale, all events are converted to moment magnitude (M_w) using the following equations given by Scordillis [13].

3.2. Source Characterization

The delineation of seismic source zones should primarily be guided by the occurrence of large earthquakes, planar distribution of all earthquakes above certain level of magnitude, activity of seismogenic fault, shape of isoseismals, intensity distribution, neotectonic activity and regional tectonic frame work. In the past, number of seismic hazard assessments have been carried out in Nepal [14, 15, 16, 17] adopting probabilistic approach. These studies have mostly considered detachment earthquake source, areal source, point source and linear source. However, these studies have not logically explained the bases of source characterization that distinguish one source from the other. In this study, seismic sources are identified based on the earthquake origin, type, magnitude and frequency, seismo-tectonics, neotectonic deformation, nature and activation of seismogenic faults etc. The source zones are broadly divided into two broad categories; fault source (or subduction interface) and aerial sources and are briefly described below.

3.2.1. Fault source (subduction interface)

Main Himalayan Thrust (MHT)

As discussed in the previous section, there are numbers of active faults that are associated with major crustal thrust faults of Nepal. Among them MHT that absorbs about 20 mm/yr of convergence out of 40 mm/yr is continuously building up elastic strain throughout the Himalaya [4,18]. In terms of seismic reactivation of the seismogenic fault, MHT is the most active as it has history of generation of micro to great earthquakes throughout the Himalaya, e.g. 1934 Bihar-Nepal earthquake (Mw 8.4), 1950 Assam earthquake, 2005 Pakistan earthquake, 1905 Kangara earthquake, 2015 Gorkha earthquake (Mw 7.8) etc. The analysis of seismicity in Nepal Himalaya has also shown that the MHT has potential of generating earthquake of Mw 9±0.2 [19].

Although there is a common consensus among the seismologists that the MHT is the key seismogenic fault in the Himalaya, there remains dispute on its deep structure beneath the Himalaya. Recently, two works with differing ideas on geometry of the MHT have been published. Elliot et al. [20] have proposed existence of single ramp along the MHT using structural analysis together with GPS based inter-seismic and co-seismic displacements due to the 2015 Gorkha earthquake. In contrast, Hubbard et al. [21] proposed a structural cross-section along with a three-dimensional model of the MHT with double ramps; i.e. moderate and deeper ramps by comparing slip patches of the 2015 Gorkha earthquake. Though there is different school of thoughts on geometry of MHT and its strike variation characteristics, the geometrical model proposed by Elliot et al. [20] is considered and incorporated in the code accordingly (Fig. 4).

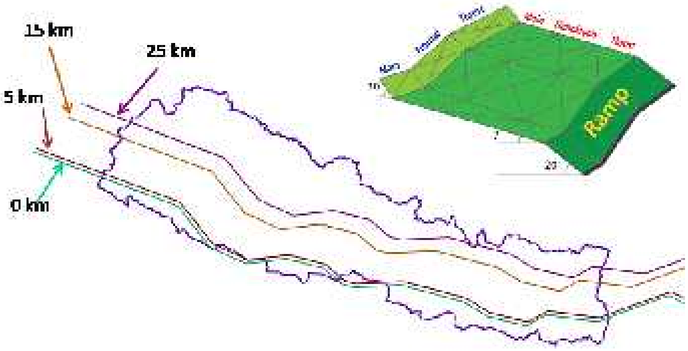

Fig. 4. Geometry of the MHT (subduction interface) considered as seismic source. The colored line with number shows the depth of the fault plane to introduce fault geometry in the code. The MHT fault plane is divided into several triangular elements for computational purpose as shown in the inset.

3.2.2. Areal Source

Beside the fault source, six additional areal sources are considered in this study based on seismicity, earthquake type and focal depth and seismo-tectonics (Fig. 5).

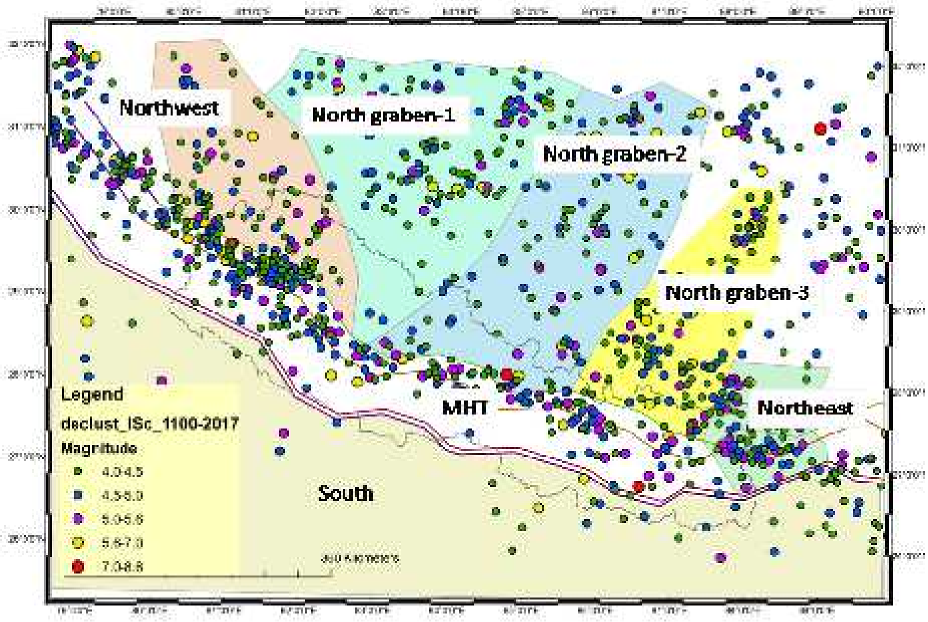

Fig. 5. De-clustered seismicity and different seismic source considered for seismic hazard assessment.

Northern Graben

Grabens of southern Tibet and the Himalaya represent the Cenozoic extensional tectonic phase, which has affected the whole Tibet and northernmost part of the Himalaya. These grabens and associated other normal faults in the southern Tibet are characterized by the normal type earthquake with strike-slip component at the approximate depth of 15 km [22]. Thus, the earthquake in and around the graben faults may cause the seismic hazard in Nepal. Three graben sources (North graben-1, -2 and -3) are, therefore, considered in this study (Fig. 5).

Northeast and Northwest source

A distinct cluster of seismic events is conspicuous in northeast Nepal. This cluster is connected with inferred strike-slip faults that connects the Shilong Plateau [23]. These events are clearly of strike-slip type with focal depth greater than 50 km, i.e. below the subduction interface. For hazard assessment, northeast seismic belt is considered as a separate source. Similarly, Northwest Nepal is also characterized by cluster of both strike-slip and normal type earthquakes with focal depth of around 20 km [24]. This zone is also considered as a seismic source that may cause severe shaking in the western Nepal (Fig. 5).

Southern Source

The seismic events are not frequent in the Indo-Gangetic plain like in the Himalayan belt. However, there are occasionally earthquakes of moderate magnitude. These earthquakes are of all types and are probably due to flexure of converging Indian Plate. To incorporate the shaking of these earthquakes in the hazard computation, the region is also considered as a separate earthquake sources (Fig. 5). The maximum magnitude of the earthquake for each source zone is given in Table 1. For multiple depths, probability approach is adopted.

Table 1-Maximum magnitude and seismogenic depth considered for the different seismic source.

SN	Seismic Source	Maximum Magnitude	Depth (km)	Reference
1	Subduction source (MFT/MHT)	M 8.5	Up to 25	Based on earthquake catalog
2	South	M 7	15/20/25	Based on earthquake catalog
3	Northwest	M 7.1	20	>M 7 suggested by Murphy et al. (2014).
4	North graben 1	M7.1	15	Elliot et al. (2010)/2008 Yuitan earthquake M 7.1
5	North graben 2	M 7.1	15	Elliot et al. (2010)/2008 Yuitan earthquake M 7.1
6	North graben 3	M7.1	15	Elliot et al. (2010)/2008 Yuitan earthquake M 7.1
7	Northeast	M7.1	50/60/70	Taplejung-Sikkim earthquake 2011, M 6.9

3.3. Recurrence parameter

Earthquakes with a moment magnitude equal to or greater than 4.0 from 1100 to 2017 were used to estimate the average annual occurrence rate of earthquakes and b values. After declustering [25] the catalog and assessing the completeness [26] . of the data for each source, an annual occurrence rate was computed. The b values were estimated for each seismic source by using the frequency-magnitude relation of Gutenberg and Richter [27].

$\log N = a - bM$

N denotes the cumulative number of earthquakes with magnitude equal to or greater than the specified magnitude M, and *a* and *b* represent the Gutenberg and Richter (G-R) parameters for a particular region. The estimated *b* values are given in Table 2.

Table 2- Computed values of a and b for different source zone.

S.No.	Source	Recurrence parameters		S.No.	Source	Recurrence parameters	
		a	b			a	b
1	South	4.34	1.01	5	Northwest	4.18	0.88
2	NG-1	3.56	0.77	6	Northeast	4.13	0.89
3	NG-2	3.86	0.81	7	MHT	4.07	0.77
4	NG-3	4.95	1.07				

3.4. Ground motion prediction equations (GMPEs)

Since there is no specific GMPEs for the Himalayan region, based on the source characterization, maximum magnitude, seismo-tectonics, earthquake and focal depth three types of GMPEs namely subduction zone, active shallow crust, stable continental area were selected and implemented. In this study, to incorporate fault distance, maximum considered magnitude, time period and shear wave velocity at 30 m depth (Vs_{30})

three GMPEs are adopted for fault source (subduction interface), three for active shallow crust and two for stable continental area (Table 3). These GPMEs also represent the Next Generation Attenuation (NGA) relations. Since these GMPEs do not exactly predict the ground motion for the Himalayan-Tibet region, to minimize the uncertainty due to GMPEs, a logic tree approach is adopted and each GMPEs are assigned with specific weight (Table 3).

Table 3- Characteristics of adopted Ground Motion Prediction Equation (GMPEs)

Tectonic Environment	Ground Motion Prediction Equations	Magnitude range (Mw)	Distance range (Km)	Period range (Sec)	Adopted weight age computation
Subduction Interface (MFT/MHT)	Zhao (2006) [28]	9-May	0-300	0-5	0.33
	Atkinson and Boore (2003) [29]	5-8.5	1-300	0 to 3.03	0.33
	Abrahamson et al. (2016) [30]	9-May	0-300	0-10	0.34
Active Shallow Crust (Northern grabens, Northwest and south)	Abrahamson et al. (2014) [31]	3-8.5	0-300	0-10	0.33
	Chiyou and Youngs (2014) [32]	3-8.5	0-300	0-10	0.33
	Campbell and Bozorgnia (2008) [33]	4-8.5	0-200	0-10	0.34
Stable Content Areas (Northeast)	Atkinson and Boore (2006) [34]	3.5-8	1-1000	0.01-5	0.50
	Tavakoli and Pezeshk (2005) [35]	5-8.2	0-1000	0-4	0.50

4. Results and Discussion

The results of the PSHA are presented in figures 22 and 23 for 2%, and 10% probability of exceedence in 50 years (i.e. return period of 2475, and 475 year) respectively. The contours of PGA are trending almost parallel to the strike of the mountains at least in the middle part of Nepal. However, small patches of relatively higher PGA values are seen along the MFT, which represents the southern expression of MHT. These higher values could be the effect of the hanging wall, which generally shows relatively greater values of PGA at least in the locked portion of the MHT. In contrast, the northern part of Nepal, PGA value is comparatively lower as the area is characterised by low rate of seismicity. The results are different to that of previous studies [14]. As the seismic model for computation considered the locked portion of the MHT fault as a separate fault source, the computed hazard is relatively higher than predicted before. Previous studies in Nepal has shown the higher values of PGA usually follow the higher concentration of the earthquake events [14, 16] and did not correspond with the locked portion of MHT. In contrast, this study has revealed consistent seismic hazard level that approximately follow the locked portion of the MHT. Recent studies [e.g. 16, 36, 37] has given relatively higher values as compared to this study as these studies have used different GMPEs without considering subduction source, i.e. MHT. The trend of PGA contours are consistent with the results of Steven et al. [37]. In the regional context, the obtained results are consistent with the seismic hazard of Pakistan and India [38, 39]. The PGA obtained for 10% probability of exceedence in 50 year has been adopted for revision of NBC-105.

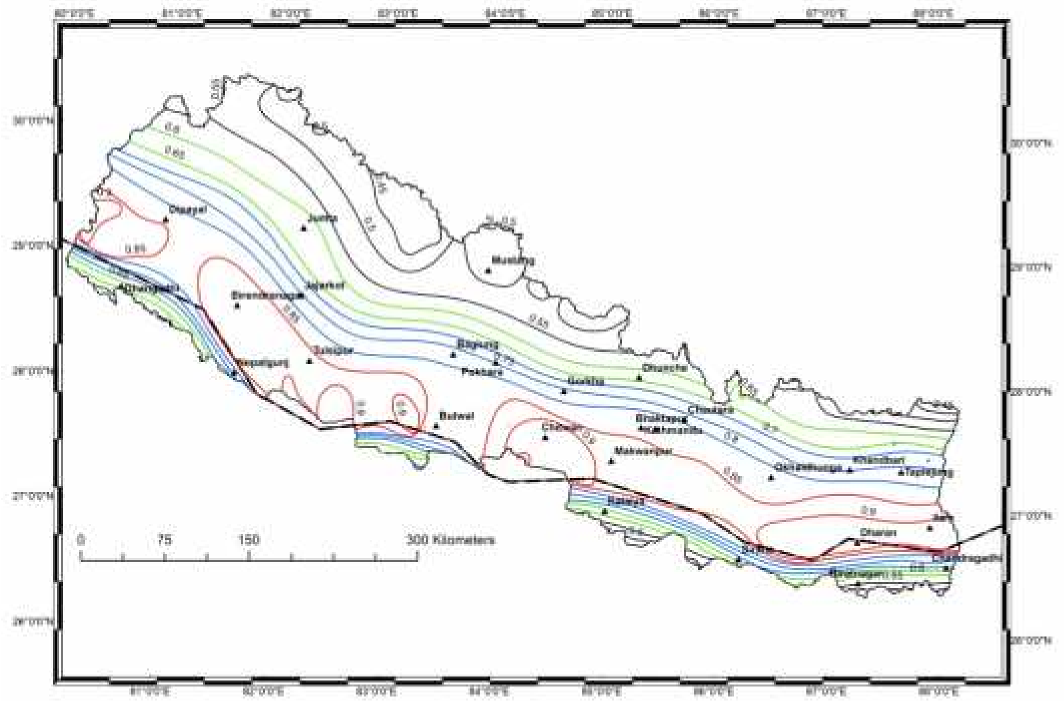

Fig. 6. Seismic hazard map of Nepal at 2% probability of exceedence in 50 years. The contour of PGA value is in g unit. The dotted black line represents the MFT, a southern expression of MHT.

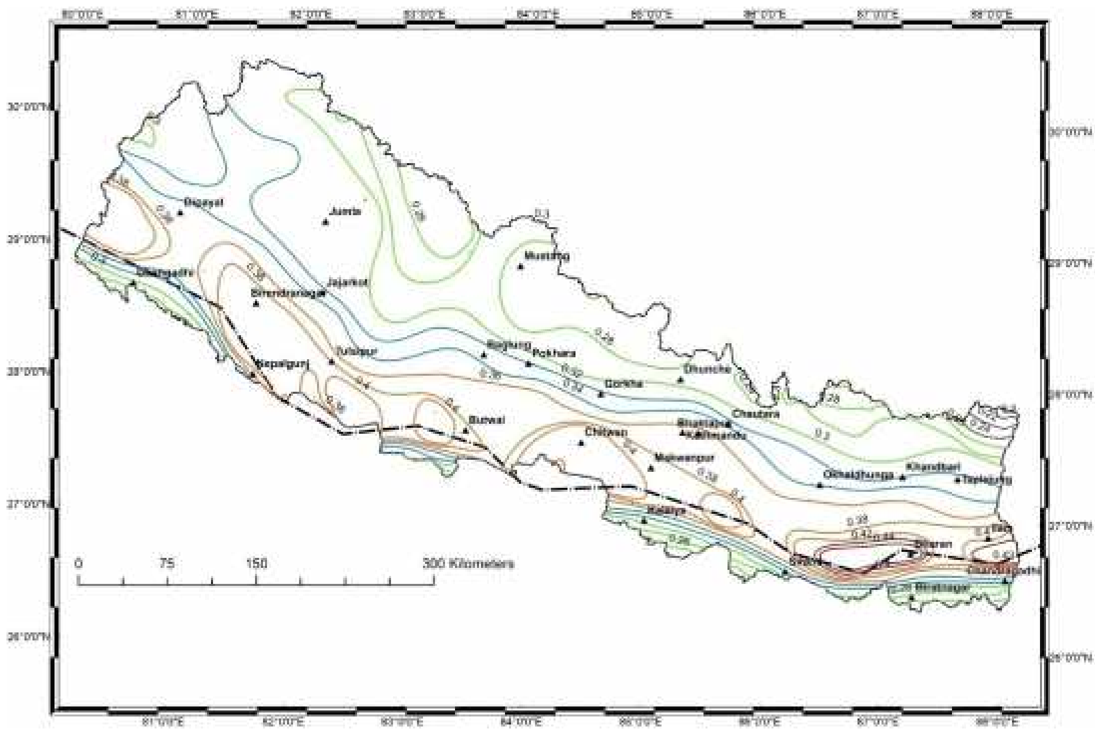

Fig. 6. Seismic hazard map of Nepal at 10% probability of exceedence in 50 years. The contour of PGA value is in g unit. The dotted black line represents the MFT, a southern expression of MHT.

5. Acknowledgements

This research is outcome of seismic hazard assessment for revision of National Building Code-105. Authors are grateful to Director, Central Level Project Implementation Unit, National Reconstruction Authority, Nepal for permitting us to present this research.

6. References

[1] Seeber L, Armbuster J (1981): Great detachment earthquakes along the Himalayan arc and the long term forecasts. In: Simpson, E.W., Richards, P.G. (Eds.), *Earthquake Prediction: An International Review*, Maurice Ewing Series 4. American Geophysical Union, Washington, DC, 259-277.

[2] MoHA (2016): *The Gorkha Earthquake: Experience and lessons*. Government of Nepal, Ministry of Home Affairs. 268p.

[3] Takai N, Shigefuji M, Rajaure S, Bijukchhen S, Ichiyanagi M, Dhital MR, and Sasatani T (2016): Strong ground motion in the Kathmandu Valley during the 2015 Gorkha, Nepal, earthquake. *Earth, Planet and Space* **68**:10, DOI 10.1186/s40623-016-0383-7.

[4] Pandey MR, Tandukar RP, Avouac JP, Lave J, Massot P (1995): Interseismic strain accumulation on the Himalayan crustal ramp (Nepal). *Geophysical Research Letters* **22,** 751-754.

[5] Pandey MR, Tandukar RP, Avouac JP, Vergne J, Heritier Th (1999): Seismotectonics of the Nepal Himalaya from a local seismic network. *Journal of Asian Earth Sciences* 17, 703-712.

[6] Pant MR (2002): A step towards a historical seismicity of Nepal. *Adarsa, 29–60*, Pundit Publ., Kathmandu.

[7] Wesnousky SG, Kumahara Y, Chamlagain D, Pierce IK, Karki A, and Gautam D, (2017): Geological observations on large earthquakes along the Himalayan frontal fault near Kathmandu, Nepal. *Earth and Planetary Science Letters* **457**, *366-375*.

[8] Campbell, A. 1833a. Account of the earthquake at Kathmandu, *J. Asiatic Soc.* Bengal, **2** (misc. II), 564–567.

[9] Campbell, A. 1833b. Further particulars of the earthquake in Nepal, *J. Asiatic Soc.* Bengal, 2(misc. VI), 636–639.

[10] Bilham R, Bodin P and Jackson M (1995): Entertaining a great earthquake in western Nepal: historic inactivity and geodetic tests for the present state of strain. *Journal Of Nepal Geological Society* **11** (1), 73-78.

[11] Rana BJB (1935): *Nepal ko Maha Bhukampa* (Great earthquake of Nepal). Jorganesh Press, Kathmandu.

[12] Cornell CA (1968): Engineering seismic risk analysis. *Bulletin of the Seismological Society of America*, **58**(5), 1583-1606.

[13] Scordilis, E. M. 2006. Empirical global relations converting MS and mb to moment magnitude. Journal of Seismology, **10**(2), 225–236.

[14] Pandey MR, Chitrakar GR, Kafle B, Sapkota SN, Rajaure SN, Gautam UP (2002): Seismic hazard map of Nepal. Deaprtment of Mines and Geology, Kathmandu, Nepal.

[15] Parajuli, HR, Kiyono J, Taniguchi H, Toki K, and Maskey PN (2010): *Probabilistic seismic hazard assessment for Nepal*. WIT Transactions on Information and Communication Technologies, WIT Press 43, doi:10.2495/RISK100351.

[16] Thapa DR, Wang G (2013): Probabilistic seismic hazard analysis in Nepal. *Earthq Eng. and Eng. Vib* **12**:577–586

[17] Chaulagain H, Silva V, Spacone E, Rodrigues H, Humberto V (2015): Seismic risk assessment and hazard mapping in Nepal. *Natural Hazards* **78** 583-602.

[18] Ader T, et al. (2012): Convergence rate across the Nepal Himalaya and interseismic coupling on the Main Himalayan Thrust: Implications for seismic hazard, *J. Geophys. Res.,* **117,** B04403, doi:10.1029/2011JB009071.

[19] Stevens V L, and Avouac J-P (2016): Millenary mw>9.0 earthquakes required by geodetic strain in the Himalaya, *Geophysical Research Letters,* **43**(3), 1118{1123, doi: 10.1002/2015GL067336, 2015GL067336.

[20] Elliott JR, Jolivet R, González PJ, Avouac J-P, Hollingsworth J, Searle MP, & Stevens VL (2016): Himalayan megathrust geometry and relation to topography revealed by the Gorkha earthquake. *Nature Geoscience,* **9**(2), 174-180

[21] Hubbard J, Almeida RV, Foster AE, Sapkota SN, Burgi P, Tapponnier P (2016) Structural segmentation controlled the 2015 M_w 7.8 Gorkha earthquake rupture in Nepal. *Geology.* doi:10.1130/G38077.1

[22] Elliott JR, Walters RJ, England PC, Jackson JA, Li Z, Parsons B (2010): Extension on the Tibetan plateau: recent normal faulting measured by InSAR and body wave seismology. *Geophys. J. Int.* **183,** 503–535. doi: 10.1111/j.1365- 246X.2010.04754.x.

[23] Diehl T, Singer J, Hetényi G, Grujic D, John Clinton J, Domenico Giardini D, Edi Kissling E (2017): Seismotectonics of Bhutan: Evidence for segmentation of the Eastern Himalayas and link to foreland deformation. *Earth and Planetary Science Letters* **471,** 54-64.

[24] Murphy M A, Taylor MHT, Gosse J, Silver CRP, Whipp DM and Beaumont C (2014): Limit of strain partitioning in the Himalaya marked by large earthquakes in western Nepal, *Nat. Geosci.,* **7,** 38–42.

[25] Gardner J, and Knopoff L (1974): Is the sequence of earthquakes in southern California, with aftershocks removed, Poissonian. Bulletin of the Seismological Society of America, **64**(5), 1363–1367.

[26] Stepp JC (1972): Analysis of completeness of the earthquake sample in the Puget Sound area and its effect on statistical estimates of earthquake hazard. *Proceedings of the 1st International Conference on Microzonazion,* Seattle 2, pp. 897–910).

[27] Gutenberg B and Richter CF (1944): “Frequency of earthquakes in California,” *Bulletin of the Seismological Society of America,* **34:** 185–188.

[28] Zhao J. X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T. 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.

[29] Atkinson GM, and Boore DM (2003): Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions. *Bull Seismol Soc Am* **93**(4):1703–1729.

[30] Abrahamson N, Gregor N and Addo K (2016): BC hydro ground motion prediction equations for subduction earthquakes. *Earthquake Spectra,* **32**(1), 23–44. doi:10.1193/051712EQS188MR.

[31] Abrahamson NA, Silva WJ and Kamai R (2014): Summary of the ASK14 ground motion relation for active crustal regions. *Earthquake Spectra,* **30**(3), 1025–1055.

[32] Chiou BSJ, & Youngs RR (2014): Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra,* **30**(3), 1117–1153.

[33] Campbell, K.W., Bozorgnia, Y. 2008. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5 % damped linear elastic response spectra for periods ranging from 0.01 to 10 s. Earthq Spectra 24(1):139–171.
[34] Atkinson GM and Boore DM (2006): Earthquake ground-motion prediction equations for eastern North America. *Bull Seismol Soc Am* 96(6):2181–2205.
[35] Tavakoli B and Pezeshk S (2005): Empirical-stochastic ground-motion prediction for eastern North America, Bull. Seism. Soc. Am. 95, 2283–2296.
[36] Rahman MM, Bai L, Khan NG, and Li G (2017): Probabilistic Seismic Hazard Assessment for Himalayan–Tibetan Region from Historical and Instrumental Earthquake Catalogs. *Pure and Applied Geophysics*, DOI 10.1007/s00024-017-1659-y
[37] Steven VL, Shrestha SN and Maharjan DK (2018): Probabilistic Seismic Hazard Assessment of Nepal. *Bulletin of the Seismological Society of America*, Vol. XX, No. XX, pp. –, – 2018, doi: 10.1785/0120180022
[38] Waseem M, Lai CV, Spacone E (2018): Seismic hazard assessment of Northern Pakistan. *Nat Hazards* **90**:563–600.
[39] Nath SK and Thingbaijam KKS (2012): Probabilistic Seismic Hazard Assessment of India. *Seismological Research Letters* **839**(1), 135-149.

