Strong ground-motion characteristics in the Kathmandu Basin (Strong-motion observation and damage assessment of 2015 Gorkha, Nepal Earthquake)

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Introduction

The Himalayan mountain range formed by the collision of the Indian and Eurasian plate is regarded as one of the earthquake prone zones in the world. The subduction of the Indian plate under the stable Eurasian plate is not continuous but intermittent with periodic release of accumulated stress in form of large earthquakes. Nepal, covering about 900 km of the Himalayan range, is not only seismically active but also vulnerable to these earthquakes.

The crustal shortening of the Himalaya brought about by the collision has formed a series of E-W trending regional thrusts running along its entire length. These thrusts are termed as Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Main Frontal Thrust (MFT) from north to south: their formation also being in the same order. These thrusts all come together and join the gently sloping decollement zone called the Main Himalayan Thrust (MHT) at depth. This decollement zone, south of the Himalaya, is where majority of earthquakes originate (Figure 1) and the slip produced by large earthquakes are also accommodated here.

A number of large earthquakes have occurred in Nepal Himalaya: in 1833 (Mw7.7), 1934 Nepal-Bihar (Mw8.2), 1980 Bajura, and 1988 Udayapur and they have left trail of damage and devastation.

On 2015-04-25 another large earthquake of Mw7.8 occurred in Gorkha (80 km north-west of capital Kathmandu) resulting in death of more than 8,000 people and leaving several thousand wounded and homeless in central Nepal. This earthquake was followed by more than 350 aftershocks: at least five of them larger than Mw6.

The present work focusses on analysis of strong ground-motion characteristics of Gorkha Earthquake in Kathmandu and damage it brought about in buildings around the seismic stations.

Study area

The study area is Kathmandu basin in central Nepal. Also referred to as Kathmandu valley or simply ‘the valley’, this bowl-shaped basin surrounded by mountains from all sides (Figure 2). With an area of nearly 665 sq. km, the basin is an urban agglomerate consisting of Kathmandu, Patan, and Bhaktapur districts: the city of Kathmandu being the political and economic capital of the country. Teeming with a population of about 2.5 million, the valley is the largest and the most densely populated area in Nepal. It is also one of the oldest settlements and is rich in traditional monuments, many of which are listed in the UNESCO World Heritage Sites. These are one of the many attractions for the tourism industry of the mountainous nation.

The basin is filled with thick deposit of a paleo-lake and the mountains surrounding it are formed by hard basement rocks. In the Pleistocene, the uplift of the mountain range south of Kathmandu was too rapid for the Bagmati River to drain the basin, and was dammed forming a lake which later drained and dried into present form. The provenance of the basin-fill sediments is the basement rocks surrounding the basin.

The basin-fill sediments of fluvio-lacustrine origin mainly consist of unconsolidated sand and gravel on the fringes and mostly silt and clay in the central part. Previous studies have shown the thickness of the central part of the basin to be more than 500 m. Nevertheless, there are hillocks of bedrocks inside the basin that occasionally breach the sediments to form exposures visible at some places, indicating that the bottom of the basin has highly uneven topography. Moreover, the boreholes data available show rocks at shallow depth at some places inside Kathmandu.

![Figure 1. a) Seismic activities in Nepal from 1994-1999[1]. b) Cross-section along AA’. Majority of epicentres are clustered in the MHT[2].](image-url)
Background of Present Work

Kathmandu due to its geo-tectonic setting has been considered seismically vulnerable for quite some time, nonetheless there are no strong ground-motion studies in Kathmandu basin.

Kathmandu suffered damages during past earthquakes especially during 1833, 1934, and 2015 earthquake. The intensities of these earthquakes inside Kathmandu were MMI –VIII to X. The Nepal-Bihar Earthquake of 1934 was by far the largest earthquake, Nepal has ever experienced. Nearly 19% of buildings inside the valley were reported destroyed and more than 8,000 people lost their life all over the country. The Gorkha Earthquake of 2015 also brought about damage to around 13% of buildings inside Kathmandu.

The devastation pattern of the past earthquakes in Kathmandu basin shows effect of site amplification due to unconsolidated sediments. The situation is similar to that of Mexico City where the destruction due to 1985 earthquake is mainly attributed to local site amplification.

The location in one of the seismically active region, wave amplification by thick soft sediments and haphazard construction of buildings without properly addressing these facts had all added to the seismic vulnerability of Kathmandu.

It has been indicated long ago that there was a probability of mega quake in the Himalayan region. The region west of recent Gorkha Earthquake epicentre has not experienced a major earthquake since 1505. This three centuries worth of stress accumulation in this seismic gap can trigger a mega quake in the region.

Though, most of the stress was released in 1934 earthquake, east Nepal still can produce an earthquake as large as M7.9. In the western part, the probability of even greater (~ M8.6) earthquake looms large.

In this background, a thorough study of strong-motion characteristics of the basin sediment in Kathmandu is a necessity. It would be helpful not only in understanding the local site effect but also in preparation of safe an accurate building code. In 2011, Hokkaido University with collaboration of Tribhuvan University, Nepal started the strong-motion study of Kathmandu basin. The main objective of the study is the evaluation of seismic site effect of Kathmandu basin using the strong-motion records.

The present work, carried out after the 2015 Gorkha Earthquake is a part of the collaborative study and has following objectives:

- Analysis of the strong-motion characteristics of earthquake before and after the Gorkha event
- Preliminary analysis of site effect around the seismic stations
- Investigation of damage to structures around the seismic stations
- Assessment of the relationship between strong motion characteristics, local site effect and damage pattern due to the Gorkha Earthquake

Strong motion Observation

Four continuous recording three-component Mitsutoyo JEP-6A3-2 accelerometers were installed in a straight line from west to east: KTP, TVU, PTN, and THM (Figure 2). The westernmost station KTP lies above the bedrock and the rest over the basin sediment.

![Figure 2. Kathmandu Basin surrounded by mountains. The red points are strong-motion stations.](image)

The shear wave velocity at KTP at 700 m/s[4] is higher than that at other stations (150-200 m/s) which indicates KTP as a rock site. It has been observed that the P-wave and S-wave arrival at the KTP during the earthquakes is slightly earlier than expected despite the sites having similar distance and azimuth from the source. This phenomenon also indicate KTP as a rock site with a higher wave velocity than other sites.

For the present work, seven earthquakes (Figure 3) were considered. Two of them are small (mₘ 4.9 and mₘ 5.0) quakes occurred before the Gorkha Earthquake in 2013-08-30 and 2014-12-30 respectively. Other five are the main shock (Mₘ 7.8), and the large aftershocks (Mₘ 6.6, Mₘ 6.7, Mₘ 7.3, and Mₘ 6.3) of the Gorkha Event occurred within the first two weeks of the main shock.

![Figure 3. The epicentres of the earthquakes considered for the study. The blue dots are earthquakes occurred before the Gorkha Earthquake. Red dots are epicentres of main shock and aftershock of the Gorkha Event.](image)
The sediment site at TVU recorded the highest PGA and PGV values for the earthquakes except for the main shock, where the PGA values is high in the rock site of KTP. The stations show a low PGA (0.24 m/s²) than expected from a large earthquake of this magnitude. The main shock is rich in long period waves which can be easily observed in the waveforms of the sediment sites (Figure 4). The waves in U-D component don’t show large site effect like in horizontal components.

The rupture causing the earthquake propagated towards east from the epicentre with a velocity similar to that of S-waves and stopped about 90 km east of Kathmandu. The rupture reached Kathmandu in ~25 s[5].

The main shock resulted in a permanent uplift of Kathmandu about ~60 cm and displacement of ~120 toward S-SW direction, which is consistent with data obtained from GPS stations of Survey Department, Nepal and Nepal Geodetic Array[6].

The earthquakes considered for the study all show peak frequencies of 0.2-0.4 Hz in the sediment sites. The spectral ratios for the earthquakes show significant amplification in the sediment sites in 0.2-1 Hz band.

**Figure 4.** Acceleration waveform of the Gorkha Earthquake. Notice the long period waves in sediment sites.

**Damage Assessment**

The Rapid Visual Damage Assessment was carried out after a week of the earthquake, on buildings in an area inscribed by 200 m radius from the seismic stations and the damage situation and waveform characteristics were compared. This gives the relationship between site response and the situation of damage around the stations. Similar study was carried out after the 2011 Christchurch Earthquake by Iizuka, et al.[7].

Kathmandu has a fair share of masonry as well as RC buildings. The traditional buildings in Kathmandu are masonry structures with mud mortar whereas recent masonry structures use cement mortar. The contemporary RC structures are designed as bare frames and unreinforced masonry in-fills are added later. For the present work, the buildings around the stations were classified as Masonry- mud mortar structures, Masonry- cement mortar, RC masonry structures, and RC steel masonry structures.

The method of damage assessment is based on the European Macroseismic Scale 1998[8]. The damage grades of the EMS98 were modified as Not Damaged, Slightly Damaged, Moderately Damaged, and Heavily Damaged.

The damage was mostly seen in masonry structures with RC buildings suffering little or no damage at most places (Figure 5). The damage to the buildings around the stations did show the influence of local site effect.

**Figure 5.** Damage distribution of buildings around the seismic stations.

Most of the buildings assessed around KTP were intact (~ 94%), save one that suffered collapse of entire façade. Old buildings constructed around the steep topography were not damaged. The earthquake had less effect around KTP as it lies above bedrock.

On the other hand, around TVU, most of the RC buildings suffered minor damages. One masonry building was complete collapsed. Statistically speaking, TVU suffered the most damages (~10%).

In PTN few buildings suffered slight to moderate damages. A couple of old masonry buildings collapsed and a few were slightly damaged. THM also had only one old masonry building that suffered moderate damages but ~ 97% buildings were intact including RC buildings.

The direct effect of site amplification was visible as KTP suffered little or no damage despite having old masonry buildings whereas in TVU even new RC buildings suffered cracks.

Other hard-hit areas of the Kathmandu basin had no seismic stations so, assessment of those areas were not carried out due to lack of strong-motion data to compare the damage with.
The acceleration response spectra (Figure 6) of the Gorkha Earthquake show high response in short periods in KTP but high response in long periods in sediment sites.

![Figure 6. Acceleration Response spectra of the Gorkha Earthquake. Also plotted are the design requirements based on building laws of Nepal (NBC) and Japan (JPN).](image)

Sakai, et al. [9] indicated that the JMA Instrumental Intensity cannot explain the damage to infrastructure properly so, they proposed an intensity based on response between 1-2 s period and found it to be directly related to heavy damages around the stations. As the response in 1-2 s period is high for TVU, it can be seen that this intensity for the Gorkha Earthquake (I*, Table 1) was also high in the TVU as it can be seen that the. This parameter can directly be associated with the damage power of the earthquake, as TVU suffered the heaviest damage among the four stations.

Figure 6 also reveals that seismic design coefficient for Type I soil (hard rock/stiff soil) and Type III soil (soft soil >30 m depth) based on the Nepal Building Code (NBC-105) is much lower than the design response of the earthquake. The design requirement of Building Standard Law of Japan for the same soil types (Centre Europèen de Géodynamique et de Séismologie, 1998) is higher than KTP response except for very short periods. The building code of Nepal has to be updated to include earthquakes of this magnitude as the seismic design coefficient is much lower than necessary.

### Result

The study shows significant amplification of seismic waves in the sediment sites. The Gorkha earthquake is rich in long period waves and response is also high in long periods. Acceleration response spectra show high response of TVU in 1-2 s period: and can be directly related to the damage to structures. Most buildings in KTP were old and built without proper engineering consideration but damage is still very less owing to its location above bed rock. Due to absence of high-rise and base isolated buildings in Kathmandu, effect of high long period response of the earthquake couldn’t be seen.

### Reference


### Table 1. Summary of damage situation around the strong-motion stations. I* is the intensity based on response spectra in 1-2 s period.

<table>
<thead>
<tr>
<th>Site</th>
<th>I* (1-2s)</th>
<th>PGA (cm/s²)</th>
<th>Damage situation</th>
<th>Number of buildings</th>
<th>Damage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KTP</td>
<td>4.28</td>
<td>241.3</td>
<td>Majority of buildings unharmed with less than 2% buildings heavily damaged</td>
<td>174</td>
<td>5.74</td>
</tr>
<tr>
<td>TVU</td>
<td>5.54</td>
<td>237.9</td>
<td>Cracks in RC building foundations, one masonry building completely collapsed</td>
<td>19</td>
<td>10.52</td>
</tr>
<tr>
<td>PTN</td>
<td>5.04</td>
<td>150.7</td>
<td>Few masonry and RC structures developed cracks</td>
<td>85</td>
<td>9.41</td>
</tr>
<tr>
<td>THM</td>
<td>5.03</td>
<td>147.1</td>
<td>Very few damage except in an old school masonry building</td>
<td>32</td>
<td>3.13</td>
</tr>
</tbody>
</table>