STRONG MOTION OBSERVATION AND DAMAGE ASSESSMENT IN KATHMANDU, NEPAL AFTER APRIL 25, 2015 GORKHA EARTHQUAKE

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Abstract

Kathmandu basin in the Nepal Himalaya, is filled with ~ 500 m thick fluvio-lacustrine sediment and has long been considered seismically vulnerable owing to its geo-tectonic setting. Although, large earthquakes in the past have left trails of damage, strong ground-motion studies in Kathmandu were lacking. Recently, the occurrence of the M_w7.8 Gorkha Earthquake on 25th April 2015 caused infrastructure damages in east and central Nepal including Kathmandu. Followed by more than 350 aftershocks larger than Ml4 with largest one (M_w7.3) occurring on 12th May, the Gorkha Earthquake was the latest entry in the list of large damaging earthquakes. These earthquakes garnered a lot of worldwide attention resulting in a recent increase in seismicity study of the Nepal Himalaya.

The Earthquake took nearly 9,000 lives all over the country with 1,739 body counts in Kathmandu alone. The official figure shows that about 13% of buildings inside the Kathmandu basin were damaged. The damage in the basin was mostly seen in masonry structures with RC buildings suffering little or no damage at most places

The present study is the analysis of strong ground-motion characteristics of the Gorkha Earthquake and its aftershocks, based on the records on four accelerometers inside the Kathmandu basin. The stations were installed by Hokkaido University in collaboration with Tribhuvan University in 2011 for evaluation of seismic site effect of the basin using strong-motion records. One of the station (KTP) lies above bedrock and was considered as reference to compute spectral ratio of other stations viz. TVU, PTN, and THM on the sediment sites.

The PGA of the main shock of the Gorkha Earthquake was highest (241 cm/s^2) in the rock site, KTP whereas the PGV was found to be highest in sediment site of TVU. The sediment sites show dominance in long-period waves (0.2-0.4 Hz). The spectral ratios show significant amplification in 0.2-1 Hz band at these sites.

The strong-motion characteristics were correlated with the damage pattern around an area inscribed by a circle of 200 m radius from the station. The damage to the buildings around the stations did show the influence of local site effect. The acceleration response spectra of the stations are much higher than the design coefficient prescribed by the Nepal Building Code. The amplification in spectral ratio, high PGV values and high acceleration response in 1-2 s period were observed in TVU. The area around TVU saw damages to 10% of buildings as opposed to KTP where only about 5% buildings were damaged. The buildings in KTP were traditional masonry structures built without proper engineering considerations, nevertheless they endured the shaking which, on the other hand, damaged RC buildings around TVU. Another sediment site PTN also showed damage to about 9% of buildings but THM, also sediment site, showed the least damage as most of the buildings were new RC structures.

Keywords: Gorkha Earthquake, Strong-ground motion, Damage assessment

1. Introduction

Kathmandu is an intermountain valley formed during the Himalayan orogeny. It is filled with fluvio-lacustrine sediment, over 600 m thick at the central part [1]. It houses the capital city Kathmandu and other towns making it the largest urban agglomerate of the country. The amplification of seismic waves due to the thick unconsolidated sediments could be understood by the devastation pattern of past earthquakes that have wreaked havoc in the valley. With the location in seismically active region and wave amplification due to thick soft sediments, the situation in valley can be analogous to that of Mexico City during 1985 earthquake. Moreover, probability of near-field earthquakes in Kathmandu cannot be ruled out due to presence of some active faults beneath Kathmandu [2].

A rapid growth of population and haphazard urbanisation without proper engineering consideration in the last decade endangered a large number of buildings and a sizeable population of Kathmandu to earthquake hazard which was evident during the Mw7.8 Gorkha Earthquake of April 2015 as 1,739 people lost their lives and 13% of buildings were damaged in the valley. The ensuing aftershocks continued for several months, five of which were greater than M6.

The region of west Nepal lies in the seismic gap of Himalaya [3] where no large earthquake has occurred for over three centuries and a probability of a mega-quake (~M8.6) [4] looms large. In order to reduce the damage and fatality in case of future earthquakes, a study of strong-motion characteristics of the basin sediments in Kathmandu has become indispensable.

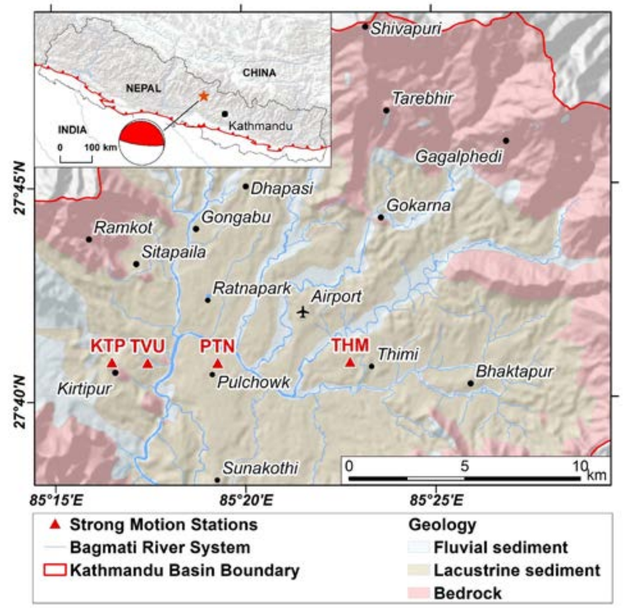

Figure 1 – Location map of the strong-motion accelerometers. Inset: Epicenter of the earthquake is marked by the red star and regional thrust MFT by red line.

In this context, a collaborative study between Hokkaido University and Tribhuvan University started in 2011 and four continuous recording accelerometers (Mitsutoyo JEP-6A3-2) were installed in Kathmandu (Fig.1). The station KTP was installed above the rock site at Kirtipur in west Kathmandu, and other three TVU, PTN, and THM were installed above the valley sediments. The shear wave velocity near KTP was 700 m/s whereas at other three sites, it was about 200 m/s [5] which imply presence of bedrock under KTP. Moreover one can see exposed bedrock around the station in KTP. To compare the response of three sites lying over the valley sediment, we considered KTP as the reference site with little or no site effect.

We carried out damage assessment of buildings around the stations to compare the records of the main shock with the damage caused by the earthquake. We compared the waveform and acceleration response spectra with the damage assessment results to determine the relationship between strong ground motion and the damage it caused around the stations.

2. Strong Motion Characteristics

The rupture of the earthquake originated form a shallow angle thrust propagated towards the east [6,7,8] triggering subsequent aftershocks with multistage rupture [7,9]. Most of energy was concentrated in the north part of Kathmandu [7]. Based on high-rate GPS station records from Kathmandu, it was revealed that the valley underwent permanent tectonic displacement of 135 cm towards S-SW direction and a vertical uplift of 63 cm [10] which matches the displacement waveform obtained from records of KTP [11].

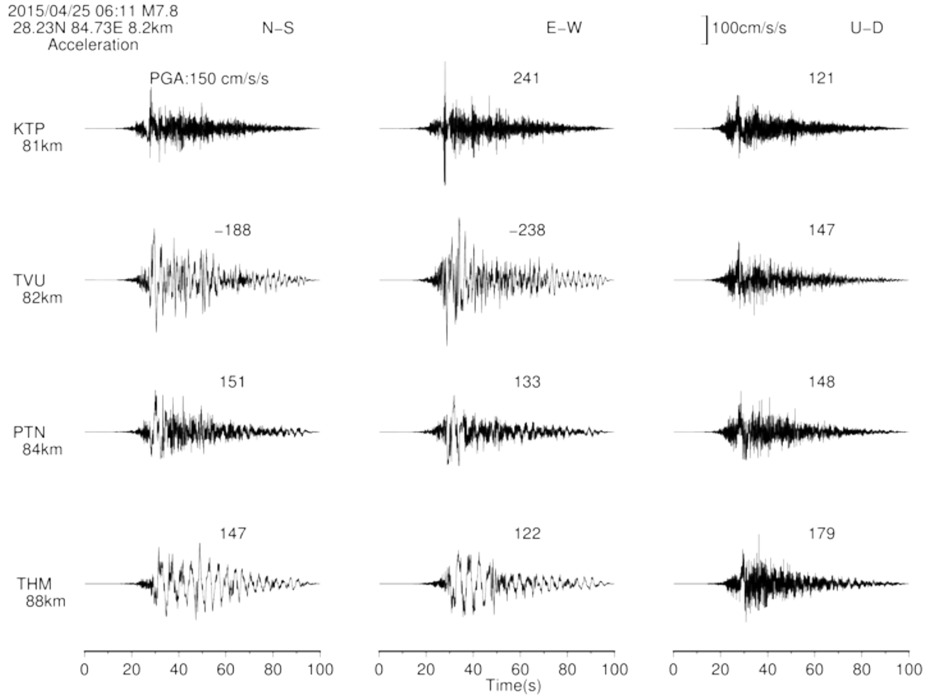

Figure 2 - Acceleration waveforms of the Gorkha Earthquake. Note the difference in horizontal waveforms between the rock site KTP and the other sediment sites. The difference is subtle in the vertical component.

The records of the Mw7.8 Gokha Earthquake (available for download in Takai et al [11]) show the highest PGA (241 cm/s^2) in the rock site of KTP (Fig.2); the velocity waveforms nevertheless, show high PGV in the sediment site of TVU (99 cm/s) [11]. The value of PGA are less than the value estimated by GMPE's [11,12,13]. The PGA of this earthquake (0.24 m/s^2) is less than expected for a large earthquake of this magnitude and the difference in predicted and observed values might be due to source effect [14] of the earthquake.

Though the Fourier spectra (Fig.3) in horizontal component in sedimentary stations clearly indicate presence of long period waves, dominant in ~0.3 Hz, the vertical component do not vary much with that from the rock site (Fig.2, Fig.3). This long period motion might have caused the rocking motion reported by people during the earthquake [14]. The Spectral Ratio shows significant amplification in horizontal components but less in vertical component.

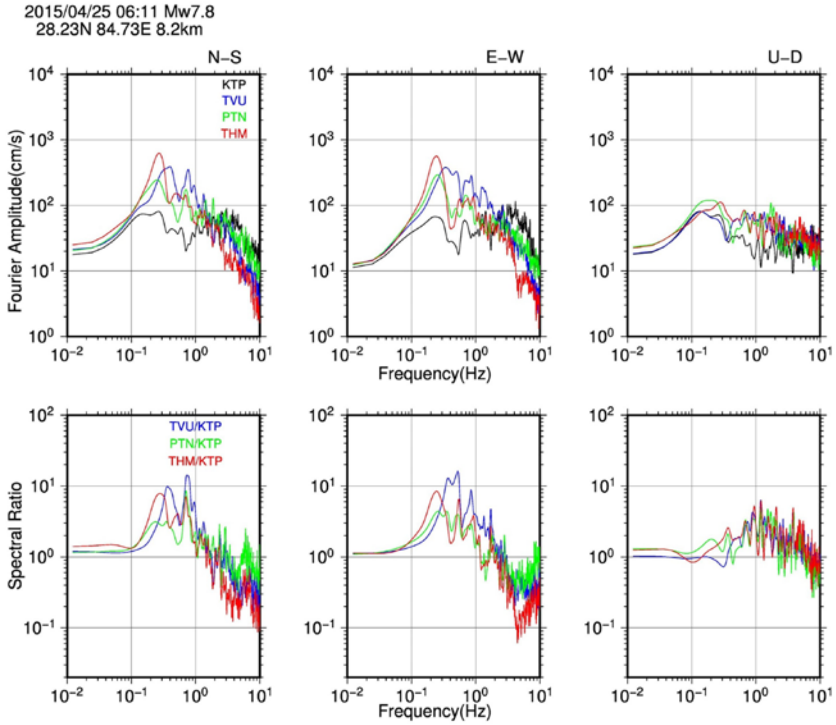

Figure 3 – Acceleration Fourier spectra (upper) and Spectral Ratio (lower).

3. Construction Practice in Kathmandu

The traditional buildings and monuments of Kathmandu are mostly made of bricks held together by mud-mortar. The contemporary RC structures also use masonry infills. The bricks were either sun-dried or fired in kiln depending on the convenience and financial status of the owner, but sun-dried bricks are not commonly found in buildings built after last quarter of the 20th century. Though, stone masonry is found in other mountainous regions of Nepal, use of bricks in Kathmandu might have started as the soft lake sediment of the valley could easily be molded into bricks and this practice has continued to the present.

The make of buildings affect its resistance to earthquake motion and structural damage and it was observed during the Gorkha Earthquake. We can broadly differentiate the buildings in Kathmandu into two classes according to material and practice of construction.

3.1 Masonry load-bearing structures

One can see a lot of vernacular architectural structures in old settlements of the Kathmandu valley. These load bearing masonry buildings typically reach 3-4 stories and were constructed using the locally molded bricks and mud-mortar. The walls are thick (~45 cm) on the ground floor but get thinner on higher floors [15]. The thickness is achieved by laying bricks in 2-3 layers or leaves parallel to the façade with gap between them filled with rubble [16]. Traditionally, the trend was to use fired brick on the outer and sun-dried bricks in the inner leaves, which has changed in favor of fired bricks on all leaves.

The old buildings have clay or mud mortar to hold the bricks but newer masonry buildings have cement mortar. In old monuments, palaces, and public buildings, a mixture of brick powder, and slaked lime [17] termed ‘*bajra*’ was used as a stronger substitute to mud-mortar.

In traditional buildings, a number of wooden joists lined parallel to each other and joined by sleepers or planks make the floor. The wooden pegs ’*chuku*’ holding these joists to the sidewall give them flexibility and restrain the sliding off during shaking but they cannot perform well during strong lateral motion from a large earthquake [18].

The low strength and lack of adequate structural members to resist lateral forces in these masonry buildings is the cause of damage during earthquake. Although, some buildings with wooden frames have withstood strong earthquakes, many load bearing structures get damaged by out-of-plane as well as in-plane failure. As time passes, the walls also get weakened by dampness and loss of mortar [19]. The mud-mortar can't hold the bricks in place and thus increase their vulnerability as was seen in city of Bhaktapur in east Kathmandu (Fig.4a).

3.2 Reinforced concrete frame structures

The contemporary Reinforced Concrete (RC) structures started to appear in Nepal around the late 70's [20]. RC buildings are designed as bare frame structures of 2-6 stories and un-reinforced masonry in-fills are added later. Construction of taller buildings nevertheless, have also been in rise. Not only have RC constructions become default practice, but many traditional masonry buildings are also being replaced by RC either by renovation or reconstruction.

The rapid rate of urbanization in Kathmandu has given rise to unplanned constructions without proper engineering consultation. This has given rise to many RC buildings with questionable qualities despite the fact that RC frame structures have better resilience to earthquakes compared to traditional load-bearing structures. The RC buildings built with current construction practices were found to be highly vulnerable to strong motion [20]. One can see buildings with highly asymmetrical designs of high vertical to horizontal ratios (Fig.4b) and RC frame structures on higher floors above mud-mortar masonry floors. In other cases, as owners wait for a suitable time to add additional floors, the RC columns and reinforcements on top of buildings are left exposed for a long time resulting in rust of rebar.

Figure 4 – a) Loss of mud-mortar from the fired-bricks in Bhaktapur, b) Asymmetrical designs of RC building in Kathmandu taken before the earthquake.

4. Damage Assessment Survey

The visual damage assessment was carried out in an area inscribed by 200 m radius from the four strong motion stations. This helps to compare the strong-motion characteristics of the earthquake and the damage it caused around the stations. We used the assessment method defined by European Macroseismic Scale 1998 (EMS98) [21]. Similar study was carried out in New Zealand after 2011 Christchurch Earthquake [22].

The damage extent described in EMS98 from Grade 1 (Negligible to slight damage) to Grade 5 (Destruction) were slightly modified for present study. We classified damage extent from 'Not damaged' to 'Heavily damaged'. The 'Negligible to slight damage (Grade 1)' and 'Moderate damage (Grade 2)' classification of EMS98 were named as 'Slightly damaged' and 'Moderately damaged' respectively. The 'Substantial to heavy damage (Grade 3)' and 'Very heavy damage (Grade 4)' classes were grouped as one: 'Heavily damaged'. The 'Destruction (Grade 5)' classification is not seen in the study as we didn't find instances of complete destruction of structures during the survey.

We evaluated the damage separately for Masonry and RC structures as mentioned in EMS98. We classified the buildings into: Masonry-mud mortar, Masonry-cement mortar, RC masonry, and RC steel masonry structures. Since, the strength of the aforementioned lime mortar '*bajra*' is considered to be more than ordinary mud mortar [17], we put the buildings using this mortar under Masonry-cement mortar.

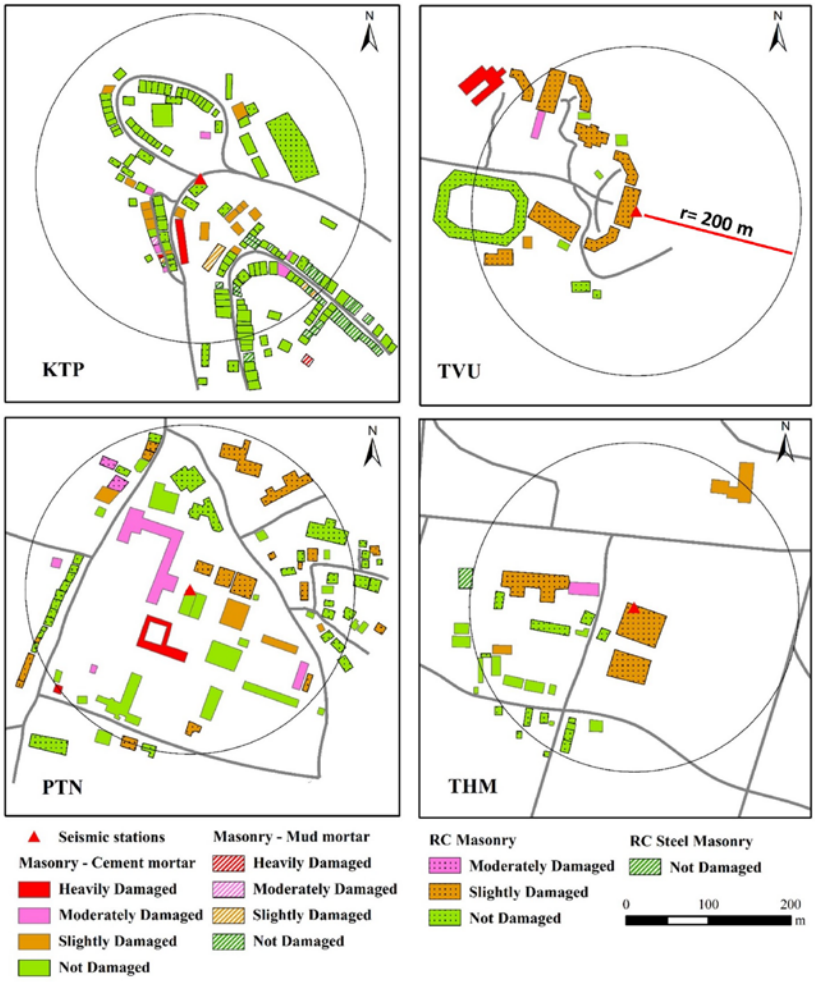

Figure 5 – Damage situation of buildings around the four stations.

4.1 KTP (Kirtipur Municipality Building)

Installed in the ground floor of a four-storied RC building of the Kirtipur Municipality Office in north-west end of the traditional town of Kirtipur in west Kathmandu, this is the station that lies above rock site conditions. Bed-rock exposures can be seen nearby. The topography is steep around the stations and buildings are constructed in a typical array system forming streets and narrow alleys. This area has a fair share (~18%) of traditional buildings with mud-mortar constructions, out of which ~81% suffered no damage during the earthquake (Fig.5). Almost all RC structures remained unscathed by the effect of earthquake.

Few masonry buildings (mud-mortar) showed instances of cracks (Fig.6a) in inner wall and we encountered few fallen roof tiles in some. A three storied building suffered complete collapse (Fig.7a) of a façade facing steep-topography baring the structural members. Overall, we found less than 6% of buildings suffered moderate to heavy damage during the earthquake.

Figure 6 – a) Cracks developed in masonry buildings of KTP, b) Damaged columns in ground floor of a RC buildings at TVU, c) Shear-cracks seen in a RC building in PTN, and d) Collapsed compound wall in THM.

4.2 TVU (Tribhuvan University)

As for TVU, the station lies in the premises of the Tribhuvan University and is installed in the ground floor of a two storied RC building of Central Department of Geology. There are only 19 buildings around it (Fig.5) which are being used as offices and lecture halls and none more than 2 stories tall. Most of them are RC structures and slight damaged were seen in most of them.

Damages in form of broken window panes and slight cracks on the ground floor were observed. There were damages to foundation and columns (Fig.6b) in some of the RC structures and a compound wall around one of the departments was completely collapsed. A single storied masonry cement mortar building constructed in late 60's suffered collapse of the walls and ceiling (Fig.7b) making it unusable. Statistically speaking, this site suffered the most damages (~10%).

4.3 PTN (Pulchowk Campus, Patan)

The station PTN is in downtown Lalitpur (Patan) city in the premises of Pulchowk Campus of Institute of Engineering, Tribhuvan University. Most of the building in the 200 m radius belongs to the campus and are predominantly masonry-cement mortar structures and the accelerometer is installed in one of the single-storied masonry building (Fig.5). The buildings outside the campus on the other hand, are mostly RC structures. Some of these RC buildings suffered cracks on the outer wall and beams. We found a multi-story building suffering from a number of shear-cracks on the outer façade (Fig.6c). Almost 9% of the total buildings considered for the study suffered moderate to heavy damage including two masonry buildings with '*bajra*' mortar (Fig.7c). One of them being used as office of the Architecture Department had been readily evacuated.

4.4 THM (University Grants Commission, Sano-Thimi)

The area under consideration in Sano-Thimi is the new settlement where most of the private buildings are RC frame structures but some public buildings of institutes, schools, and government offices are masonry structures. There is also a RC buildings with steel columns and we put it under the RC- steel masonry class. The strong motion accelerometer THM is installed on the ground floor of the four storied RC building of University Grants Commission. This building in this site suffered the least damage compared to others (Fig.5). The compound walls of the school and other office premises fell down (Fig.6d). A masonry building of high school developed wall cracks and tiles fell from roof of another masonry building (Fig.7d).

Figure 7 – a) Collapsed facade in KTP, b) Damaged masonry building in TVU, c) Damage to masonry building with '*bajra*' mortar, and d) Damaged school building in THM.

5. Discussion

The damage assessment carried out around the seismic stations can be compared with the strong motion records at the respective stations. In 2004, Sakai et al. [23] proposed an earthquake intensity based on acceleration response between 1-2 s period (I*) to explain damage to infrastructures and found that the JMA Instrumental Intensity couldn't explain the damage properly. We referred to this and found I* directly relates to heavy damages around the stations during the Gorkha Earthquake. We can see that this intensity is high for TVU (I*, Table 1) during the Gorkha Earthquake. This parameter can directly be associated with the damage power of the earthquake, as TVU suffered the heaviest damage among the four stations. The direct effect of site amplification can be clearly understood as area around KTP suffered less damage despite having old masonry buildings whereas in area around TVU, even comparatively new RC structures suffered damages.

In a similar damage assessment carried out in New Zealand after the 2011 Christchurch Earthquake, Iizuka, et al. [22] found a direct relationship between the response in 1-2 s and heavy structural damage. This shows the disastrous effect of high acceleration response in that particular period. Sakai and Nakamura [24] suggested that damage to masonry building is related to acceleration response in period shorter than 1-2 s which was observed in KTP, TVU, and PTN where masonry structures indeed suffered damage.

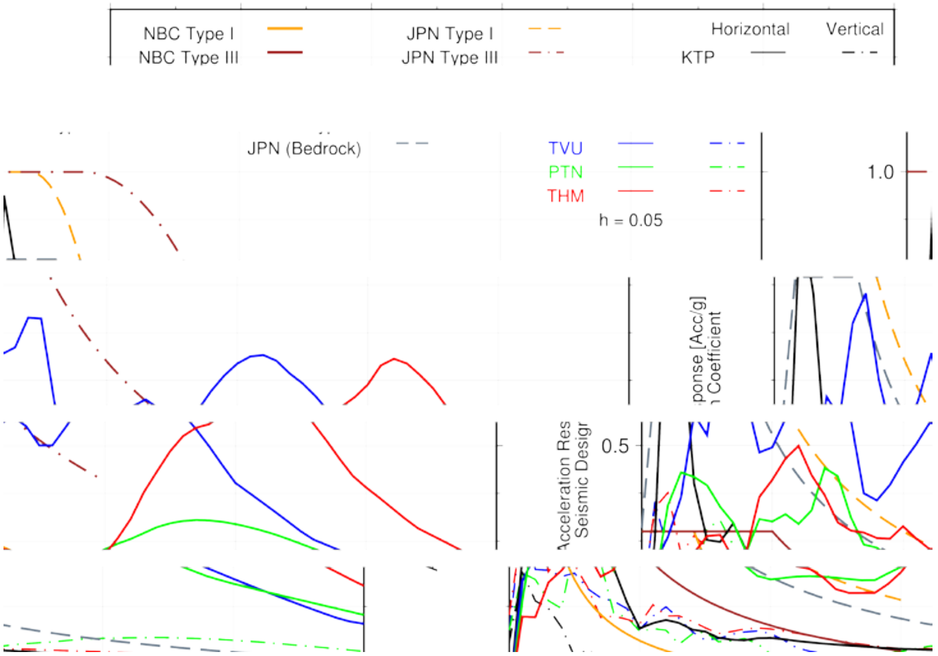

Figure 8 – Normalized acceleration response spectra of the mainshock; these were obtained based on records shown in Figure 2. The seismic design coefficient based on Nepal Building Code (NBC) and Building Standard Law of Japan (JPN) are also shown.

When we compare the acceleration response spectra with the seismic design coefficient based on Nepal Building Code (Fig.8), we can see that the code doesn't address an earthquake with these strong-motion characteristics. The Nepal Building Code (NBC-105) [25] drafted after 1988 Udaypur earthquake uses the basic seismic coefficient method and relates the seismic design coefficient (C_d) as a function of basic seismic coefficient (C), seismic zone factor (Z), importance factor of buildings (I), and structural performance factor (K).

The seismic design coefficient for Type I soil (hard rock/stiff soil) and Type III soil (soft soil > 30 m depth) based on NBC-105 is much lower than the responses of the record. The design requirement of Building Standard Law of Japan [26] for the same soil types, on the other hand is higher than the response of the earthquake. The Safety limit curve for engineering bedrock according to Building Standard Law of Japan [27] is also higher than KTP response except for very short period.

The high response of waves in longer periods indicates the dominance of low frequency waves which effect high rise buildings rather than low-rise buildings predominant in Kathmandu. This might explain the relatively low damages occurred in Kathmandu during this earthquake which is less catastrophic than previously anticipated [28]. Nevertheless, the low strength of load bearing masonry structures can be the cause of damages to vernacular architectures in the valley. The earthquake, on the other hand, would have seriously damaged high-rise buildings and base isolation structures which have longer natural period had there been any inside the valley. The acceleration responses for the vertical component are shown by dotted lines in Fig.8. As the vertical responses are considerably smaller than the horizontal ones, we believe contribution of the vertical component to damage is lower, if any, than the horizontal component.

Table 1– Summary of damage situation around the stations (I*: earthquake intensity based on acceleration response between 1-2 s period proposed by Sakai et al. [23])

Site	I* (1-2s)	PGA (cm/s^2)	Damage situation	Number of buildings	Damage Ratio (%)
KTP	4.28	241	Majority of buildings unharmed with less than 2% buildings heavily damaged	174	5.74
TVU	5.54	238	Cracks in RC building foundations, one masonry building completely collapsed	19	10.52
PTN	5.04	151	Few masonry and RC structures developed cracks	85	9.41
THM	5.03	147	Very few damage except in an old school masonry building	32	3.13

6. Conclusion

The Gorkha earthquake is rich in long period waves with high response in long periods and the records show significant amplification in the sediment sites. Acceleration response spectra show high response of TVU in 1-2 s period and it can be directly related to the damage to structures. This can be seen in contrast to the damages in KTP and TVU. Most of the old buildings built without proper engineering consideration in KTP survived the earthquake without substantial damage whereas even relatively new RC structures in TVU suffered visible damages. 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. The acceleration response spectra of the sites were much higher than seismic design coefficient prescribed by the Nepal Building Code which necessitates an update to the present building code to accommodate potential earthquakes of this magnitude which can occur anytime in the seismically vulnerable region of the Himalaya.

7. Acknowledgements

We would like to acknowledge Prof. Dr. M. R Dhital and Mr. Sudhir Rajaure from Central Department of Geology, Tribhuvan University, Nepal for their important role in maintaining the strong-motion network. A part of this study was supported by the Grant-in-Aid for Scientific Research No. 23404005 from MEXT, Heiwa Nakajima Foundation, Obayashi Foundation, and MEXT of Japan, under its Earthquake and Volcano Hazards Observation and Research Program. We would also like to thank anonymous reviewers for the insightful and constructive comments and suggestions.

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