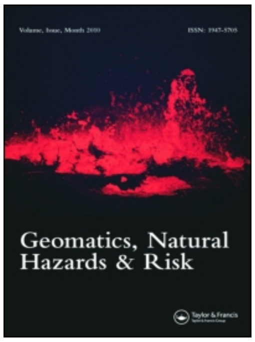

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Letter

Reconnaissance of the effects of the M7.8 Gorkha (Nepal) earthquake of April 25, 2015

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The M7.8 earthquake of 25th April, 2015 caused widespread damage in the Nepal region by destroying many residential, public, religious and cultural heritage buildings and roads due to intense shaking, surface fissures and landslides. This earthquake provided an opportunity to study the vulnerability of the built environment and reassessment of the risk exposure of the region. The reconnaissance trip was aimed at surveying the Kathmandu valley region in Nepal and adjoining districts of Bihar state in India due to their high population density and rapid urbanization. The observed damage in Kathmandu and the northern districts of Bihar were consistent with the intensity reported in these regions. Complete collapse was observed in RC buildings and old unreinforced masonry buildings due to inherent structural defects in regions of MM intensity VIII and IX. Significant number of cultural heritage structures suffered partial to complete collapse. These observations provide a perspective on the widespread lack of preparedness even when the seismic hazard of the Himalayan region is well established. This letter cites some of the poor construction practices that are followed in the Kathmandu valley region which make the built environment vulnerable to unacceptable levels of damage under expected design levels of shaking.

Keywords: Earthquake effects; seismic risk; Himalayan earthquake

1. Introduction

Learning from earthquakes is very essential as it provides an opportunity to re-evaluate the seismicity of the region, comprehend the good and bad construction practices, assess the risk exposure of the society and develop a framework for better preparedness during future seismic events. Nepal and the neighbouring regions suffered a major earthquake on 25th April, 2015 which was followed by strong aftershocks even after a fortnight of the main event. The disaster killed more than 8000 people, destroyed about half a million buildings completely and disrupted the road network in the hilly terrain by surface ruptures and landslides. On the positive side, this event lent an opportunity to understand the seismicity of the north-eastern Himalayas, built environment and the vulnerability of the region. The lessons learnt will help improve mitigating the seismic risk by ensuring earthquake-resistant construction suitable for the appropriate level of the hazard present, effective emergency response teams, and identifying topics for follow-up research activities in hazard estimation

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and measures adopted to reduce the vulnerabilities of the built environment (EERI 1986, 1996). This letter aims at providing a brief overview of the earthquake and its effects on structures as observed in the affected areas of Nepal and adjoining Indian states of Uttar Pradesh and Bihar during the field trip undertaken by authors during May 3–9, 2015 traversing over 2200 km.

2. Earthquake and its seismological setting

The M7.8 earthquake of April 25, 2015 struck at 11:41 am IST (11:56 am local time) with its epicentre located in Gorkha district (28.15°N 84.7°E) in the central Nepal, about 80 km NW of the capital Kathmandu (Figure 1). It was a shallow focus event (focal depth 15 km), felt in Nepal, India, Bhutan, Bangladesh, Tibet and China. Strong aftershocks of magnitude 6.6 and 6.7 were felt within a day of the main shock. Another strong aftershock of M7.3 occurred on 12 May 2015, 17 days after the main shock which was located at about 80 km NE of the Kathmandu (Figure 1). In Nepal,

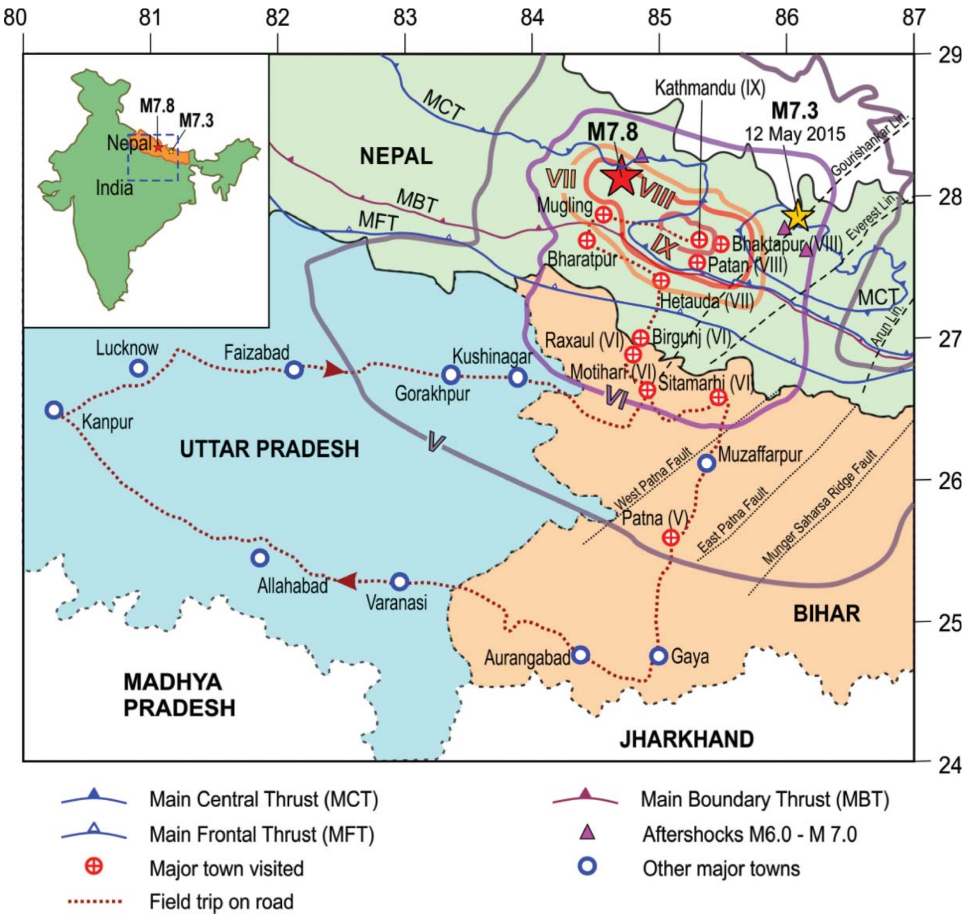

Figure 1. Location of epicentre of the earthquake and its aftershocks, Main Central Thrust (MCT), Main Boundary Thrust (MBT), Main Frontal Thrust (MFT), the towns visited in affected areas and isoseismals of the main event. To view this figure in colour, please see the online version of the journal.

the earthquake caused unprecedented loss of life and devastation. The worst affected regions in Nepal were Kathmandu, Bhaktapur, Nuwakot, Sindhupalchok, Dhading and Gorkha. A large part of the northern India, especially eastern UP, Bihar and north Bengal, also experienced moderate shaking during these earthquakes. Total deaths reported as on 25 May 2015 were 8686 in Nepal, 80 in India, 25 in China and 4 in Bangladesh.

The Himalayan region is one of the most seismically active regions in the world producing significant number of earthquakes of M8.0+ magnitude in the past due to the thrusting of Indian plate underneath the Eurasian plate at the rate of 40–50 mm/year. This boundary region has a history of large and great earthquakes especially in between the Major Boundary Thrust (MBT) and Major Central Thrust (MCT). The 25 April and 12 May 2015 earthquakes occurred as the result of thrust faulting on or near the Main Himalayan/Frontal Thrust (MFT) interface between the Indian plate and the Eurasian plate (USGS 2015). Four events of larger than M6.0 have occurred within 250 km of this earthquake over the past century. The largest M8.1 event, known as the 1934 Nepal–Bihar earthquake, caused widespread damage in Kathmandu and Bihar, and around 10,000 fatalities were reported. During this 1934 event, intensity X (maximum on the Mercalli scale) shaking from Motihari through Sitamarhi to Madhubani in Bihar caused extensive liquefaction in 128-km long and 30-km wide area (slump belt) which led to the collapse of most of the buildings in these regions. The M7.8 earthquake was not completely unexpected in the Central Nepal region, as several studies had indicated likelihood of earthquakes of magnitude greater than 8.0 based on the slip deficit estimation and accumulation of strain energy in the region. This has been anticipated in early 1990s and further confirmed by recent studies (Bilham 1994; Bilham et al. 1995, 2001; Ader et al. 2012; Sapkota et al. 2013; Bollinger et al. 2014).

The ground motions of main event and aftershocks were recorded at USGS station KATNP (27.71 N, 85.32E), Kathmandu; these records are available at Center of Engineering Strong Motion Data (CESMD 2015). The reported values of peak ground acceleration and velocity were 0.164 g and 107.30 cm/s, respectively (see Figure 2(*a*) for acceleration and velocity time histories). It should be noted that the peak ground velocity is much larger than typically expected for the observed PGA of 0.16 g (Newmark and Hall 1982). This is important as peak ground velocity is better correlated with the damage statistics of mid- to high-rise buildings (Wu et al. 2003). Moreover, the peak ground displacement (PGD) recorded at the USGS station in Kathmandu was around 100 cm. Such high PGD can significantly influence the response of very flexible systems such as buried pipelines and railway tracks.

Kathmandu lies in zone A on the seismic zoning map of Nepal (NBC 1994a), whereas the districts of Bihar (India) adjoining the Nepal border lie in zones IV and V on Indian seismic zone map (BIS 2002). The seismic zone A of Nepal is equivalent to zone V of India which corresponds to very severe seismic intensity. In Figure 2(*b*), response spectra of the recorded ground motions are compared with the code-prescribed elastic design response spectrum in zone A of the Nepal seismic code and zone V of the Indian seismic code for the design basis earthquake (DBE) in soft soil site. The USGS global V_{S30} server indicates that the central part of Kathmandu valley has soft soil deposits which are typically NEHRP site class D (V_{S30} between 180 and 360 m/s). It is clear that in the acceleration-controlled regime (i.e. short period range which is typical for low-rise unreinforced masonry and infilled reinforced

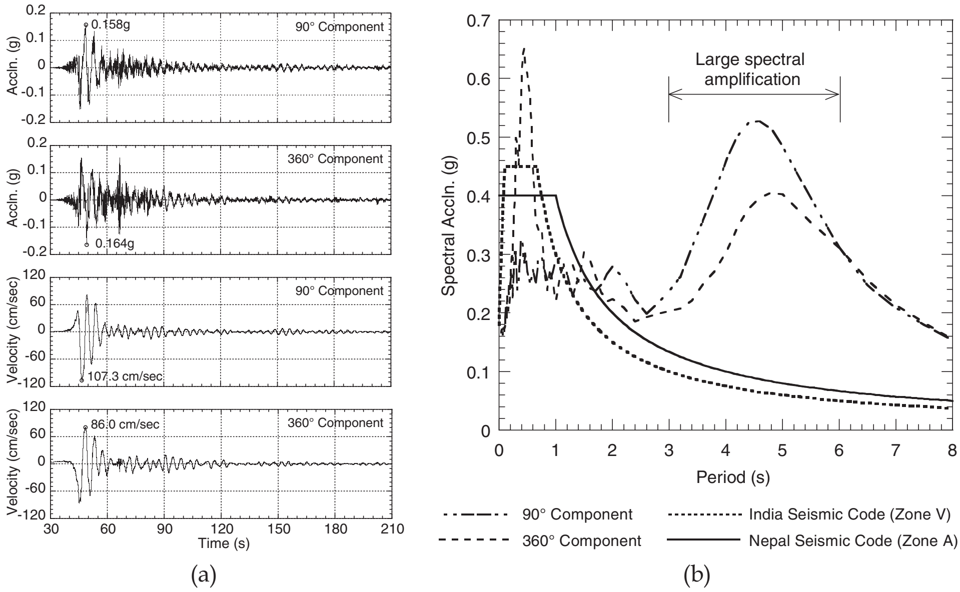

Figure 2. (*a*) Acceleration and velocity time histories for the main shock of the 25 April 2015 event recorded at Kathmandu, and (*b*) comparison of 5% damped acceleration response spectra of recorded ground motions with the Indian and Nepalese seismic code-specified elastic design response spectrum for the design basis earthquake in soft soil site.

concrete (RC) frame construction), the ground motion has higher acceleration demand than the code-expected demand in the most severe seismic zone.

Geologic studies show that the Kathmandu valley is covered by thick semi-consolidated quaternary sediments with the maximum depth of 550 m in the central part of the valley (Piya 2004). An earlier study on local site amplifications due to unconsolidated quaternary sediments of Kathmandu valley has indicated that the resonant frequencies were in the range of 0.5−8.9 Hz with the maximum amplification occurring at 2 s in the central lacustrine area (Paudyal et al. 2012). However, in addition to amplification at 0.5 s (2 Hz), unusual higher spectral amplification was observed in the range of 3−6 s (0.17−0.33 Hz), which could also be due to the complex influence of underlying unconsolidated quaternary sediments in the basin. These sediments were deposited in two stages with granular fluviatile stage overlain by the clayey lacustrine. Similar basin effect has been observed in the past few earthquakes including the notable 1985 Mexico City earthquake where the ground acceleration was amplified by about 10 times at 2-s period due to the presence of lake deposits which resulted in large devastation even at a distance of 300 km from the epicentre (Kramer 1996).

3. General observations

During 3 May to 9 May 2015, authors undertook a reconnaissance survey of the earthquake affected regions and visited (by road) major towns in Bihar (India) and Nepal (visited towns are marked in Figure 1). In the April 25, 2015 earthquake, the Kathmandu valley experienced intensity IX shaking, which left many buildings and temples in ruins. The regions around Kathmandu reported an intensity of VII in Nepal. In India, maximum intensity of VI was observed in some parts of northern

Bihar, hence only few buildings were damaged during the event. Isoseismals of main earthquake event are shown in Figure 1. These isoseismals are generated based on the observations during the field visit and intensity map reported by USGS (USGS 2015)

3.1. Extensive damage in Kathmandu valley, Nepal

Kathmandu valley, comprising major cities Kathmandu, Bhaktapur and Lalitpur, is surrounded by four mountains Shivapuri, Phulchoki, Nagarjun and Chandragiri. Kathmandu, with a zone factor 1.0 according to the Nepal seismic code NBC 105 (NBC 1994) is expected to experience PGA value higher than the recorded value. Though it is about 80 km away from the epicentre, it experienced a shaking intensity higher than the regions around the epicentre. From the structural damage evaluation, it has been found that the damage was concentrated in a few pockets of the Kathmandu valley such as Khadka Gaon, Sitapaila, banks of Bishnumati River in Machha Pokhari and Nikosera. Similar localized site responses were observed in Los Angeles during the 1994 Northridge earthquake and in Mexico City during 1985 earthquake. The San Fernando and Los Angeles basins containing alluvial deposits experienced high site response factors due to the amplification of the ground motion and the focusing effect of the valley (USGS 1996).

The microtremor study (Paudyal et al. 2012) shows that the dominant period of the ground in Kathmandu valley changes abruptly within a short distance due to the variability in the sediment thickness and its properties. The geomorphological map of Kathmandu valley (OCHA, Nepal) shows the central region of the valley; mainly Kathmandu, Bhaktapur and Patan are formed by recent river deposits. Hence, it is understood that the extensive damage in few regions of the Kathmandu valley can be because of the amplification due to the soft soil deposits and the long-period domination in the central part of the valley which is also observed in the response spectra of recorded ground motion (Figure 2(*b*)). The valley surrounded by four mountains is also susceptible for focusing of seismic waves. There could be other factors which have resulted in concentrated damage but due to the lack of sufficient ground motion records the soil amplification and focusing effect cannot be proved currently.

The contour map of dominant period of ground of the Kathmandu region is shown in Figure 3 (redrawn after Paudyal et al. 2012). Various places where major damage was observed are also indicated in Figure 3. These dominant period contours provide some valuable information which can be correlated with the observed damage. The old unreinforced masonry buildings in Nikosera (marked as 3 in Figure 3) generally fall under the acceleration-sensitive region of the spectra with a period range of 0.1–0.6 s which closely matches with the dominant period of ground of the affected region (0.11–0.80 s). Similarly, the failure of the Dharahara tower (12), a 203-feet tall unreinforced masonry tower, could also be related to the long-period dominance in the central region (1.30–2.05 s). The USGS station KATNP (13) also lies in the central area of the valley with long-period dominance, hence the record from this station cannot be used as a representative data for the entire Kathmandu valley. Thus, for better understanding of the seismicity of the region, strong motion stations should be set up at numerous locations.

The fundamental time period of multi-storey RC buildings can be approximated as $0.1N$, where N is the number of storeys (Kramer 1996). Hence, buildings of 10–20-storey height possess fundamental time period in the range of 1–2 s, which is the predominant frequency in the central region of the valley. The time period of 14-storey Parkview Horizon building (6), which suffered major damage to the masonry infills,

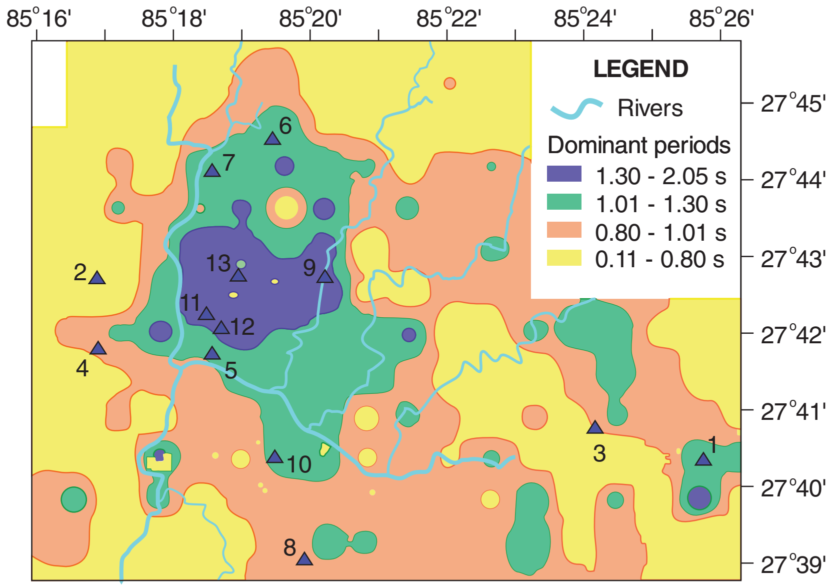

Figure 3. Variation of dominant period of ground of the Kathmandu valley (Paudyal et al. 2012). Various places where major damage was observed are also indicated in the map (1: Bhaktapur Durbar square, 2: Sitapaila, 3: Nikosera, 4: Kalanki bus stop, 5: Teku road, 6: Parkview Horizon apartments, 7: Gongbu new bus stand: 8: Cityscape apartments, 9: Kalopul, 10: Patan Durbar square, 11: Kathmandu Durbar square, 12: Dharahara tower, 13: USGS KATNP station). Reproduced with permission from J. Earthquake Engineering, 16, 8 (2012). Copyright 2012 Taylor and Francis. To view this figure in colour, please see the online version of the journal.

falls dangerously close to the dominant period range of 1.01–1.30 s. Thus, the development of new high-rise buildings should be regulated based on the study of soil profile and its properties. The construction of buildings along the banks of river such as in Kalopul (9) and along banks of river Bishnumati near Gongabu Bus stand (7), Machha Pokhari also led to severe damage.

3.2. Damages on the earthquake affected regions in India

In India, since the intensity of shaking was small (less than VI), even poorly built structures did escape serious damage during this event; however, damages were reported in *kaccha* houses (non-engineered masonry buildings constructed from stone/bricks and mud mortar) in Sitamarhi district, north Bihar. About three such houses were completely collapsed and 142 were partially collapsed. Damage to free-standing masonry walls were also reported in parts of Bihar and Uttar Pradesh. Most of the RC frame buildings in affected regions in Bihar are not constructed as per the Indian code of practice and have many structural deficiencies. Thus, a significant portion of the building stock in Bihar is highly vulnerable to severe damage under expected shaking intensity of IX (corresponding to zone V). This region had already witnessed the maximum shaking intensity of X on Mercalli scale during the M8.1 1934 Nepal–Bihar earthquake which caused widespread damage in north Bihar districts. Civic authorities in these areas in spite of being aware of the unacceptable level of seismic risk appear to have no risk mitigation strategies.

4. Structural damages

General damage to buildings and other structures agreed well with the intensity of ground shaking observed at various places, with the maximum of IX at Kathmandu, Nepal; VIII at Bhaktapur and Patan, Nepal; and VI in and around Sitamarhi, Bihar on MSK scale. The most popular types of buildings in the Kathmandu valley were those of reinforced concrete followed by unreinforced masonry. The common building types along with their structural components and major structural defects are summarized in Table 1.

4.1. Unreinforced masonry buildings

The unreinforced masonry (URM) buildings in the Kathmandu valley region were characterized by thick walls (450–750 mm) made of clay brick units with thin mud mortar which were unsupported over a large height. Many such 50–60-year-old unreinforced masonry buildings in Nikosera (near Bhaktapur) were severely damaged not only due to their deteriorated strength but also due to their inherent structural defects. The poor performance of the URM buildings can be attributed to the absence of box action under lateral loads (Figure 4). The provision of continuous horizontal bands at different levels of the building helps the structure maintain integrity, with all the walls and the floor acting together as a single unit. Hence, most URM buildings suffered moderate to major damages mainly due to the lack of

Table 1. Common building typologies and observed damage due to various structural defects.

Building type	Observed damage	Structural system	Major structural defects
Unreinforced masonry buildings	Extensive damage in old Bhaktapur city and rural parts of Nepal	• 450–750 mm thick handmade clay brick walls • Timber floor and roof system	• Lack of interlocking connection between main and cross walls • Flexible diaphragm and poor diaphragm-to-wall connection • Absence of continuous horizontal bands for developing confining box action of walls
RC frame buildings	No to moderate damage in well-built structures but extensive damages in poorly built and non-engineered buildings	• Moment resisting RC frame system • Clay brick and concrete block masonry infills • Rigid RC slabs	• Presence of soft/weak stories • Projection of walls beyond the column grid lines • Lack of continuous RC bands above and below openings • Absence of RC columns at critical locations
Old cultural heritage structures	Extensive damage in the Durbar squares	• Double leaf thick masonry walls with random bricks or earth filled in between • Timber frame • Timber floor and roof system	• Thick walls with improper connections between floor/roof diaphragm and intersecting walls • No interlocking between the masonry wythes • Deteriorated strength of masonry and timber

Figure 4. Performance of 50–60-year-old URM buildings at Nikosera in Bhaktapur: (*a*) collapse of three-storey unreinforced masonry building, (*b*) out-of-plane failure of the masonry wall, (*c*) combined in-plane and out-of-plane failure of the wall, and (*d*) collapse of a building due to poor connection of wall with the floor and cross walls. To view this figure in colour, please see the online version of the journal.

horizontal bands, which was further aggravated due to the poor connection between the walls and floors (Figure 4(*a*)–(*d*). The absence of confining members at the corners of the building plan added to the poor performance of the buildings, as vertical cracks were initiated along the corner of masonry walls leading to loss of structural integrity, making the walls highly vulnerable to out-of-plane collapse (Figure 4(*a*) and 4(*c*)). The timber floors and roofs used created a flexible diaphragm and the poor connection between diaphragm and walls was ineffective in resisting the lateral forces. Also, the poor bonding of the cross walls with the main wall along with the associated heavy mass resulted in the collapse of the walls in out-of-plane direction as shown in Figure 4(*d*). The in-plane damage caused step-type diagonal cracks in the masonry wall which were extended to the full storey height. It also resulted in the decrease of the out-of-plane capacity of the wall, which caused the combined in-plane and out-of-plane failure of the wall in some buildings as shown in Figure 4(*c*).

4.2. Reinforced concrete buildings

Most of the RC buildings in Kathmandu suffered varying degree of damage, ranging from moderate to complete collapse during this earthquake. Many inherently poor

(a) (b)

Figure 5. (*a*) Open ground storey failure of four-storey building in Sitapaila, Kathmandu, and (*b*) intermediate storey failure of four-storey building in Kalopul, Kathmandu. To view this figure in colour, please see the online version of the journal.

construction features significantly added to the seismic vulnerability of these structures. Buildings with open ground storey have performed very poorly in the past earthquakes and similar performance was observed during this earthquake. As shown in Figure 5(*a*), a residential building with open ground storey in Sitapaila, Kathmandu, which stood immediately adjacent to another building, collapsed due to plastic hinge formation in the ground storey columns and moved away laterally about 3 m from the adjacent building. Another residential building in Kalopul, Kathmandu collapsed due to the presence of weak storey at the second floor (Figure 5(*b*)). There were many examples of pancake collapse of various commercial and residential buildings (Figure 6). The collapse of these buildings was caused by the formation of

(a) (b)

Figure 6. (*a*) Open ground storey failure of two adjacent buildings in Sitapaila, Kathmandu, and (*b*) complete collapse of residential building in Khadka Gaon, Kathmandu. To view this figure in colour, please see the online version of the journal.

Figure 7. Various structural defects in newly constructed residential buildings: (*a*) absence of column at the intersection of two walls, (*b*) projection of masonry wall beyond the column grid line, (*c*) and (*d*) damage to the wall panel due to absence of confinement all around the openings. To view this figure in colour, please see the online version of the journal.

weak storey mechanism due to the inadequate wall area, small sizes of RC frame members and poor reinforcement detailing at critical locations.

Severe damage was observed in many non-engineered buildings which had been constructed recently. Use of half-brick thick partition walls (about 120 mm thick) and construction of buildings on sloping ground without proper assessment of the site condition increased the level of damage in the buildings. The absence of confining members/columns at the critical locations such as at the intersection of two walls, areas adjacent to door openings and at the outer periphery of the building resulted in extensive damage in many houses (Figure 7). The lack of adequate columns at the corners of the building resulted in lower stiffness of the walls projecting beyond the column line, leading to separation cracks at the regions of projection and severe damage to masonry walls (Figure 7(*a*) and 7(*b*)). The absence of continuous horizontal concrete bands around openings, as in the case of URM buildings of Bhaktapur, also caused severe damage in the masonry infill RC frame buildings (Figure 7(*c*) and 7(*d*)).

Figure 8. Seventeen-storey apartment building in Patan: (*a*) shear cracks in the lower storeys of infill wall; (*b*) combined in-plane and out-of-plane failure of the extended infill wall in upper storeys. To view this figure in colour, please see the online version of the journal.

It was rather surprising that many tall RC apartment buildings which were supposed to be engineered construction had suffered significant damage. These high-rise RC structures suffered from similar structural defects as observed in the non- engineered construction. Large diagonal cracks in masonry panels and cracks at the interface between boundary frame and the wall was very common in multistorey-infilled RC frames. A 17-storey tall RC apartment building in Patan suffered damage in the form of diagonal cracks and combined in-plane and out-of-plane failure of infill panels (Figure 8), which can be attributed to the use of weak and slender walls, partial open-ground storey and box-type extension of walls beyond column line. Non-compliance with the building codes and poor monitoring of the development in the valley have led to conversion of many three-storey buildings to multi-storey high-rise structures which have contributed in further increasing the seismic vulnerability of the valley.

Buildings in the worst affected regions were built very close to each other, in many places with almost no gap between them. Pounding of such buildings led to chain of collapses in the densely built environment and some leaned out of plumb (Figure 9(*a*) and 9(*b*)). Buildings were also collapsed due to the vertical irregularity caused by the extension of the upper storey plan beyond the column grid lines (Figure 9(*b*)). An overview of the seismic performance of RC buildings suggests that some of the key features that contributed to the poor performance of the structures include inadequate size and poor reinforcement detailing of the RC frame members, poor beam–column connection details, weak and slender brick masonry partition walls, extended floor plans in upper stories supported on cantilevered beams and slabs, open ground and soft storey, large vertical and horizontal plan irregularity, discontinuity in load transfer system, and lack of soil investigation. Such poor construction features also resulted in widespread damage to RC buildings in Sikkim during the M6.9 India–Nepal border earthquake of September 2011 (Rai et al. 2012).

4.3. Cultural heritage structures

The cultural heritage structures suffered extensive damage during this earthquake. Especially the historical temples and palaces in the urban centres of Kathmandu,

(a) (b)

Figure 9. (*a*) Collapse of intermediate storey due to pounding of adjacent building, and (*b*) collapse due to extension of the upper storey plan beyond the column grid lines which created vertical irregularity. To view this figure in colour, please see the online version of the journal.

Bhaktapur and Patan suffered severe damage. The *dega* temples of Nepal are built with timber structural frame and brick masonry walls. The thick masonry walls are made of two leaves, with the inner leaf of simple rendered finish, the outer leaf well dressed and the cavity filled with rammed earth (Bonapace & Sestini 2003). Such *dega* temples have collapsed completely and some were moderately damaged in Kathmandu, Bhaktapur, and Patan Durbar squares (Figures 10 and 11). These temples have been found to be short-period structures (fundamental natural period less than 0.6 s), and masonry piers near the base were the most critical components susceptible to large compressive and tensile stresses (Jaishi et al. 2003). Unreinforced masonry buildings in the Palace complex of Kathmandu Durbar Square also suffered severe damage (Figure 11(*b*)). The flexibility of the wooden flooring system and lack of rigid connection between the walls and the diaphragm led to the poor lateral

(a) (b)

Figure 10. (*a*) Complete collapse of dega temples in Hanuman Dhoka, Kathmandu, and (*b*) collapse of Vatsala Durga temple made of sandstone in Bhaktapur Durbar square. To view this figure in colour, please see the online version of the journal.

(a) (b)

Figure 11. (*a*) Partial to complete collapse of temples in Bhaktapur Durbar square, and (*b*) severe damage to unreinforced masonry buildings in the Palace complex of Kathmandu Durbar square. To view this figure in colour, please see the online version of the journal.

strength of the structure, and the heavy mass of the buildings due to the presence of thick walls increased the seismic vulnerability of these *dega* temples.

Stone temples are less in number in Kathmandu valley; however, many of them survived with minor to no damage. In Bhaktapur, Vatsala Durga temple made of sandstone collapsed completely (Figure 10(*b*)) whereas Siddhi Lakshmi stone temple had a toppled spire. The famous 203-feet tall Dharhara tower in Sundhara, Kathmandu, rebuilt with clay brick masonry after the destruction in 1934 Nepal

(a) (b)

Figure 12. Dharhara tower in Sundhara, Kathmandu: (*a*) before earthquake ("Creative Commons Dharhara November 10, 2011" by Sugat Shrestha is licensed under CC BY-SA 3.0, link: creativecommons.org/licenses/by-sa/3.0/), and (*b*) after earthquake. To view this figure in colour, please see the online version of the journal.

earthquake was completely collapsed as shown in Figure 12. Almost all the brick masonry temples suffered severe damage during the earthquake.

5. Rescue and relief

The rescue operations were still in progress in the Kathmandu valley as well as in other places after a week of the event. The Nepal Army, the Armed Police Force of Nepal, the National Disaster Rescue Force (NDRF) of Indian Army and army personnel from 12 countries were deployed in the severely affected areas of Nepal. From NDRF, 16 teams of 50 personnel each have carried out rescue operations across Nepal. However, the rainfall that followed the earthquake and the risk of collapse of buildings due to potential aftershocks impeded the rescue efforts. A closely spaced group of guest house buildings in Gongabu, Kathmandu suffered partial to complete collapse and people trapped under the rubble were still being evacuated by the rescue teams by drilling passages in the building at the time of the visit. Also, there was concern about epidemics due to lack of safe drinking water and toilet facilities. International aid was received from different countries across the world in the form of rescue and relief teams, as well as relief materials such as aircrafts for search and rescue operations, dry food, drinking water, medicines, blankets and tents.

6. Preparedness for future earthquake

The Gorkha earthquake and its strong aftershocks have provided an opportunity to review the preparedness of the society and the government at times of disaster.

(1) *Implementation of seismic design practice*: The reconnaissance study shows that the severe damage and complete collapse were in old unreinforced masonry buildings, traditional heritage structures with flexible building components and RC buildings with poor design and construction. The damage was localized in few places of the valley and well-built buildings endured the shaking with minor cracks, which substantiates that the damages were due to local site effects and poor building construction and design. Hence, the construction of new structures and retrofitting of old buildings should consider the local characteristics of the ground and implement the required seismic design guidelines.

(2) *Microzonation of Kathmandu valley*: The peak ground acceleration though low, the long-period dominance in the ground motion data shows the influence of soft soil deposits on the seismic waves. Seismic microzonation of the Kathmandu valley has to be developed based on the geomorphological characteristics of the region. The design acceleration spectra given in the Nepal Building code has to be modified considering the soil amplification effect. The construction of high-rise buildings in the region, which are vulnerable to resonance with the longer dominant period of the sub-surface, has to be regulated.

(3) *Dense network of strong motion recording stations*: There has been a severe dearth of ground motion data during this event, which if available would have been of great use to the scientific community in understanding the soil amplification, basin effect and focusing effect of seismic waves in the valley. Implementation of strong ground motion sensors in this seismically active region will provide significant information.

(4) *Protection of heritage structures:* Kathmandu is very rich in history and culture, and its palaces, temples and monuments are important for the economy and tradition of the society. Kathmandu has lost many of its monuments in the past earthquakes and in the April 2015 Gorkha earthquake. Hence, scientific experimental and analytical studies on the surviving structures have to be performed for devising retrofit measures and also for reconstruction of collapsed buildings.

(5) *Economical earthquake-resistant construction for rural regions*: The majority of buildings in the seismically active Nepal and north Bihar are unreinforced masonry buildings of one- or two-storey height. Confined masonry with good plan configuration and sufficient wall thickness is an effective and economical solution (Singhal & Rai 2014). Since most of the buildings in this region are non-engineered, the masons have to be trained in earthquake-resistant practices to minimize the damage in future event reminiscent of the devastating 1934 Bihar–Nepal earthquake.

(6) *Awareness among stakeholders*: After the damage from main shock, buildings become vulnerable to complete collapse during the aftershocks. The strong aftershocks of this earthquake have exposed the lack of sufficient temporary shelters to accommodate the people, large open spaces and rapid repair and retrofitting of buildings. Awareness on seismicity of the region among the people, rapid response from the government officials and promotion of economical earthquake-resistant construction have to be improved.

7. Conclusions

The damage to built environment and number of casualties due to the Himalayan earthquakes have been increasing proportionally with the growth of population and settlements. The seismic vulnerability of different types of structures was exposed during this event. While most of the old masonry structures including the heritage temples suffered partial to complete collapse, well-constructed RC frame structures performed well with minor cracks. However, dramatic collapse of many RC frame structures was observed due to the poor construction practices such as open ground storey, inadequate size and poor reinforcement detailing of columns, poor geometric configuration of the buildings, insufficient spacing between adjacent buildings, projection of walls beyond the column lines, weak and slender masonry infill walls and lack of proper site investigation for constructions on sloping ground.

Many historical structures of cultural importance in the World Heritage sites of the Dharahara Tower and the Durbar square Complexes in Kathmandu, Bhaktapur and Patan suffered maximum damage during this event. Proper seismic evaluation of the old temples and heritage structures which survived this event is essential so that they can be safeguarded against future earthquakes. On the Indian side, even the poorly constructed buildings escaped from damage due to the low intensity of shaking. However, the high density of population in northern Bihar and similar flaws in construction practices increase the seismic risk in the region to unacceptable levels. This trend may lead to a large-scale disaster as evidenced by the M8.1 1934 earthquake, if the growing seismic risk is not mitigated by promoting the elements of seismic safety and the earthquake-resistant construction practices. Despite the available knowledge base, it is unfortunate that society is not adequately prepared due to lack of implementation and, therefore, the seismic risk in the region capable of large earthquakes has risen to unacceptable levels which may lead to a large-scale disaster, if not mitigated.

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