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A FAULT SOURCE BASED PROBABILISTIC SEISMIC HAZARD ASSESSMENT OF KATHMANDU VALLEY, NEPAL

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Abstract

Kathmandu valley is an intermontane basin in the lesser Himalaya of Nepal, and three ancient cities; Kathmandu, Bhaktapur, and Lalitpur, hosting seven world cultural heritage sites are located within this valley. Being its location just above the Main Himalayan Thrust; main seismogenic plate boundary thrust fault, Kathmandu valley had been repeatedly devastated by more than seven historical earthquakes. Some of these events might have a close relation to the 1934 Bihar-Nepal earthquake, and possibly the repetition of this 1934 event. Due to these past earthquakes, not only there was a huge economic loss, but the country had also suffered from thousands of casualties and injury as well as damage of several historical monuments.

The Mw 7.8 Gorkha earthquake of 25th April 2015 caused significant damages in Kathmandu valley, though the epicenter was located about 78 km northwest of the valley. The recorded peak ground acceleration at rock site was almost as double that of the soil site. It is, therefore, necessary to estimate the realistic seismic hazard parameters for Kathmandu valley at bedrock site. After the Gorkha earthquake, two models of the MHT are proposed, i.e. single and double ramps. In this contribution, taking different geometries, i.e. single ramp, double ramp of the MHT and using measured shear wave velocity (Vs_{30}), a new probabilistic seismic hazard map for the Kathmandu valley is prepared. Double ramp model has given peak ground acceleration (PGA) of 0.29 g at the bedrock site, which is close to measured PGA, i.e. 0.3 g, (combined EW-NS motion using the square root of the sum of a square) for main shock of the Gorkha earthquake.

Keywords: Kathmandu Valley; Seismic Hazard Assessment; Main Himalayan Thrust (MHT).

1. Introduction

There are many intermontane basins within the Lesser Himalaya, among them one is Kathmandu basin (Kathmandu valley) that mainly consists of three ancient cities viz: Kathmandu, Bhaktapur, and Lalitpur. The valley is surrounded by two mountain range; Shivapuri (2732 m) and Pulchauki (2762 m) in the north and south respectively. The valley is rich in cultural and religious heritage sites and it is the capital city of Nepal. Main Himalayan Thrust (MHT) is the main seismogenic plate boundary thrust and Kathmandu valley lies just above it. This is the reason behind the devastating earthquake in the past, e.g. 1255, 1404, 1681, 1803, 1810, 133, and 1866 earthquakes. Not only the huge number of human casualties, those past earthquakes severely damaged infrastructures including most of the cultural and religious heritage sites, buildings, hospitals and many more.

After the 1934 Bihar-Nepal earthquake, the most recent largest seismic event in Nepal was 2015 Gorkha earthquake which has the magnitude Mw 7.8 [1]. The epicenter of this Gorkha earthquake was located 78 km NW of the Kathmandu valley. Not only within the valley, this earthquake severely damaged the outskirt of the valley. After the Gorkha earthquake, there are number of studies that focused on the geometry of MHT. There are two school of thought that proposed single and double ramp models. Elliot et al. [2] 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. [3] 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. In this contribution, it is aimed to estimate peak ground acceleration at bedrock in Kathmandu valley using probabilistic approach considering the effect of all sources i.e. areal sources and fault (MHT) source.

1.1 Geology of Study Area

In Kathmandu Valley, Quaternary sediments were deposited on the top of the basement rocks. The lithology of the basement rocks comprises two groups (Pukchauki and Bhimphedi) of rocks and both of the groups are a thrust sheet named Kathmandu Complex [4]. The Phulchauki Group is ~5-6 km thick and it comprises of weakly metamorphosed sediments containing early-mid- Paleozoic fossils. This unit is further differentiated into five formations; Tistung, Sopyang, Chandragiri, Chitlang and Godavari Formation. Similarly, the Bhimphedi Group comprises relatively high-grade metamorphic rocks of Precambrian age. The total thickness of this group os ~8 km and further divided into six formations; Raduwa, Bhainsedobhan, Kalitar, Chisapani, Kulekhani, and Markku Formation in ascending order [4]. The quaternary deposit was derived from the surrounding hills by the ancient drainage channel system and mainly consists of a thick layer of semi-consolidated fluvio-lacustrine detritus. Based on the gravity measurements, the estimated maximum thickness of this quaternary deposit is 650 m [5]. The arenaceous sediments composed of fine- to coarse-grained sand with a small quantity of rocks fragments which were derived from the northern gneiss rocks which are widely exposed on the northern belt. Similarly, the argillaceous sediment composed of clay and silt resulting from the erosion of limestone and phyllite from the eastern, western and southern belt. Lignite and diatomite are also present in the valley. Agglomerate of boulders and gravel with clay and silty matrix are well preserved in the southern portion of the basin were derived the southern hill.

2. Seismo Tectonics of Study Area

Indian and Eurasian plate started to collide since early Cenozoic and this process is still undergoing with the rate of convergence ~35-38 mm/year [6]. The present Himalayan Seismicity is a result of this collision. In different time span the geometry and the velocity of the Indian plate in relation to Eurasian Plate varies. Since the India-Eurasia collision, several tectonics structures; namely Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) were active in different time span, that resulted the upliftment of the Himalayan Orogen (Fig. 3). All of these three thrusts are propagated in a North to South direction and found throughout the Himalayan orogeny, and are inferred to be splay thrusts of the Main Himalayan Thrust (MHT), which marks the under thrusting of the Indian Plate (Fig. 1).

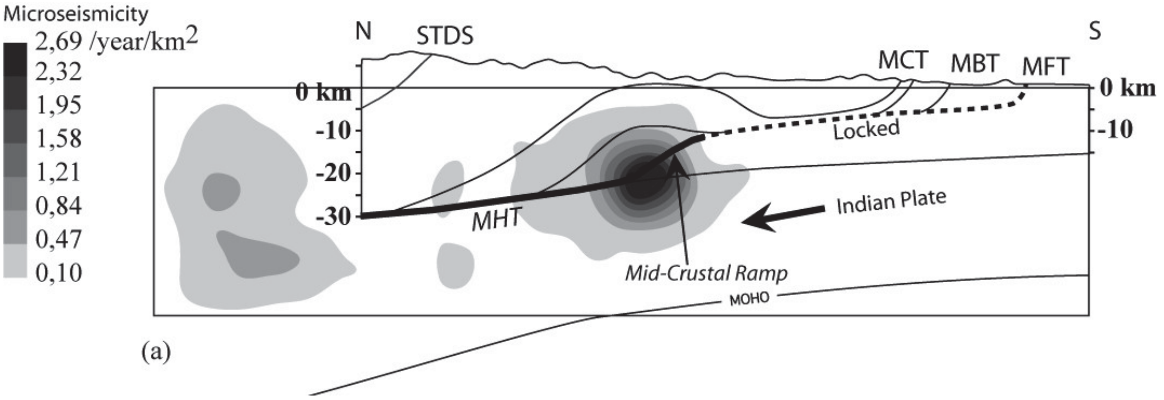

Fig. 1 North-South geological cross-section of Nepal Himalaya showing major thrust system and micro seismicity [7]

2.1 Seismicity of Nepal Himalaya

The convergence between Indian and Eurasian plate is highlighted through the shortening across the Himalaya, Tibet Plateau, and Tien Shan and deformation of the Tibetan through eastward movement of crustal material and southward rotation about the eastern syntaxis [8]. Almost half a portion of the convergence is absorbed across the Himalaya in straining the crust and the aggregated stress is thus responsible in generating large earthquake. Despites of the short instrumental records, the major trend of seismic events have been recognized and in general this trend consists of a narrow belt of predominantly moderate sized earthquakes beneath the Lesser Himalaya just south of the Higher Himalayan front [9]. Before 1978, there was not any proper instrumental record system within Nepal, however, through paleo seismological studies, large catastrophic historical earthquakes in past were documented. Hence, we categorized the past earthquake records into historical and instrumental records.

2.1.1 Historical earthquake

Since a long time before, there was a record of an extensive loss of property and casualties' large earthquakes in Nepal. Some of the major listed events happened in 1255, 1408, 1681, 1803, 1833, and 1866 [10]. Bihar-Nepal earthquake occurred in 1934 was supposed to be the repetition of some of those past events, especially 1933 earthquake [11]. Conceivably rest of the events are linked to smaller magnitude earthquakes that would have occurred close to the Kathmandu valley.

2.1.2 Instrumental earthquake

Since 1978, National Seismological Center (NSC) under the Department of Mines and Geology has been continuously monitoring the earthquake events in Nepal. The past records of the earthquake have shown the intense micro-seismicity and moderate earthquake events throughout the Nepal Himalaya clustering along the foothills of the Higher Himalaya [7]. However, the great earthquake generally occurs along the locked portion of the decollement beneath the Siwalik and Lesser Himalayan and the induced deformation is propagated towards the southern part of the Himalaya along the MFT. The major fault lines and seismicity pattern in Nepal Himalaya are shown in Fig. 2.

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3. Probabilistic Seismic Hazard Assessment

3.1 Source Characterization

The seismic source characterization is an important step to identify and locate the probable seismic zone that can produce devastating earthquake in future. The source zones are divided into two broad categories; continental collision source and aerial sources. In the present study, seismic sources were delineated based on the earthquake origin, type, magnitude and frequency, seismo-tectonics, neotectonics deformation, nature and activation of seismogenic faults etc.

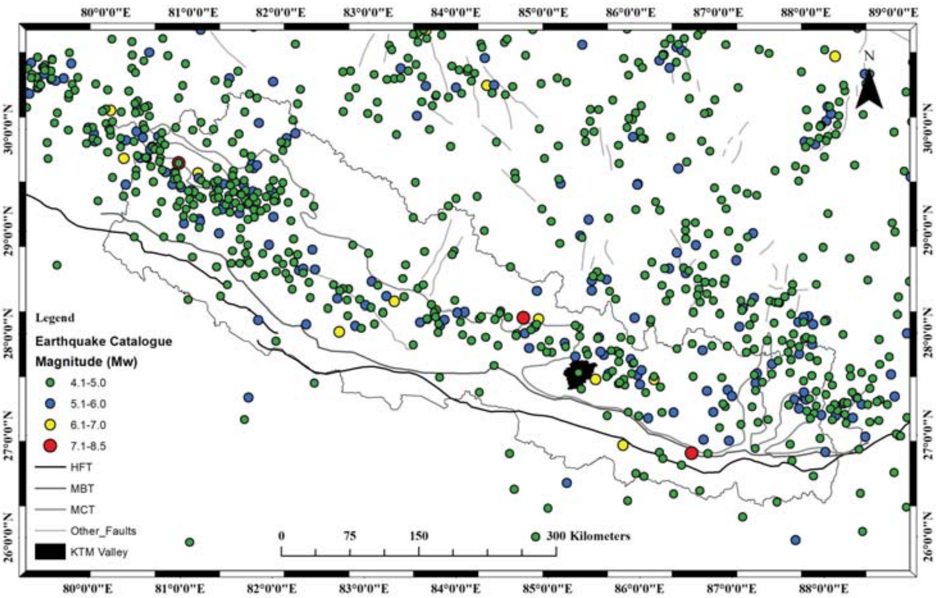

Fig. 2 Major fault line and de-clustered earthquake distribution (1100-2017 AD) map considered for the hazard computation (source: ISC)

Continental collision sources comprise of MHT, MFT, MBT and MCT, whereas areal sources comprise of six zones, namely; South, North Graben 1 (NG-1), North Graben 2(NG-2) North Graben 3 (NG-3), North East (NE), and North West (NW) (Fig. 3). These differentiations of zone are mainly based on the observed seismicity rates and the present study analyzed the reoccurrence parameters were developed for each source.

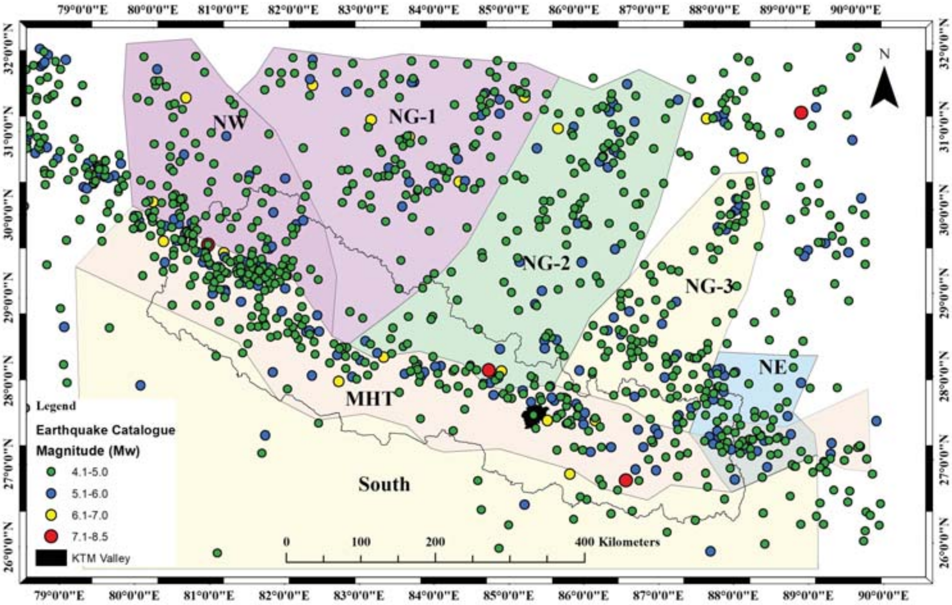

Fig. 3 Seismic source characterization (abbreviation in main body).

3.2 Ground Motion Prediction Equation

Ground motion Prediction Equation (GMPE) is one of the major components that governs the seismic hazard, however, so far in our understanding there is not any record of such specific GMPE study in Nepal. Hence, the present study used and analyzed the GMPE from the previously published dataset in the surrounding regions. The details of the tectonic regions, sources and the weight are presented in Table 1.

Table 1 GMPE selected for various tectonics setting

Tectonic Region	Sources	GMPE	Weight
Active Shallow Crust	North Graben 1, North Graben 2, North Graben 3, North East, South	Abrahamson et al.2014 [12]	0.33
		Chiou and Youngs 2014 [13]	0.33
		Campbell and Bozorgnia 2008 [14]	0.34
Subduction	MHT	Atkinson and Boore 2003 [15]	0.33
		Kanno 2006 [16]	0.33
		Zhao et al. 2006 [17]	0.34
Stable Continent	North East	Atkinson and Boore 2006 [18]	0.5
		Tavakoli and Pezeshk 2005 [19]	0.5

3.3 Seismicity Parameters

In regards to obtain the seismicity parameters, the earthquake catalogue at distance of 200 km from Nepal boundary has been obtained from International Seismological Center (ISC). Different magnitude scale of earthquake was converted to moment magnitude using the equation proposed by Scordillis [20] and delustering of each event was done following the method given by Gardner and Knopoff **[21]**. Similarly, completeness test of the catalogue after delustering was done using the method developed by Stepp **[22]**. After completeness test, *a* and *b* value for each source are estimated and the dataset is presented in Table 2.

Table 2 Seismicity Parameters for hazard estimation

S.No	Sources	a	b	Minimum Magnitude (M_w)	Maximum Magnitude (M_w)	References for Maximum Magnitude (Mw)
1	MHT	4.10	0.78	4.00	8.40	Earthquake Catalogue
2	North East	4.68	1.04	4.00	6.90	Largest Recorded
3	North Graben-1	3.56	0.77	4.00	7.10	Elliot et al. [23]
4	North Graben-2	3.86	0.82	4.00	7.10	Elliot et al. [23]
5	North Graben-3	4.95	1.07	4.00	7.10	Elliot et al. [23]
6	North West	4.18	0.88	4.00	7.10	Murphy et al. [24]
7	South	4.36	1.01	4.00	7.00	Earthquake Catalogue

4. Result and Discussion

The present study adopted the OpenQuake code for probabilistic seismic hazard assessment (PSHA). The focus area of study is subdivided into a grid of 9.5 x 9.5 km and PSHA was carried out at each grid points at bed rock. Comparative analysis has been done by considering all seismic sources as mentioned above and the MHT alone and the result has shown that the main contribution in hazard of Kathmandu valley is solely by MHT, while other sources have insignificant contribution (Table 3). So, further calculation of hazard is done by considering both single ramp (SRM) and double ramp model (DRM) of MHT. We compare the computed results at 10% probability of exceedence in 50 year with the measured data by computing square root of sum of square (SRSS) at Kirtipur (KTP) site. The recorded SRSS spectra have PGA of 0.30 g and the SRM and DRM individually has given PGA value of 0.26 g and 0.29g respectively (Table 3 & Fig. 4).

Table 3 PGA (10% probability of exceedance in 50 years) for different seismic sources at Kirtipur (KTP) site

S. No	Sources	PGA, Calculated	PGA, Observed
1	SRM	0.267	0.303
2	DRM	0.29	0.303
3	SRM including all areal sources	0.267	0.303
4	DRM including all areal sources	0.29	0.303

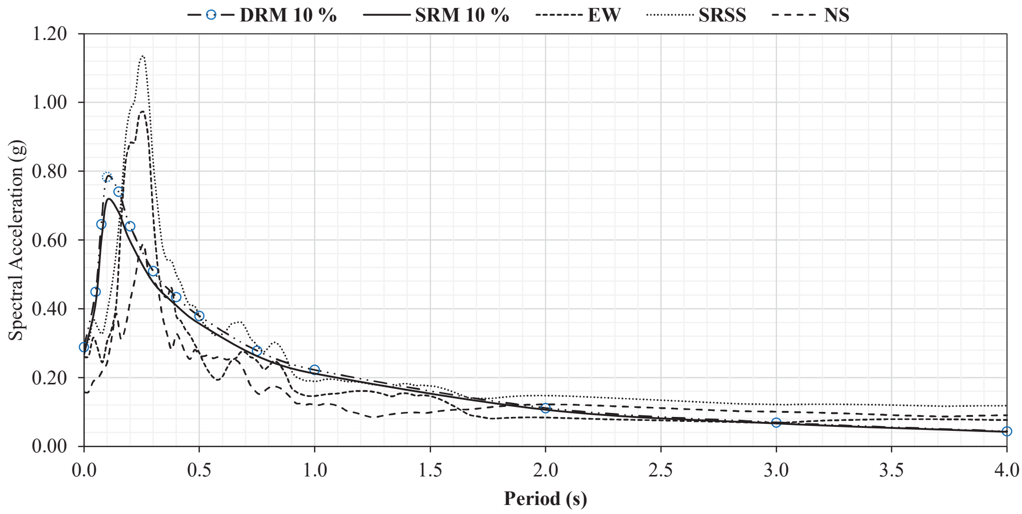

Fig. 4 Comparison between observed and computed response spectra (10% probability of exceedance in 50 years) at KTP site.

Although there is some discrepancy in computed and observed spectra, PGA is better captured by double ramp model. As in the present study, the double ramp result (computed using double ramp model) are closer to observed spectra at Kirtipur (KTP) site. Contour map of PGA for Kathmandu Valley is presented in the Fig. 5 using double ramp model. Here PGA is estimated between 0.26g to 0.31g and it has been found that the higher values are obtained in the southern part which decreases gradually towards north as per the locking characteristics of MHT.

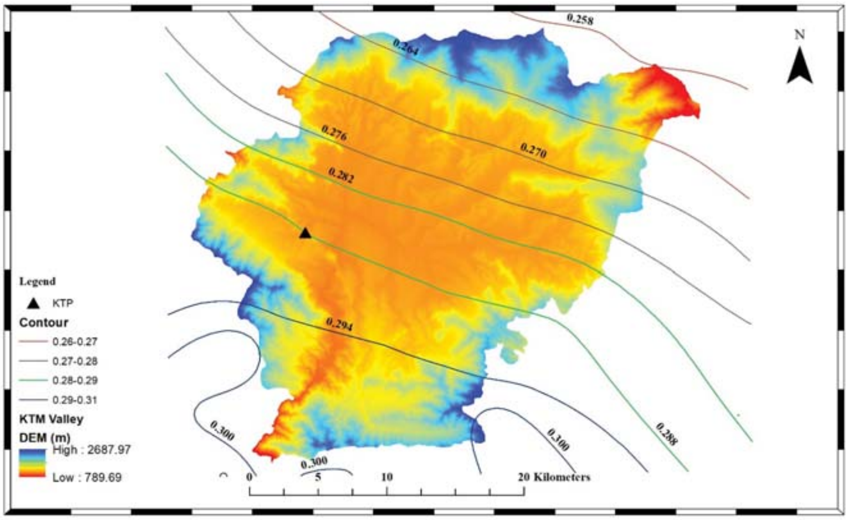

Fig. 5 PGA contour at 10% probability of exceedance in 50 years. Filled triangle shows accelerometric station (KTP) on bedrock in Kirtipur

5. Conclusions

Probabilistic seismic hazard map for Kathmandu valley has been prepared by considering earthquake catalogue from 1200 to 2017 A.D. Considering the single ramp and double ramp geometry of MHT analysis has been performed and compared with the recorded motion at Kirtipur bedrock. Double ramp model has given peak ground acceleration (PGA) of 0.29 g at the bedrock site, which is close to measured PGA, i.e. 0.3 g, (combined EW-NS motion using the square root of the sum of a square) for main shock of the Gorkha earthquake. Thus, the double ramp model geometry of the MHT is more appropriate for the seismic hazard assessment.

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