Reconnaissance Investigation on the damages of the 2015 Gorkha Earthquake, Nepal

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1. INTRODUCTION

The Gorkha earthquake (reported as Mw 7.8 by USGS and as ML 7.6 by NSC) with epicentre in Barpak village of Gorkha district occurred on April 25th at 11:56 a.m. Nepal Standard Time (NST). The earthquake epicentre were reported from two different sources as: (a) at 28.147°N, 84.708°E with a focal depth of 15 km reported by USGS and (b) at 28.24°N, 84.75°E by NSC. The epicentre was located approximately 80 North-West from Kathmandu, the capital city of Nepal. Several aftershocks were recorded after the main event of 25th April. On the noon (12:50 p.m. local time) of 12th May, a major aftershock (reported as Mw 7.3 by USGS and as ML 6.8 by NSC) with epicentre at Dolakha district struck the region resulting in further damages and casualties.

The earthquakes had a significant effect on the hilly district of central Nepal including Kathmandu Valley. The earthquake had significant on the heritage structures and temples and traditional buildings. Kathmandu valley, situated on the bank of river Bagmati, is house to numerous historic buildings and seven UNESCO world heritage sites. Amongst the seven UNESCO world heritage sites, Kathmandu Durbars Square had the most severe damages with the collapse of multiple temples and damages to others. The quake also resulted in the collapse of historical structures at Patan Durbar Square, Bhaktapur Durbar Square, Swayambhu monastery and Changu-Narayan temple.

Extensive damages to the built structures were observed in the epicentral areas of Gorkha. Damages of similar proportion occurred in Sindhupalchowk district, the epicentre of 6.9 magnitude aftershock of 26th April. The aftershock of 12th May resulted in significant damages to the areas of Dolakha district. These aftershocks further aggravated the damages at the central hills of Nepal that were already stricken by the main shock of 25th April. Many structures already weakened by the earthquake 25th April event and following numerous aftershocks could not survive the temblor of 12th May. Nearly 8 million people were affected by the earthquake sequence.

This report presents the finding of a reconnaissance study carried out in the Central Nepal after the earthquake of 25 April 2015. The study was undertaken on behalf of the Australian Earthquake Engineering Society (AEES) to collect the on-site data and information from the field that could provide the useful lesson for future. The details presented are based on the reconnaissance works carried out in the various sites of Kathmandu valley, Kavrepalanchok, Sindhupalchok and Dolakha districts as presented in Fig.1 during the period from 26th April to 28th May 2015. A brief discussion on regional seismotectonic and past seismicity is presented in the report followed by a discussion on the performance of the building structures during the earthquake. Finally, geotechnical failures observed during the earthquake are discussed.

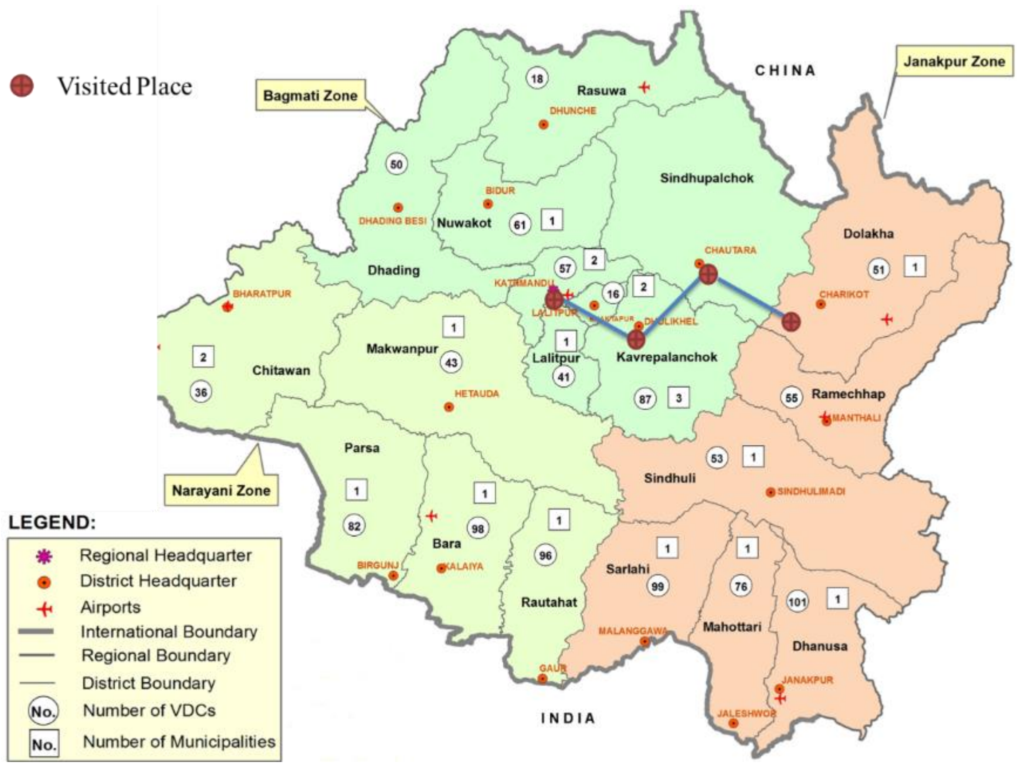

Fig. 1 Districts visited in the affected area.

2. SEISMOTECTONICS AND PAST SEISMICITY

Seismicity in the Himalaya region results from the continental collision of the Indo-Australian plate with Eurasian plate, which is converging at a relative rate of 30-50 mm/yr. The convergences of two plates generate numerous earthquakes and consequently make this place one of the most seismically active regions on the earth. Fig. 2 shows the tectonics features of the region. Northward underthrusting of Indian plate beneath Eurasian plate resulted into the development of two regionally northerly dipping convergent zones; the MCT and MBT. The MBT is a series of thrusts that separates the lesser Himalaya from the sub-Himalaya belt (Rout et al. 2015). The MCT at the base of the central crystalline zone dips northward separating the Higher Himalaya from the Lesser Himalayas (Gansser 1977).

Nepal takes approximately one-thirds of the length of the Himalaya and has been frequently hit by large earthquakes. Records noted on some Nepalese religious tract indicate that a big earthquake hit Kathmandu in 1255 AD (Parajuli 2009). The quake killed approximately one-third of its population in Kathmandu and then King Abhaya Malla. Severe earthquakes have been reported in 1405, 1408, 1505, 1681, 1803, 1833, 1866, 1934 and 1988 (BECA 1993, Ambraseys and Douglas 2004). The earthquake of 1934 with the magnitude of 8.4 was the greatest to hit the region in the recent time. This earthquake resulted in significant damages in Kathmandu valley and towns of Bihar in northern India, and fatalities were recorded to nearly 11,000. In 1988, another earthquake with magnitude Mw 6.8 with epicenter at Udaypur (southeastern hills of Nepal) caused deaths of

1004 people in Nepal and India. The 2011Nepal-Sikkim earthquake also had a significant effect on the eastern regions of Nepal (Shakya et al. 2013).

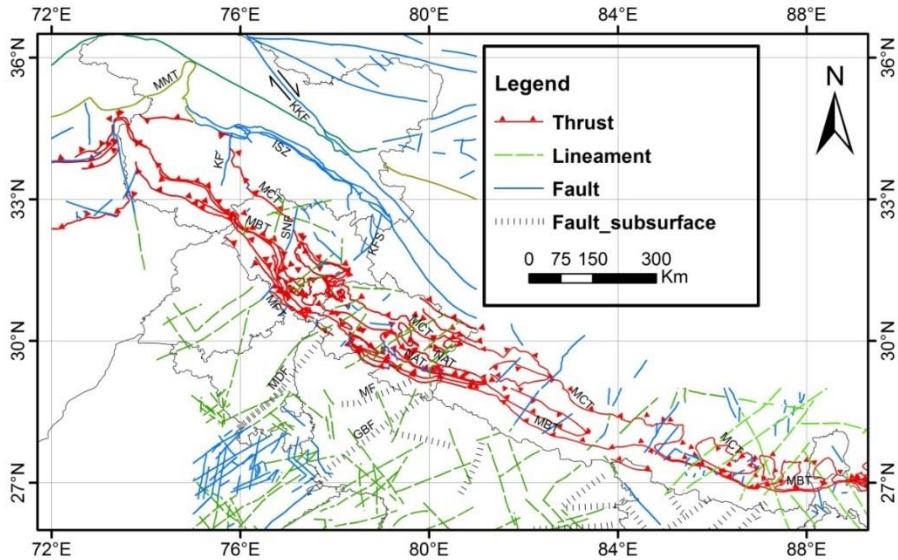

Fig. 2 Tectonic features of central Himalaya. (After Rout et al. 2015)

3. THE EARTHQUAKE SEQUENCE

Earthquake usually occurs as a cluster in many regions around the world where complex fault systems exist. This is mainly due to the initial rupture, which causes the first earthquake does not necessarily relieve all accumulated strains; therefore high stresses at difference locations at the fault system keep on forming. This stresses result in sequential ruptures that decay when the fault system is completely stabilized.

In the case of Gorkha earthquake, the mainshock was followed by significant numbers of strong aftershocks. Fig. 3 shows the distribution of the main shock and aftershocks greater than or equal to ML that had occurred until 1st of June 2015. The aftershock data are based on the recording from National Seismological Center (NSC), Nepal. The main shock of Gorkha earthquake was followed by an aftershock of ML 6.6 at 12:30 pm local time exactly 34 minutes after the main shock. The epicentre of this aftershock was located in the Gorkha district close the epicentre of the main shock. On 12th May 2015 a notable aftershock measuring ML 6.8 (Mw 7.3) with epicentre at the north-western part of Dolakha district, north-east of Kathmandu, resulted in additional damages and casualties.

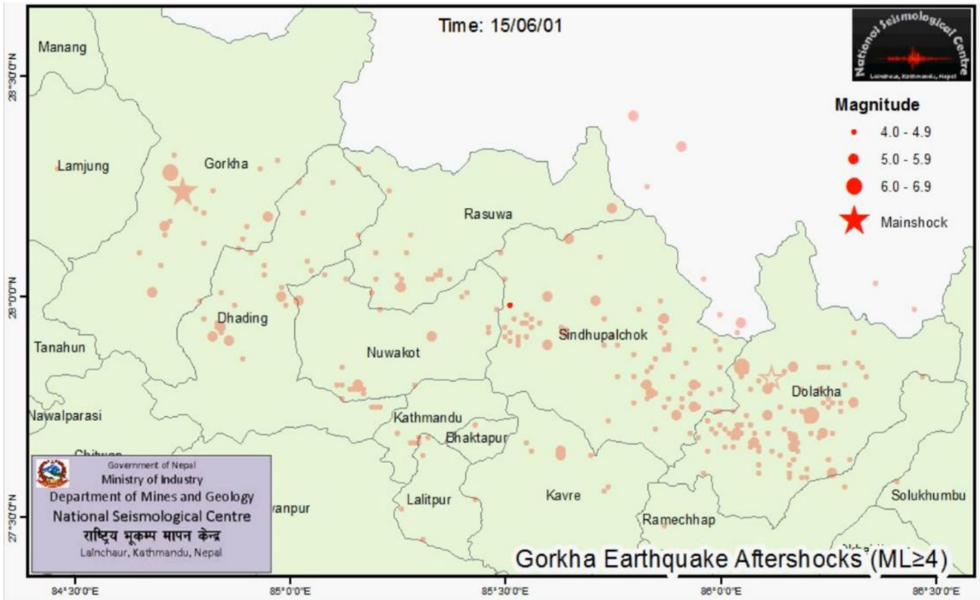

Fig. 3 Aftershock distribution of the 2015 Gorkha earthquake. (Source: NSC)

4. RECORDED GROUND MOTIONS

The only ground motion publicly available till date from Gorkha earthquake is from the KATNP station located at Kantipath at the city centre of Kathmandu. In the absence of public release of data from other stations, the ground motions recorded at KATNP is the only reference available to the authors. Fig. 4 shows the acceleration time history of the ground motion recorded by KATNP during the main event of 25th April and the aftershock of 12th May. The Peak Ground Acceleration (PGA) of three orthogonal components of ground motions are 0.16 g, 0.16 g and 0.19g respectively for HNE, HNN and vertical components of 25th April earthquake. PGA value of the ground motion recorded on 12th May aftershocks are 0.07 g, 0.09g, 0.08g, respectively for HNE, HNN and vertical components.

Fig. 5 shows the 5 percent damped response spectra for the mainshock and aftershock. Due to the comparatively larger amplitude of motion recorded during the mainshock of the Gorkha earthquake at the KATNP station the spectral values are also higher for the mainshock. For the HNN(360) component of the mainshock, two peaks of response spectra appear at the period of 0.4-0.6 seconds and around 4.5-6.0 seconds. However, for HNE (90) component a single peak appears at around 4.0-6.0 seconds. While the peaking of spectra at around 0.4-0.6 second range is understandably due to the high frequency content of the ground motions. The peak on both the components at around 4.0-6.0 second is rather puzzling. On the observation of response spectra for aftershock, no such peak could be found at the similar period range; thus site response only may not be responsible for this. The peaking of the response spectra at the latter period of horizontal ground motion for the mainshock may be attributed to the combination of source effect and local site effects. The fault rupture plane of the mainshock of the earthquake was located nearly 14 kms from the city centre; thus the recordings could have been influenced by the near source long period waves.

Kathmandu valley is located on a thick sedimentary basin typically measuring more than 550 m in core city areas (Pandey 2000, Sakai et al. 2002). These sediments are formed of thick layers of lacustrine and fluvio-lacustrine sediment. The geological setting of the Kathmandu valley is hence comparable to that of the Mexico City (Paudyal et al. 2013). The thick sediment layers are usually held responsible for the amplification of the ground at the latter periods. However, previous studies have found the fundamental frequency of soil sites around the city centre to be around 0.48 Hz (Paudyal et al. 2013). The nonlinear response of the sediment layers might have been responsible for cresting of the spectra at the period of 4-6 secs, which is higher than the measured fundamental period of the site.

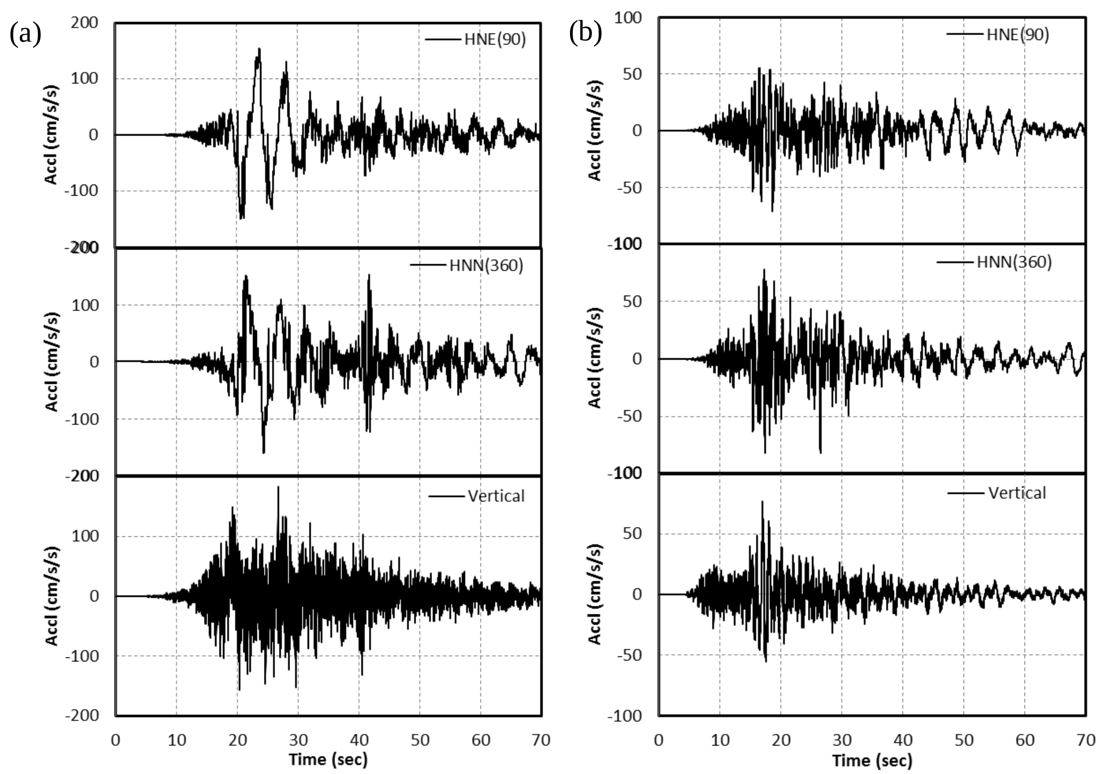

Fig. 4 Acceleration time history at KATNP (a) for the main shock of 25th April (b) for the aftershock of 12th May.

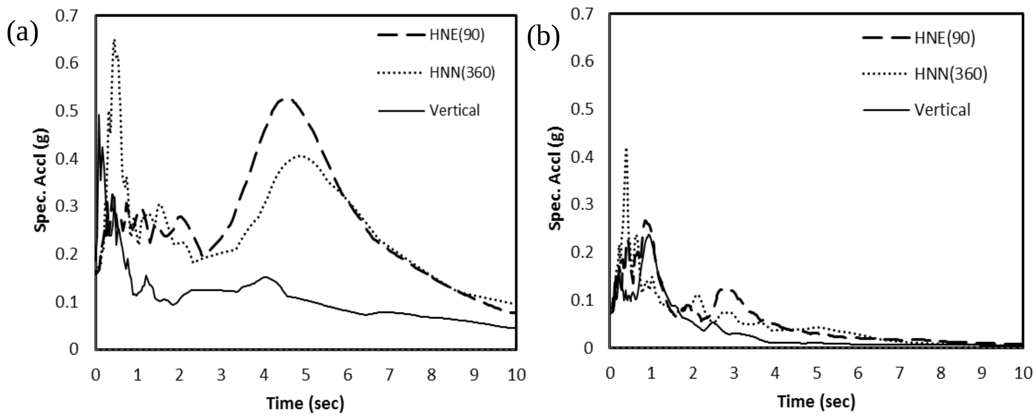

Fig. 5 Response spectra of the recorded motion (a) the main shock; (b) the aftershock.

5. STRUCTURAL PERFORMANCE

The earthquake had a significant effect on the built structures of central hilly districts of Nepal. The areas that were visited during field reconnaissance visit involve historical centres, urban areas and suburban of Kathmandu and urban/rural areas of hill districts with modern and traditional constructions, significant numbers of which were either fully or partially damaged by the earthquake. As mentioned, the aftershocks of the 12th May also contributed to the damage of significant numbers of structures. Table 1 presents the figure of damages during the mainshock of 25th April and aftershock of 12th May. In total 470,000 houses were damaged by the earthquake. The mainshock of 25th April accounted for the most of the damaged structures while nearly 5.2% of the damaged buildings were caused by the aftershock of the 12th May.

Table 1. Number of Damaged buildings (Source: Nepal Police, 27 May 2015).

Building type	Damaged on 25th April	Damaged on 12th May	Total
Personal houses	430,957	21,143	452,100
School buildings	3,534	683	4,217
Hospital and health posts	277	49	326
Government building	1,154	113	1,267
Heritage structures and temples	673	53	726
Police offices and units	710	94	804
Total	445,066	24,473	469,539

There were significant damages to the heritage structures and historical temples of Kathmandu valley due to the earthquake sequence. The historical construction in Kathmandu used a variety of unreinforced masonry in conventional mortars, such as mud mortar or lime surkhi mortar. During the earthquake, these structures performed very poorly and resulted in the collapse of partial damages of hundreds of historical buildings. Another form of construction closely related with the historical construction method is the traditional masonry constructions which also use mud mortar as the binding material. The traditional masonry constructions usually found in sub-urban regions of Kathmandu have brick masonry walls in mud-mortar with timber floor and roofing structures. Urban areas of Kathmandu valley and hill towns usually have the Reinforced Concrete (RC) structures with masonry infill walls as a major building type. In the majority of the cases, such structures were of a non-engineered type. The hill towns also consist of the traditional construction in stone and mud mortar with timber floor and roof structures, typically referred as random rubble masonry structures. In this report, damages that were observed in the field is categorized based on the aforementioned construction types. The damages are reported for historical constructions, traditional masonry construction, reinforced concrete structures and stone masonry structures. With respect to the former, the main focus in provided on the performance of the UNESCO world heritage sites and nine storey tower (Dharhara) based on the Kathmandu valley. For other construction types, analysis of their performance was addressed based on the data obtained from rapid visual damage assessment or road side survey at various places of Kathmandu valley and from Kaverpalanchowk, Sindhupalchowk and Dolakha districts. The data provided sufficient information to interpret the important seismic damage issues. Thought, the extensive area was covered during the filed visit, a significant portion of damaged area of central Nepal was not visited. The presented findings are hence representative of visited areas.

6.1 Historical Buildings

The affected area in central Nepal houses many heritage buildings. There are seven UNESCO world heritage sites in Kathmandu valley and many other historical structures of cultural and archaeological significance. The tremors of 25th April and following aftershocks had significant impact on these structures. In total 762 monuments and historical structures were damaged due to the earthquake. This section focuses on the performance of these structures during the earthquake.

Structural system

The temples of Nepal could be broadly classified as of pagoda style and shikhara style. However, it is difficult to generalize the overall description of the temple style since many conceptual differences occur within the one basic style. Beside the pagoda and shikhara style stupa style monasteries are also a common feature in Kathmandu valley. The main load-bearing system in traditional temples is the brick masonry wall. However, the stone masonry is also found to be abundantly used, specifically on temples of shikhara style. In case of multi-tiered pagoda wall thickness of the masonry wall is not the same for every tiers, it usually reduces from ground storey to top floor. The thickness of the masonry walls usually range from 50 to 75 cm and constructed in three layers in single cross section (Jaishi et al. 2003). The outer layer of the walls are made of fired clay bricks with smooth finishing and inner face is made of sun dried bricks while middle core is filled with brick fragment and mud. The bonding mortar inside the massive walls, which are not visible from the outside, has a significant influence on the structural strength and capacity of the temples. In many temples, yellow clay mortar, mud mortar and more rarely lime-surkhi mortar are used (Ranjitkar 2000). Typical masonry wall system arrangements of multi-tiered pagoda are shown in Fig. 6. Timber beams are used as wall plates, cross-beams and rafters for floors and roof of Nepalese pagoda temples. The main peculiarities of Nepalese temples to other historical structure abroad are their considerable wall thickness, multiple tiers, considerable plinth width and box type configuration (Jaishi et al. 2003). The ambient vibration testing of few pagoda temples of Kathmandu valley suggest that their fundament vibration frequency ranges between 1.67 Hz to 3 Hz (Jaishi et al. 2003, Shakya et al. 2014).

Description of Damages

The earthquake caused extensive damages to the temples of the Kathmandu Valley; however, the effects were seen to vary significantly from temple to temple. In this section, an overall description of the principal damages that were observed in temples of three Durbar square complexes and other important structures are summarized. Amongst the three Durbar squares, the most severe damages were seen at Kathmandu Durbar Square (KDS). The map of collapsed and partially damaged temples and palace of Kathmandu Durbar square is presented in Fig. 7. An erratic situation of damages level was observed in the temples of Kathmandu Durbar square, where Kastamandap, Trilokya Mohan temple and Maju Degal temples fully collapsed while Taleju temple with similar structural configuration had no significant damages. The variation of damages of these temples may have been due to the variation in construction method built at various times from 12 to 17th century AD. However, the difference in present structural status of these historical temples might have a significant role on the damage behaviour. Fig. 8 and 9 present the map of the damaged temples of Bhaktapur and Patan Durbar square.

Fig. 10 shows the pictures of 9 storey Basantapur Tower before and after the earthquake. The top three stories of the tower collapsed while other stories despite receiving significant damages did not collapse. The tower was supported on brick masonry wall combined with wooden frames. Fig. 11 shows the pictures of Kastamandap temple, originally built in around the 12th century, before and after the earthquake. The temple fully collapsed during the mainshock of 25th April and claimed the life of dozens of people gathered for the blood donation program. This temple was mainly supported on wooden frames. Fig. 12 shows the damages to the Gaddi Baithak, influenced by European style building built on 1907, on west and south façade. Partial damages to this building include the damages to parapet walls and out-of-plane failure of the masonry structures. Fig. 13 shows the picture of Trilokya Mohan, Maju Degal and Narayan temple before and after the earthquake. The exterior portion of the temples was supported on the timber frames while the inner core was made of a masonry wall. All three temples collapsed during the earthquake of 25th April.

Fig. 14 (a) and (b) present the damages to the roof structures of the Taleju Temple and masonry wall of the Bhimsen Temple at Patan Durbar square. The roof collapse of the Taleju temple could be attributable to the amplification of the earthquake acceleration at the top of the building. In Bhimsen temple, significant damage to the masonry walls was observed in addition to the residual deformation on the ground floor level of the temple. In Patan Durbar square 3 temples (Jagnarayan temple, Harishanker Temple and Mani mandap pati) as shown in Fig. 9 were fully damaged. Fig. 15 displays the picture of Phasi Degal temple of Bhaktapur Durbar Square (BDS) devoted to God Mahadev. The Masonry walls at the three sides of the temple failed during the earthquake after the development of diagonal shear cracks. The remaining portion of the masonry wall as shown in the Fig. 15 (b) was later demolished to prevent any mishaps.

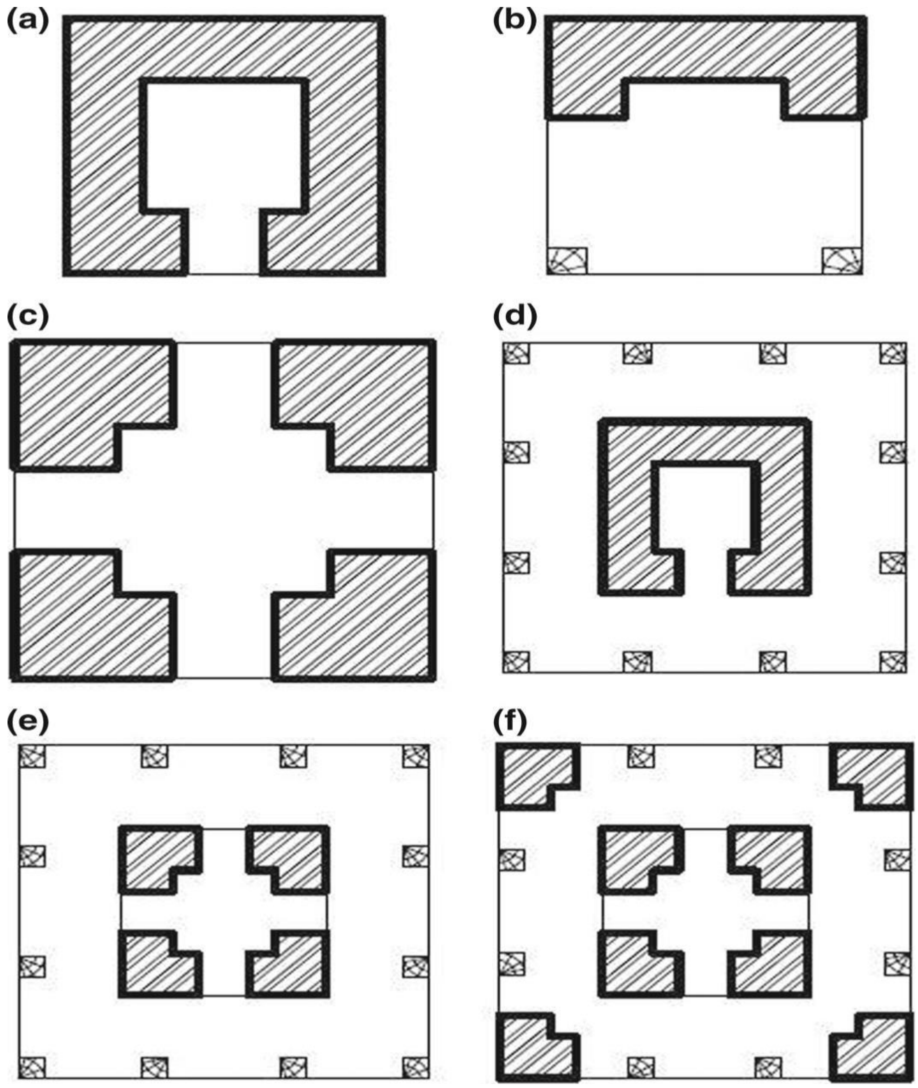

Fig.6. Wall system of Nepalese pagoda temples. (After Shakya et al. 2014)

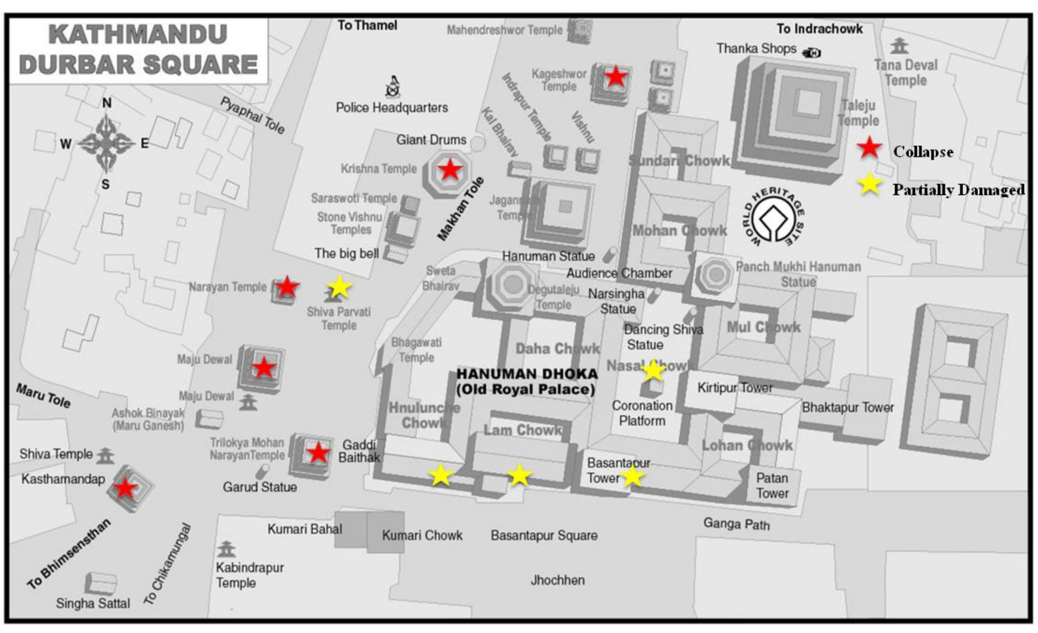

Fig. 7 Damages to the heritage structures in Kathmandu Durbar square. (Base map: digitalhimalya.com)

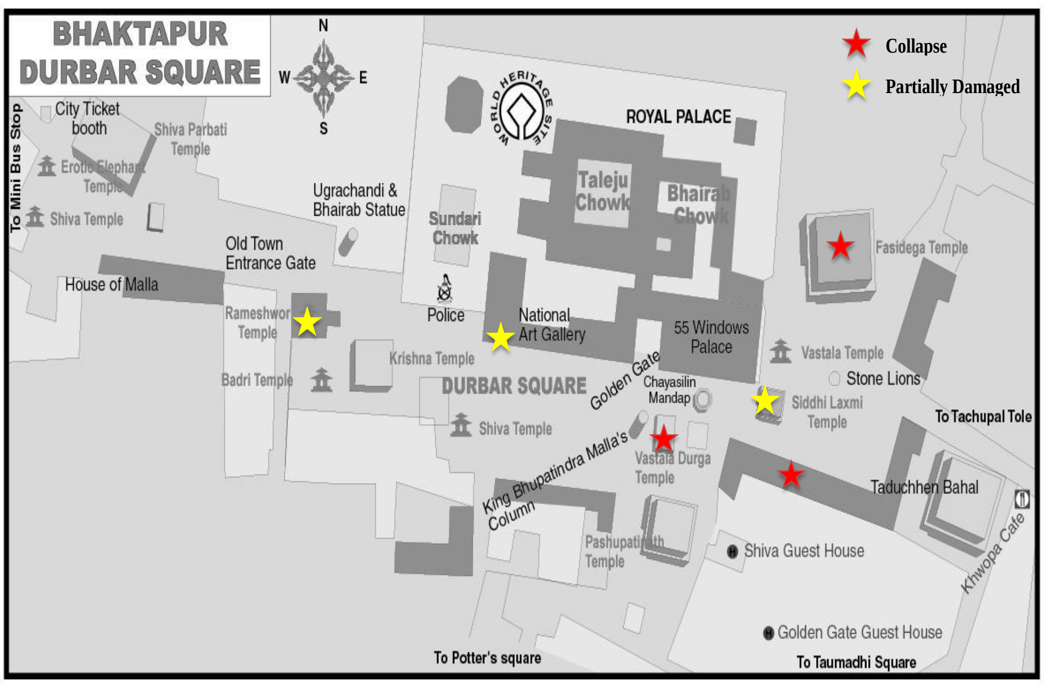

Fig. 8 Damages to the heritage structures in Bhaktapur Durbar square. (Base map: digitalhimalaya.com)

The observed damages clearly highlight the structural vulnerability of the historical temples and heritage structures in Nepal. Though similar lesson were also learned during the earthquake of 1934 very little initiative was taken on proper renovation and seismic improvement of these structures. At present, there are very limited studies on the seismic behaviour of these structures. Clearly, extensive research is required to understand the seismic behaviour of these structures and solve the mystery of better performance of some historical temples while many similar structures around them fully collapsed.

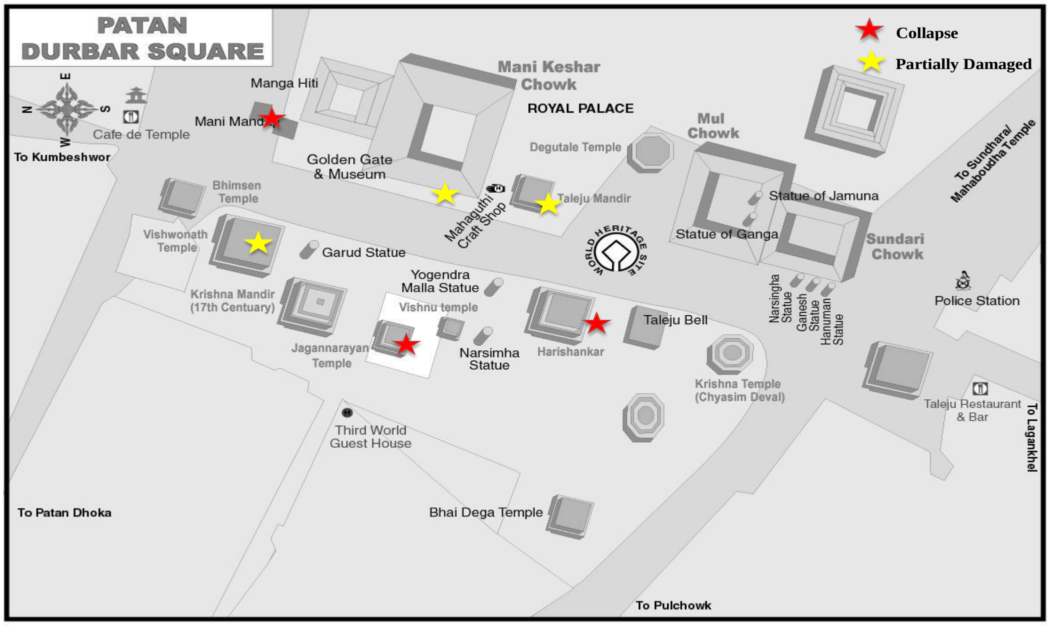

Fig. 9 Damages to the heritage structures in Patan Durbar square (map source: digitalhimalya.com)

Fig. 10 Nine storey Basantapur tower (a) before earthquake (b) after earthquake

Fig. 11 (a) Kastamandap before earthquake (b) Kastamandap after earthquake

Fig. 12 Gaddi baithak palace (a) west facade (b) south facade

Fig. 13 Trilokya Mohan temple, Maju Degal and Narayan Temple from left to right (a) before earthquake (b) after earthquake

Fig. 14 (a) Partial collapse of Taleju temple (b) Damages to masonry walls and leaning structure of Bhimsen temple at Patan.

Fig. 15 Phasidegal, Bhaktapur durbar square (a) before earthquake (b) after earthquake.

6.2 Traditional Brick Masonry Structures

Nepal police census data indicates that about 452,100 privately owned housing units were damaged due to the earthquake. In this section, the performance of the traditional brick masonry structures that constitute a significant portion of the damaged privately owned housing units is discussed. These structures are typically found in and around Kathmandu valley. These structures accounted for the majority of structures in the suburban towns just outskirts of Kathmandu city, such as Sankhu, Bungmati and Harisiddhi, etc. There were severely damaged to these suburban areas with the majority of private buildings were of these type. It is to be noted that all the above-mentioned towns were located on the edge of Kathmandu valley. The soil sediments at an edge of the valley are much shallower than at the central valley. The shallower soil sediment may have resulted in much lower de-amplification of seismic waves at short period range. Moreover, the location of these areas at the edge of the basin close to hills indicates towards possible basin-edge effects that traps and reflect the incident seismic waves resulting in an amplification of seismic motion.

These structures are usually constructed using the kiln burnt or sun-dried bricks with mud mortar. The age of these structures was typically from nearly 50 years to 200 years old. These structures have very thick masonry wall usually ranging from 450 mm to 600 mm. The heavy weight of the thick masonry wall and roof would have attracted large inertia force. The poor quality brick masonry with fragile mud mortar that had been significantly deteriorated with the age hardly had the strength to resist such an inertia force.

Fig. 16 presents an out-of-plane failure of masonry wall at the top floor of a building. Apparently the masonry walls collapsed even when not taking any vertical loads except the self-weight as seen in the Fig. 16 (a) for building with corrugated metal roofing supported by timber posts. The poor bonding of the mud mortar was unable to prevent the out-of-plane failure of the walls subjected to higher ground acceleration at the top of the building. Additionally, the long length of the unsupported wall, usually created in the traditional building to get open spaces on the top floor, could have contributed to the inferior performance of the masonry walls in the out-of-plane direction. Failure of the connection is also visible at the corner of the walls due to again poor bonding behaviour of the mud mortar. Fig. 17 presents out-of-plane failure and in-plane diagonal cracks in walls of a building. The diagonal cracks initiated from the middle portion of the wall at the roof level of the top floor and terminated nearly to the plinth level close to the edge of the wall. In the background of the building other two building are also visible. Due to the lack of integrity in these structures the walls of the buildings vibrated as a different unit rather than vibrating in unison. As could be seen in the figure a building in the background with Reinforced Concrete (RC) frame infilled with masonry wall not only survived the earthquake but also had very minimal damages. This indicates toward the poor seismic capacity of the traditional brick masonry structures in comparison the RC structures. Fig. 18 presents pictures of diagonal cracks at two facades of a building. Multiple diagonal cracks along with out-of-plane failure are clearly observable on all sides of the building expect to the side attached to an adjacent building. This suggests the wall attached to the adjacent buildings might have benefited from the attachment thus enhancing the stability of the walls. Moreover, the absences of horizontal bands (sill, lintels) at various levels in the traditional buildings clearly aggravated the damages suffered by these buildings.

Fig. 16 (a) Out-of-plane failure of wall (b) out of plane failure along with connection failure.

Fig. 17 Out-of-plane failures of wall and diagonal cracking of wall, in the background a RC frame structures with no damage.

Fig. 18 Diagonal cracking on the walls of a building due to lack of lintel and floor bands.

Out-of-plane failure of solid masonry walls and out-of-plane failure combined with the overturning of the wall facade was a frequent scenario in many traditional buildings. For example the wall of historical Durbar high school shown in Fig. 19 and in traditional building showed on the same figure. Large thicknesses of the masonry walls are clearly visible in these pictures, which is usually the case in many traditional constructions to provide good thermal insulation during chilly winter in hills of central Nepal. However, the large inertial forces of these walls worsen their performance during the earthquake. In additional to these failures, the failure of corner walls of the building that separated from the main wall during the shaking due to weak bonding and lack of horizontal bands were also observed in few cases (Fig. 20). Also observable in the figure is the failure of gable end walls at the roof level, which was a common feature in many traditional buildings due to the higher acceleration at the top of the building. In few buildings, other modes of failure such as delamination of the masonry walls and cracking to the irregular thickness of the masonry walls were also observed as shown in Fig. 21. To summarize the observed failures of the traditional buildings during the Gorkha earthquake highlighted the poor performance of the masonry walls due to poor bonding between the brick layer, lack of integrity in the building and large inertia force.

Fig. 19 (a) Out-of-plane failure of wall of Durbar high school, (b) Out-of-plane combined overturing failure of wall.

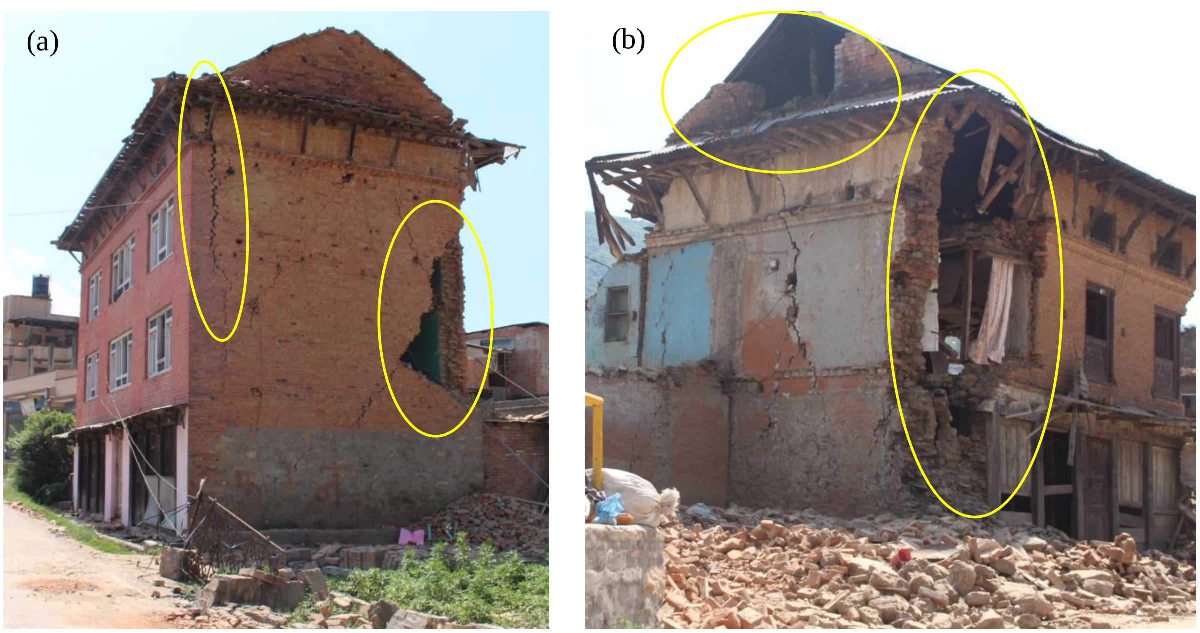

Fig. 20 (a) Failure of walls at corner and wall separation at corner, (b) failure of walls at corner and at gable.

Fig. 21 (a) Splitting of layers of wall, (b) cracking in the building with irregular wall thickness.

6.3 Reinforced concrete structures

These are the most common form of constructions used in recent times in the Kathmandu Valley and other urban areas of the country. RC frames structures are constructed with infilled unreinforced masonry walls to fulfil the function requirements. Though, this building type performed well compared to the traditional buildings, significant cases of failure of these structures were also observed. A majority of the cases of failure of RC structures with masonry infill wall was caused as a consequence of architectural or functional requirements leading to inadequate seismic behaviour. In many buildings upper storeys had masonry infill walls that possess higher lateral stiffness, while the ground storeys were usually flexible due to the open configuration to accommodate parking spaces or shops. The difference in lateral stiffness and strength of the ground floor with respect to the upper storeys resulted in the development of the well-known soft storey mechanism under the earthquake loadings. The soft-storey have consistently resulted in poor performance and collapse of many buildings during the past earthquakes across the world (Murty, 2007).The presence of soft storey resulted in significantly increased deformation demands, and the burden of energy dissipation on the first storey columns leading the collapse of the buildings. Fig. 22 shows some of the representative building with soft-storey failure observed in Kathmandu. All of these building had used the ground floor for shops or parking purposes.

Concrete quality is critical for RC structures to obtain the assumed behaviour during the earthquake event. During the field visit, it was observed that the quality of the concrete used was very poor, and its compressive strength in some buildings was lower than the expected strength. Moreover, aggregate used was of elongated shape and flaky and compaction was not done using a mechanical vibrator. Examples of the damage due to the use of low strength concrete observed in RC building are shown in Fig. 23. All these showed that one of the main problems in damaged/collapsed RC building was the poor quality of the concrete.

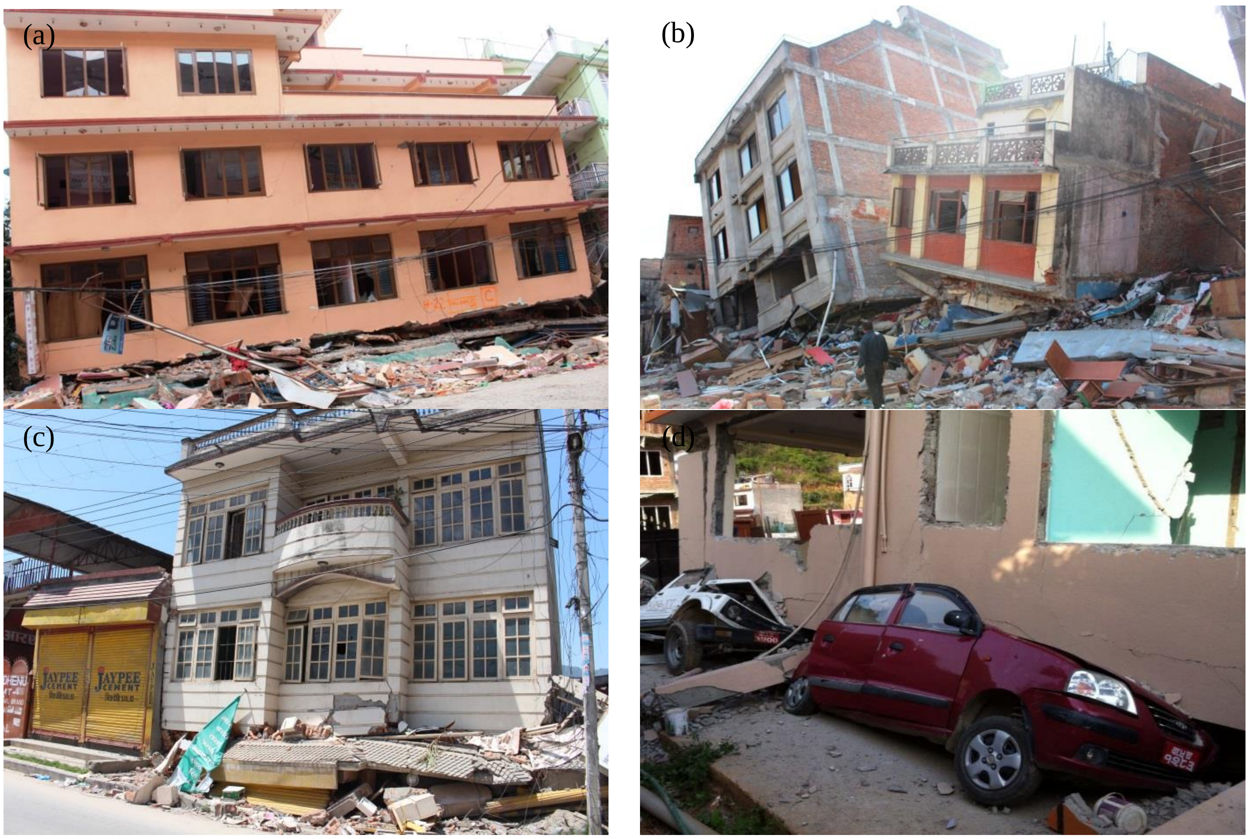

Fig. 23 Soft storey failure of open ground floor at various places of western Kathmandu.

Moreover, the poor detailing of transverse reinforcement at the plastic region of columns, beams and beam-column joint resulted in damages of many RC buildings due to insufficient confinement. The wide spacing of ties resulted in shear failures, buckling of the longitudinal bars and poor confinement of the core concrete. In addition to inadequate transverse reinforcement, insufficient cross-sectional dimension were another reason for the widespread damage. Few examples of the damages due to the combination of poor quality concrete, inadequate confinement and insufficient cross-sectional dimension are shown in Fig.24. Fig. 25 shows the damages to a column of a school college Kathmandu. The close up view of the damaged column revealed that not only the spacing of the transverse reinforcement in large (around 200 mm) but the ends of ties were not bent at 135°, and the length of the hook was less than ten times diameter of the ties as required by the ductile detailing code. The construction of the building was completed only a few years ago. This incidence showed that there was clearly the lack of implementation of ductile detailing even in recent constructions.

Well-designed RC frames in the seismic regions seek to ensure that hierarchy in the strength of the components of the structures is followed so that building could behave in a ductile manner. In order to resist intense earthquake in ductile fashion, it is required that the damages on the beams precede the damages in columns, due to the risk to the building stability due to damages in columns (Murty 2007). However, such design hierarchy is not enforced by the building codes of the region (such as NBC 105:1993, IS 1893:2002). As a consequence many RC structures, even the newly constructed one in Nepal, have stronger beams compared to the columns. During the earthquake in many damaged buildings, it was observed the supporting columns suffer from shear failure or compression crushing while beams were behaving almost elastically. For example in Fig. 25(a), a building at Kathmandu city had the weak columns compared to deep beams. Not surprisingly, the building collapsed overturning towards its weaker axis. The Fig. 25(b) shows the damage to a building observed at Sindhupalchowk district where the building had collapsed due to the failure of columns whereas the beams were damage free.

Fig. 24 Damages due to the poor quality concrete.

Fig. 25 Failure due to the insufficient confinement and low quality concrete at columns.

Fig. 26 Weak Column strong beam failures and damages.

Damages due to the short column were also frequently observed during the field observation. During the earthquake, lateral forces are transmitted to the columns as moment and shear forces. When the length of the column is short, it becomes stiffer and receives higher moments. Since the moment arm is short, the shear force becomes more pronounced could result in the failure of the column. Fig. 26 shows some of the cases of damages due to the short column effects observed in the field. The first two pictures, taken in Kathmandu, show the damages to the columns due to the influence of the placement of openings in the infill wall and bisection of the column by landing beam, respectively. The bottom picture (Fig. 26(c)) shows the damages to the columns of district hospital at Chautara, Sindhupalchowk district caused by short column effect due to the construction on the sloping ground.

Fig. 26 Damages due to Short column effects.

6.4 Stone Masonry Structures

These types of structures are typical of hilly rural areas of Nepal where the stone are abundant. These structures are usually constructed using locally available stones in mud mortar. The roofs are usually made of timber joist or truss overlaid by corrugated sheets or slates. In most of the cases, timber joists are placed over the walls without any proper connection between them. The walls are constructed with stones usually placed in a random manner (referred as random rubble masonry), and hence do not have the usual layers as seen in the brick walls. These un-coursed walls have two vertical layers of stones (referred as wythes) filled in between with loose stone rubble and mud mortar. In some areas buildings, masonry walls with dressed stone in mud mortar or cement mortar are also found. While at other areas masonry wall of dry stone stacked top of each other without any bonding mortar is also found. A typical building of these types observed in the affected area had a relatively smaller footprint of tentatively 40 sq.m. and masonry wall thickness of around 600 mm. The excessive thickness of the stone walls, along with heavy floors or roof, results in heavy structure that attracts significant inertial forces during an earthquake. Historical earthquakes have shown that the stone masonry with very low-strength mortars without properly layered courses of stone are extremely vulnerable to the seismic loadings (Murty 2007, Bothara and Brzev 2012).

During the earthquake sequence, stone masonry structures performed badly with the collapse of many buildings and many others with partial damages. The most commonly and widely observed pattern of damage in these buildings were the out-of-plane failure of the roof gable. Fig. 27 shows some of the representative damages to the roof gable wall observed in the field. These walls at the top of the building were not connected to the roof structures hence could vibrate as a free standing unit. Moreover, its location at the top of the building, where higher acceleration is expected might have contributed to the out-of-plane failure. Stone masonry walls with two wythes separated by weak stone rubble mixed mud masonry are prone to delamination failure. Fig. 28 presents some of the cases of observed delamination failure of the masonry wythes. The weak bonding of mud mortar is unable to hold heavy outer wythes constructed using large stone boulder with rounded or irregular shape resulting in delamination during the seismic event. Fig. 29 shows the roof collapse in the stone masonry buildings during the earthquake due to the failure of the supporting walls and lack of wall to roof anchorage. Unlike in the usual cases with this type of failure the roofs were made of lightweight materials (corrugated sheet). However, the poor strength of the supporting walls might have contributed significantly to the failure of these roofing systems.

Fig. 30 presents the out-of-plane failure of the stone masonry walls. As previously mentioned the floor and roof on these kinds of buildings are not properly anchored to the walls. Moreover, connecting ties to the walls, such as lintel and sill bands, are usually not provided thus the buildings lacks the integrity required to resist seismic loadings. Consequently, the walls of the buildings can vibrate as a single unit and could collapse in the out-of-plane direction. In multi-storey buildings, this usually occurs at higher floor levels due to amplified acceleration at the top of the structures. However, the failure is also possible in single storey structures due to the long walls without any cross wall bisecting it (Fig. 30 (c)). In some cases, the out-of-plane failure was combined with overturning failures, such as in Fig. 31. The entire wall separated from the adjoining walls and overturned into the ground due to its large inertia. Again the lack of connecting element between the walls, and walls and roof are clearly visible.

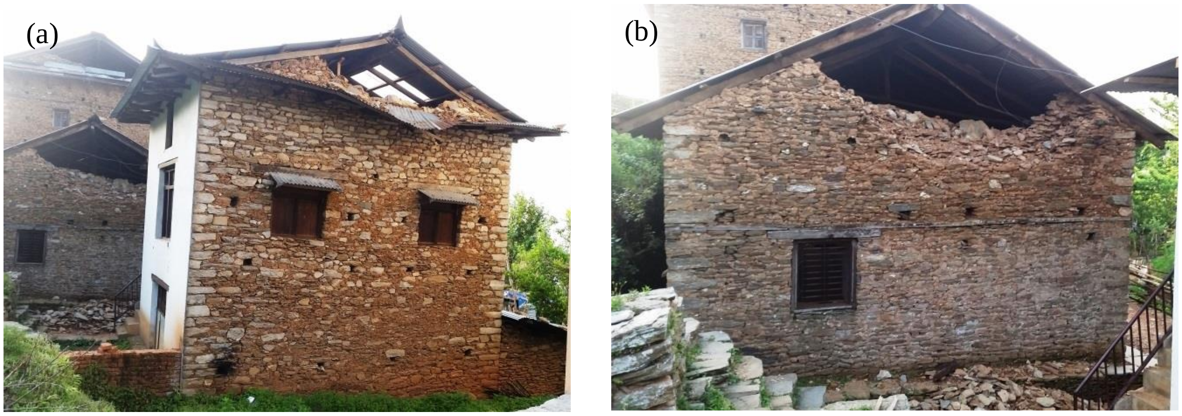

Fig. 27 Out-of-plane failures of roof gable walls.

Fig. 28 Delamination of wall wythes.

Fig. 29 Failure of roof structures.

Fig. 30 Out-of-plane failures of stone masonry walls.

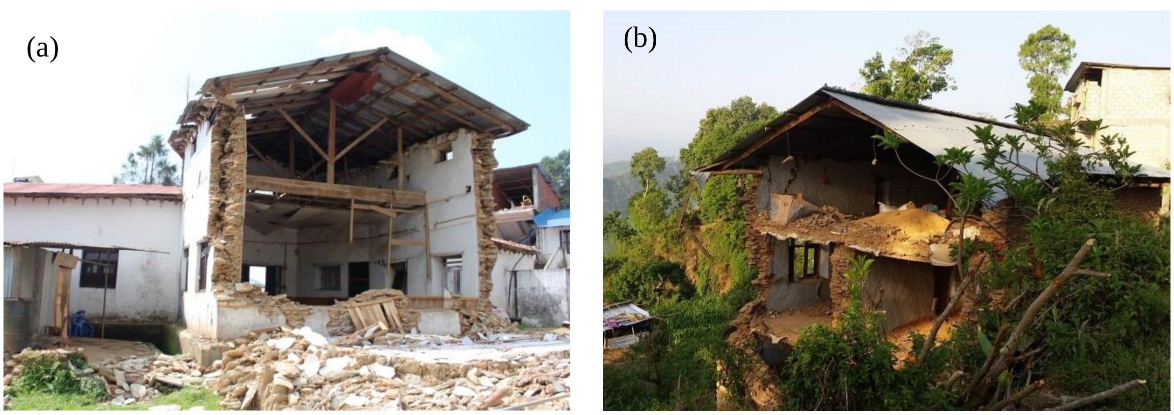

Fig. 31 Out-of-plane cum overturing failures of stone masonry walls.

7. GEOTECHNICAL FAILURES

7.1 Soil Liquefaction

Soil liquefaction is caused by the generation of pore water pressure during the seismic movement. The liquefaction phenomenon is observed when ground consists of fully saturated soil. Previous investigations (Piya 2004) have found that multiple sites with the Kathmandu valley could be susceptible to liquefaction during a strong earthquake, due to the presence of liquefiable soils and high groundwater level. Fig. 32 shows the liquefaction susceptibility map of Kathmandu Valley prepared by the Piya (2004). During the field investigations, sand boils were found at few places in Kathmandu valley. The liquefaction was observed at Changu Narayan (Location 27.701, 85.428) located at the east part of Kathmandu valley and at Imadol (Location 27.654, 85.341) on the bank of Manohara River in Lalitpur district. The liquefaction at the Changu Narayan and Imadol are shown in Fig. 33 (a) and 33 (b), respectively. During the Gorkha earthquake soil liquefaction observed were sparser than usually presumed under such earthquake intensity. The occurrence of the earthquake in the middle of the dry season when the moisture level in the soil was quite low might have contributed to lower instances of soil liquefaction.

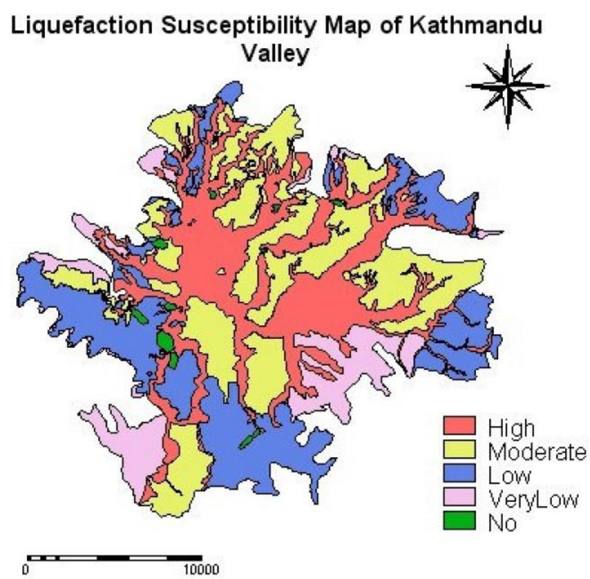

Fig. 32 Liquefaction susceptibility map of Kathamandu valley (Piya 2004).

Fig. 33 Liquefaction observed at Kathmandu Valley during the Gorkha earthquake.

7.2 Soil settlement

Densification of granular soils subjected to seismic loading is a well-known phenomenon responsible for settlements of structures. Settlement of the soil resulted in damages of many building structures inside Kathmandu valley. In most of the cases the damages were slight ones; however, in some exceptional cases the unequal settlement of foundation resulted in large residual deformation of the building. In Fig. 34 (a) and 34 (b) damages observed to two buildings at Balkhu and Kirtipur in Kathmandu Valley is presented. The first building presented had a slight damages resulting from the settlement of the building with peak settlement of nearly 40 mm. A multi-storied building in Kirtipur; however, suffered severe damage due to the settlement of its foundations resulting in a residual inclination of nearly 1°. Settlement of the soils also resulted in the damages to the transportation network. Fig. 35(a) and (b) shows damages to the Ariniko highway and a pedestrian bridge in Ariniko highway at Lokanthali in Kathmandu. Due to the settlement of a lane of the highway built on filled land large cracks appeared on the highway. The settlement also affect a pedestrian bridge in which due to the settlement of a northern pier (right side of the picture) bridge deck was slightly inclined.

Fig. 34 Settlement induced damages in buildings.

Fig. 35 Settlement induced damages in transportation network.

7.3 Slope failure and landslides

Numerous landslides and slope failure were observed in the hilly regions of central Nepal due to the Gorkha earthquake. Amongst the fatalities, few hundred were caused by the landslides and avalanches. Landslides were also responsible for the blocking of highways to the northern border of Nepal and many villages routes. These blockages significant restricted the rescue and relief material distribution after the earthquake. Many hilly villages were only accessible by the air, which significantly delayed the distribution of relief materials. Landslides from the earthquake also blocked many rivers and impounded lakes behind the dams formed from landslide debris.

Some of the representative landslide and slope failures observed by the authors during their field visit to Sindupalchowk and Dolakha district is presented here. Fig. 36 shows representative cases of slope failure and landslides observed during the field visit.

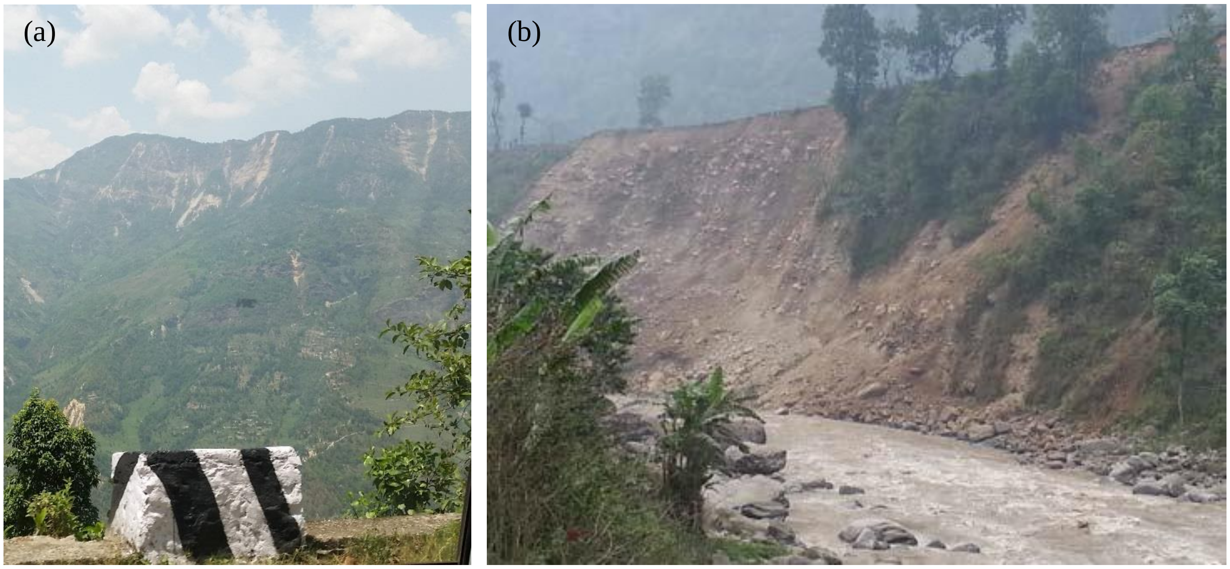

Fig. 36 Landslide observed from at Sindupalchowk and Dolakha district.

7.4 Rockfall impacts

The earthquakes resulted in the instability of rocks slopes and resulted in falling of large rocks. In few incidences, buildings built close to the slope were hit by the falling rocks. Rock fall also led to damages to the vehicles on the road. In many cases, the stones were large and had sufficient energy to damage the buildings significantly. Few representative cases of such damages observed during the field visit is presented here. Fig. 37 presents some the damages observed at Sindupalchowk and Dolkha district.

Fig. 37 Rock fall impact on the built structures.

8. SUMMARY

The Gorkha earthquake sequence 2015 inflicted a heavy damage toll on lives and livelihoods in the central hilly region of Nepal. Nepal lies in an active tectonic region where the Indo-Australian plate subducts under the Eurasian plate, creating an elongated region of high seismicity. The report presents the observation made on the field during reconnaissance visit to the some of the affected area of central Nepal. The reconnaissance visit mainly focused on the observation of the performance of various building typology in the affected regions. Moreover, the damages resulting from the geotechnical failures during the earthquake sequence were also documented.

The ground motion recorded at Kathmandu city centre showed the peak at an unusually long period of 4 to 6 second. This phenomenon might have been a result of the ground motion directivity along with local site effect at the deep valley basin. Moreover, the nonlinear response of sediment layers might also have contributed to this. However, ground motion from a single site is publically available. The lack of available strong motion records restricts drawing of any generalized conclusion of the ground motion characteristics. It is imperative to have more strong ground motion station in the regions and strengthen the concerned authority to be able to disseminate the data in timely fashion.

In the Kathmandu valley, significant damages were observed on the historical buildings. All three Durbar square in Kathmandu valley were affected. Damages to the Kathmandu Durbar square was more severe than other six UNESCO world heritage sites in Kathmandu. The earthquake sequence also had the significant effect of traditional masonry constructions. The aging structures with thick and equally fragile wall system were not strong enough to resist the strong earthquake motions. Reinforced concrete structures without ductile detailing also performed very poorly. Catastrophic failure of soft storey structures was observed in many affected areas. However, the damages in Kathmandu valley were of sporadic nature. The damages were mainly concentrated at the places closer to the edge of the valley, indicating towards the possibility of the influence of basin edges on the damage concentration.

Hill towns close to the epicentre of the mainshock and following aftershocks experienced severe damages. Mainly the stone masonry building that are typical of the hilly regions were severely affected. Nearly all the building with stone rubble masonry received significant damages. Moreover, a significant number of damages were observed due to the geotechnical failures inside the Kathmandu valley and hilly regions. In Kathmandu valley, the damages were mainly due to liquefaction and settlement. In hilly areas, main problems arrived from slope failure, landslide and rockslide. There were thousands of landslides resulting from the earthquake sequence and the Araniko highway, the busiest highway in Nepal, was completely closed due to the landslides.

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REFERENCES

Ambraseys NN, Douglas J. Magnitude calibration of north Indian earthquakes. Geophysics Journal international 2004; 159(1): 165-206.

BECA World International. Seismic Hazard Mapping and Risk assessment for Nepal. 1993.

Bothara J, Brzev S. A tutorial: improving the seismic performance of stone masonry buildings. Earthquake Engineering Research Institute, 2012.

Bureau of Indian standards. Criteria of earthquake resistant design of structures: Part 1 general provisions and buildings. IS 1893 (Part 1) New Delhi, India, 2002.

Murty CVR. Earthquake Tips. Indian Institute of Technology Kanpur, India, 2005.

Gansser A. The great source zone between Himalaya and Tibet: a preliminary account. Centre national de la recherche secientifique 1976; 268: 181-192.

Jaishi B, Ren WX, Zong ZH, Maskey PN. Dynamic and seismic performance of old multi-tiered temples in Nepal. Engineering Structures 2003; 25(14): 1827-1839.

NBC 105, 2015. Nepal national building code: Seismic design of buildings in Nepal. Ministry of physical planning and works, Government of Nepal; 1994.

National Seismological Center (NSC), 2015. (http://www.seismonepal.gov.np/ind-ex.php?action=earthquakes&show=recent.)

Pandey MR, Molnar P. The distribution of intensity of the Bihar-Nepal earthquake 15 January 1934 and bounds of the extent of the rupture zone. Journal of Nepal Geological Society 1988; 5(1): 22-44.

Parajuli HR. Dynamic analyses of low strength masonry houses based on site specific earthquake ground motions. PhD thesis, Kyoto University, Japan, 2009.

Paudyal YR, Yatabe R, Bhandary NP, Dahal RK. Basement topography of the Kathmandu Basin using microtremor observation. Journal of Asian Earth Sciences 2013; 62: 627-637.

Piya BK. Generation of a geological database for the liquefaction hazard assessment in Kathmandu Valley. Natural Hazard Studies 2004, Enschede, The Netherlands, ITC.

Ranitkar RK. Seismic strengthening of the Nepalese Pagoda: progress report. In: Proceedings of the ICOMOS International Wood Committee (IIWC), earthquake-safe: lesson to be learned from traditional construction, international conference on the seismic performance of traditional buildings 2000, Istanbul, Turkey.

Rout MM, Das J, Das R. Probabilistic seismic hazard assessment of NW and central Himalayas and the adjoining region. Journal of earth system and science 2015; 124(3): 577-586.

Sakai H, Fujii R, Kuwahara Y. Changes in the depositional system of the Paleo-Kathmandu Lake caused by uplift on the Nepal lesser Himalayas. Journal of Asian Earth Sciences 2002; 20(3): 267-276.

Shakya K, Pant DR, Maharjan M, Bhagat S, Wijeyewickrema AC, Maskey PN. Lesson learned from performance of buildings during the September 18, 2011 earthquake in Nepal. Asian journal of civil engineering 2013; 14(5): 719-733.

Shakya M, Varum H, Vicente R, Costa A. Seismic sensitivity analysis of the common structural components of Nepalese pagoda temples. Bulletin of earthquake engineering 2014; 12(4): 1679-1703.