Lowland Technology International 2016; 18 (2): 141-164
International Association of Lowland Technology (IALT): ISSN 1344-9656
Special Issue on: Nepal Earthquake & Disaster

Research Paper

Damages and causative factors of 2015 strong Nepal Earthquake and directional movements of infrastructures in the Kathmandu Basin and along the Araniko Highway

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ARTICLE INFORMATION

Article history:

Received: 28 July, 2016
Received in revised form: 28 August, 2016
Accepted: 30 August, 2016
Publish on: 26 September, 2016

Keywords:

Nepal Earthquake
Geological/geotechnical failures
Damages
Causative factors
Directional movements
Kathmandu Basin

ABSTRACT

The strong earthquake on April 25, 2015 (7.8 M_w) and the aftershock on May 12, 2015 (7.3 M_w) claimed the lives of 8,659 people, plus 21,150 people injured and huge economic loss together with serious damages on eight World Heritage sites. Our two field surveys in the month of from May 9-21, 2015 and 19-23 July, 2015 revealed understanding of damages to traditional towns, historical monuments, and modern buildings. Regionally, damages on buildings are confined to the traditional houses which are remnants of or renovated after the 8.1 magnitude 1934 AD earthquake. Widespread cases of inadequate engineering and construction practices for RCC (Reinforced Cement Concrete) buildings and renovated old buildings have been severely affected. The affected region includes the main shock along the 150 km long rupture zone towards east. The aftershock reached farther south at a shallower depth towards the end of the eastern rupture zone. As a result damages inflicted in the structures from both quakes revealed different shaking directions. The April 25 main shock caused eastward leaning structures while May 12 aftershock caused southward leaning and/collapsed structures. It is important to identify whether the direction is due to aftershock at the end of initial rupture zone or if it represents a newly exposed fault.

1. Introduction

The strong earthquake on April 25, 2015 with moment magnitude 7.8 M_w struck at 11:56 a.m. local time, originating at Barpak of Gorkha District (about 80 km northwest of Kathmandu near Lamjung). The intensity at the epicenter was determined to be VIII while the intensity in the Kathmandu Valley was VI-VII. Similarly, the largest in a series of hundreds of aftershocks was a very strong magnitude 7.3 M_w with epicenter at the border of Sindhupalchowk and Dolakha Districts (about 35 km east of Kathmandu) occurring May 12 at 12:50 p.m. local time, still with VI intensity measured both in Kathmandu Valley and Arniko Highway (USGS, 2015). The hypocenters for both the main quake and aftershock were at the depths of 8.2 km and 18 km respectively.

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Note: Discussion on this paper is open until March 2017

Since the hypocenters are of shallow type, the consequences of such tremors produce strong shaking at the ground surface causing more damages across the affected area (**Fig. 1**). These tremors have affected traditional cities/towns, rural villages, new reinforced concrete buildings, world heritage sites and historic temples together with landslides and slope failures along the highways causing great loss of life. According to the Ministry of Home and Affairs (2015), the total number of fatalities was 8,659 people and 21,150 injured by the initial earthquake and M7.3 aftershock. Among them 4,772 females lost their lives.

The two surveys by the authors were conducted during May 2015 and July 2015 in the Kathmandu Valley and along the Arniko Highway up to Jhyale after Barhabise and near the border of China at Sindhupalchowk district (**Fig. 1**). During the survey, damages and causative factors of the areas were assessed in Kathmandu Basin and along the Arniko Highway in Sindhupalchowk District. Sequential damages of buildings in traditional towns, urbanized centers and historical sites/monuments of Kathmandu Valley were traversed after the first major earthquake (Manandhar et al., 2015; Hino and Manandhar, 2015). The survey team also experienced the largest aftershock during field observation on May 12, 2015. This paper discusses some major geological, tectonic, geotechnical and structural causes of damages around the area of strong seismic wave propagation. Furthermore, authors have identified directional movements of partially tilted, fully damaged and cracked infrastructures due to both major shocks. It is noteworthy that the seismic movements of the April 25 and May 12 revealed different directions of movements throughout our surveyed sections.

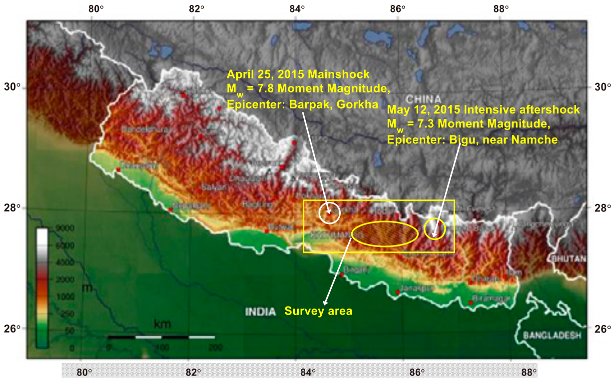

Fig. 1. Location map of April 25, 2015 main shock, May 12, 2015 aftershock and survey sites.

2. Damages on old/traditional towns

The historic traditional towns of Kathmandu, Lalitpur and Bhatkapur Districts of the Kathmandu Basin suffered extensively with partial and total building damages. Most of the remnants or renovated buildings were constructed after the 1934 AD. magnitude 8.1 MI earthquake. Renovations predated design benefits of modern building codes. Buildings older than 82 years were generally severely damaged/collapsed (**Fig. 2**). Many renovations on these old buildings were performed without considering any engineering designs, hence have high vulnerability.

2.1 Damages around Jhochhe and Ason (Kathmandu district)

Premises of Kathmandu's Durbar square have a dense, well cultured settlement of the renowned Newari people. The north, west and southern parts of Durbar Square have well interlocked and interconnected houses with hundreds of courtyards approached by narrow streets passable only by two-wheeled carts (**Fig. 3**). Most of these houses are remnants of the 1934 AD earthquake and many renovated structures again lack consideration proper engineering design. Most of buildings experienced severe cracking. Many unreinforced row houses survived aided by long chain-like lateral shear support to each other. In cases where one row house needs to be demolished, the demolition likewise adversely affects support to other inter-connected houses. As a result,

Fig. 2. April 25 main shock and May 12, 2015 aftershock contributed to intensive damages on old aged buildings. Photograph represents areas from (a) Bhaktapur and (b) Sankhu.

demolition or sometimes even renovation of single house is unfeasible with current local shoring practices. In some cases, it was found that the demolition of one house led to collapse of others, for example a total seven houses collapsed in the inner core side of Jhochhe area.

2.2 Damages around Sankhu area (Kathmandu district)

A section of Kathmandu extending 17 km along north-east corner contains an ancient city believed to be 3147 years old and the first developed town, long before Kathmandu city according to local people we surveyed. The city lies within the Kathmandu district of Shankharapur Municipality. Like Kathmandu Durbar Square, this is another typical Newar town developed with a long chain of inter connected row houses with typical history (https://en.wikipedia.org/wiki/Sankhu). Similar damage conditions can be clearly observed throughout the section (**Fig. 4**).

2.3 Damages around Bungamati area (Lalitpur district)

Bungamati lies in Karyabinayak Municipality in Lalitpur District, Nepal. It is also a Newar village on settled on a river spur. This historical city has a tradition of a primordial rain god called Bungadeya, also named as the compassionate Aryavalokiteshvara and Raktapadmapani Lokeshvara worshipped by Buddhists. Meanwhile, the terminology Machhindranath is given by Hinduism and worshipped by both religions, a practice unique to Nepal. Newari people call this “Karunamaya” meaning an embodiment of love and kindness (**Fig. 5**). This city culture is in agriculture as well as typical wooden handicrafts based on traditional ancient architecture also renowned worldwide. Severe damage occurred in most of these buildings (**Fig. 6**) and also the world heritage sector which will be discussed in the following section.

2.4 Damages around Naag Pokhari and Khala (Bhaktapur district)

Bhaktapur District belongs to the most attractive traditional city for domestic and international tourists due to well preserved traditional architecture and cleanliness in comparison to other towns. Throughout the section several interconnected old row houses and renovated houses were partially to fully damaged. The foundation and origins of the most of the houses are more than 82 years old (**Fig. 7**).

2.5 Damages along the Araniko Highway

The Araniko Highway connects Kathmandu with Kodari, 115 kilometres northeast of the Kathmandu Valley along the Nepal-China border. During the strong earthquake and aftershocks, most of the houses along this highway have been severely affected. Barhabise, Jhyale near the Chinese border are famous trade towns for imports. They suffered almost complete damage in the buildings (**Fig. 8**). According to the District-wide damage summary report (2015), almost 3440 human casualties occurred and all 557 government schools were destroyed during the earthquake, making it the most affected area. The Araniko highway was subjected to compound disasters of earthquake induced landslides/slope failures and damages of buildings throughout the Sindhupalchowk district. In the following sections damages on road and buildings due to landslides will be discussed.

3. Damages on historical monuments

Nepal is enriched with historical monuments including Hindu temples and Buddhist monasteries. UNESCO has declared ten World heritage sites in Nepal, categorized into cultural and natural sites. Kathmandu Valley (Kathmandu Durbar Square, Patan Durbar Square and Bhaktapur Durbar Square) and Lumbini where Buddha was born are renowned as cultural heritage sites while Chitwan National Park and Sagarmatha (Everest) National Park are the legendary natural heritage sites. Out of ten, eight World Heritage Cultural sites in the Kathmandu Valley have been severely affected. In the following subsections, damages reflected in those well-ornamented and beautifully crafted sites in the premises of Kathmandu Valley are discussed. Kathmandu Valley itself occupies seven World Heritage cultural sites in which Pashupatinath (Hindu pilgrim), Boudhhanath (Buddhist Stupa), Swayambhunath-Monkey temple (Buddhist Stupa), Kathmandu Durbar Square (living god premises), Patan Durbar Square, Bhaktapur Durbar Square and Changunarayan situated (UNESCO, 2015).

3.1 Kathmandu Durbar Square premises

Kathmandu Durbar Square surrounds quadrangles, encompassing with courtyards and temples, and is also known as Hanuman Dhoka Durbar Square a name derived from a statue of Hanuman, the monkey devotee of Lord Ram in Hinduism, at the entrance of the palace.

Fig. 3. Iron and wooden frames are used to give support on the narrow streets of south Durbar square. Clusters of old aged, renovated buildings combined with RCC buildings are distributed along this narrow streets. Most of the houses remain intact from support interconnected with each other.

Fig. 4. Damages on ancient Newar town of Sankhu area.

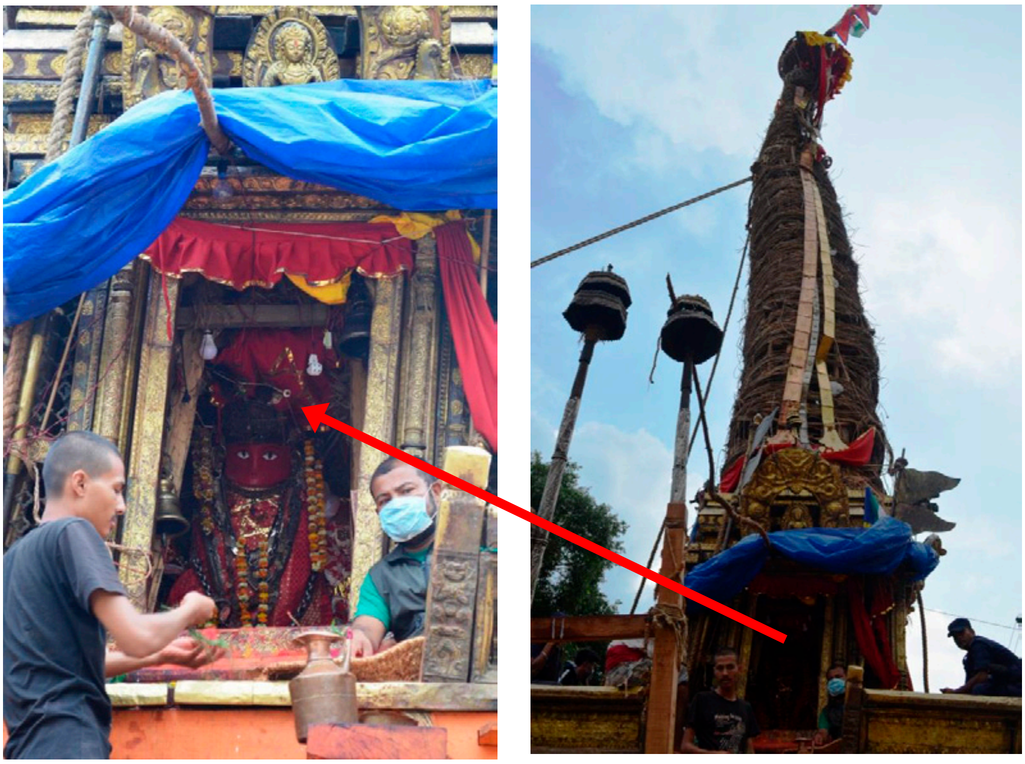

Fig. 5. Compassionate Aryavalokiteshvara and Raktapadmapani Lokeshvara worshipped by Buddhist. Hindu followers called Macchindranath.

Fig. 6. Entire Newar ethnic town of Bungamati was damaged due to main shock and aftershock. This place is enriched in wooden handicraft business and UNESCO announced the area as the World Heritage sector.

Fig. 7. Damages around Naag Pokhari and Khala of Bhaktapur Durbar square. Many old-aged buildings were severely damaged together with occassional new buildings due to inadequate construction.

This is the former royal palace of Malla and Shah Kings dynasties (UNESCO, 2015).

Several temples in this premises collapsed during the first strong earthquake. One of the most important is Kasthamandap, as the name Kathmandu is derived from it (Majupuria, T.C. and Kumar, R., 1993; British Library, 2009). The square is conquered by the massive pagoda roofs of Maru Satah (Kasthamandap) on the northern side of the square with presence of a shrine Gorakhnath inside the building at the center at the ground floor. The square was constructed in the 12^{th} century. The strong shaking of the earthquake cut the base of the Kasthamandap and collapsed the whole structure (**Fig. 9**). During the event there was blood donation program ongoing inside the Kasthamandap pagoda and several people were buried in the collapse debris.

Furthermore, the White Palace (Lal Baithak) built by British Government on 1908 AD. during Rana regime was severely damaged (**Fig. 10**). The Northern and northeastern side contains the former royal palace. Not only the Nautale Durbar (also known as Basantapur tower) and Hanuman Dhoka but also most of temples and monuments of Malla Dynasty have been severely affected through earthquakes (**Figs.11, 12, 13 and 14**).

Besides, the Kumari Ghar, the House of the Living Goddess which was first built in 1757 by King Jaya Prakash Malla has been partially damaged during the seismic shaking (**Fig. 15**). The Kumari is a young girl who is believed to be the incarnation the Hindu goddess Durga, aged in between three to five from the Buddhist Shakya clan. The cult of the Kumari is popular in both Hindus and Nepalese Buddhists (Reed, 1999).

The biggest attraction and tallest tower of Nepal, Dharahara also called Bhimsen Tower, is at the center of Sundhara in Kathmandu. It was first constructed by Bhimsen Thapa under the commission of Queen Lalit Tripura Sundari in 1825 AD. The original structure was destroyed during 1934 AD. earthquake. In 1936, Prime Minister Juddha Samsher Jung Bahadur Rana rebuilt it with a nine-story, 61.88 m tall (203.0 ft) tower. The tower constituted 213 spiral steps with a circular balcony for panoramic view of Kathmandu Valley at the 8^{th} floor held a circular balcony for observers that provided a panoramic view of the Kathmandu valley with a 5.2 m (17 ft) bronze mast on the roof (**Fig. 16a**). The April 25, 2015 earthquake demolished the tower with remnant of basal part (**Fig.16b**) and took the lives of 180 people.

3.2 Patan Durbar Square premises

Patan Durbar Square is situated at the city core of the Lalitpur district in Nepal, recognized by UNESCO World Heritage Sites and belonged to the ancient royal palace of Malla Dynasty. Durbar Square is enriched with typical Newari architecture incorporating red brick flooring. The temples premises of the square aligned opposite of the western face of the palace. In Patan, the Char Narayan Mandir, the statue of Yog Narendra Malla, a *pati inside Patan Durbar Square, the Taleju Temple, the Hari Shankar, and Uma Maheshwar Temple were severely damaged when the strong quake hit on April 25, 2015. **Figure 17** shows damages of monuments before and after the quake. Before quake pictures are adapted from Wikipedia (Patan Durbar Square).

3.3 Bhaktapur Durbar Square premises

The Bhaktapur Durbar Square is situated 13 km east of Kathmandu district. The square located in the current town of Bhaktapur, also known as Bhadgaon or Khwopa (an ancient Newar city). While the complex consists of at least four distinct squares named Durbar Square, Taumadhi square, Dattatreya square and Pottery square (Sharma et al., 1993). Until the second half of the 15^{th} century, it belonged to the capital of Nepal during the great Malla Dynasty and was recognized as the largest of the three Newar kingdoms. Bhaktapure is rich in culture, temples, and wood, metal and stone artworks. During the earthquake the main temple in the premises lost its roof. In addition, the most famous Vatsala Devi temple, constructed with sandstone walls and gold-topped pagodas was shattered by the shaking. Several other temples and monuments in this premises were also affected (**Figs. 18 and 19**).

4. Damages on RCC buildings

Several RCC buildings in the valley were demolished owing to their poor design and improper construction. The new bus park areas of Samakhushi, Machha Pokhari, along the ring-road between sections through Swayambhu, Sitapaila, Anand Naga, Gongabu and Samakhushi were intensively damaged. Strong base shear at the columns of the ground floor caused the collapse of buildings in several places (Manandhar et al. 2015). **Figures 20-25** show damages on RCC buildings in the city area. The Gongabu-Samakhusi area was reclaimed from swamps and a rice paddy field. The rapid urbanization starting more than twenty years ago did not consider proper treatment of these swampy lands. The poorly compacted ground experience in large shaking induced deformations and settlements causing building damage.

Fig. 8. Damages appeared along the Araniko Highway in Sindhupalchowk district: (a) Tilted poles and rubbles of houses can be seen at Lamosanghu area (b) Soft-story failure in RCC building at Lamosanghu, (c) Total collapse of concrete building at Barhabise, and (d) Debris of houses and severely damaged stone wall house at Barhabise.

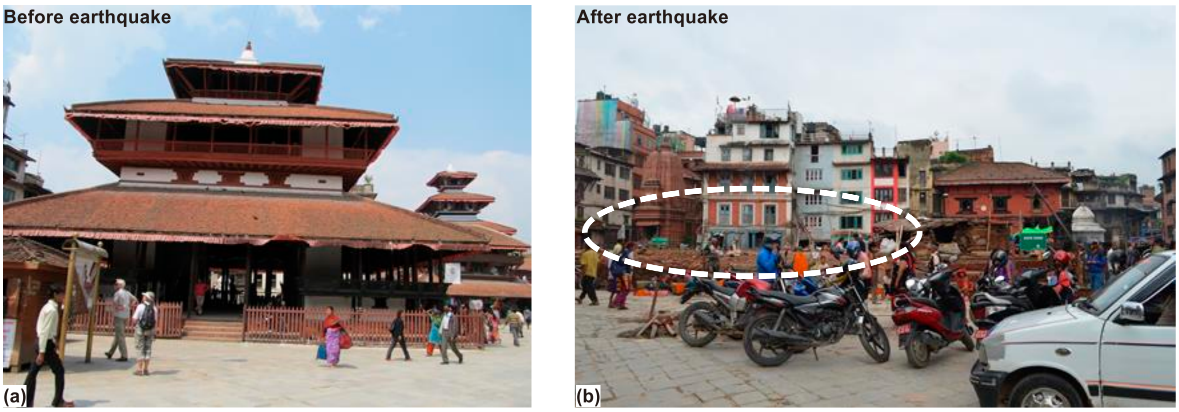

Fig. 9. Photograph representing Kasthamandap (Maru Satah): (a) Before earthquake (Courtesy: Wikipedia) and (b) After the earthquake. The name of the Capital Kathmandu is originated from this historical shrine.

5. Damages on road and infrastructures due to landslides

The 115 kilometre section of Araniko Highway in Sindhuplachowk district is suffering with numerous landslides and slope failures with presence of riverbank under-cutting the slopes during seasonal high river levels throughout the section. Torrential monsoon season rains produce massive sediment transport damaging building settlements, roads and bridges. During the strong earthquake, numerous shallow slope failures hit these features. **Figures 26-29** reveal shattered houses, roads, culvert and Sunkoshi Hydropower in Jhyale, Barhabise, Chaku, and Tatopani along the highway.

6. Damages on gabion structures

Gabion structures are most often used as retaining walls, revetments, river embankments and river dikes in order to protect against slope failure and river scouring/erosion at the toe of the slope. During the quake, sparse damages can be noticed along the Araniko Highway. Retaining walls have bulged up to about 20-30 cm in front of the road, which might be the effect of slope

Fig. 10. British Government constructed this White Palace in 1908 AD. It was extensively damaged during the quake. Photographs (a), (b) and (c) represent the survey immediate after the main shock and aftershock in the month of May, 2015 while photographs (d), (e) and (f) show the rod framework supports on both sides of the palace to protect from immediate collapse. The photographs were snapped during the second survey on July 21, 2015.

creep. However, the overall effect of earthquake caused only limited failure of these gabion structures.

7. Causative factors

The vast rugged seismically active the Nepal Himalaya produces regional damages impacting human lives, their property and existing infrastructure. The main causative factors are geological and tectonic, geotechnical and structural phenomena of the area. In the following sections, mechanisms and causative factors are discussed.

8. Geological and tectonic causes

Geology and variations of lithology together with evolution of structures control the geomorphological distributions of the area. It is noteworthy that the strong earthquake and aftershocks occurred relatively close to Main Central Thrust (MCT) which is further discussed in following sections. The Higher Himalayan Crystalline or Kathmandu Complex forms the hanging wall of the MCT and resting over Lesser Himalayan Sequence or Nawakot Complex. The Higher Himalayan Crystalline chiefly distributes resistant metamorphic rocks of gneiss, quartzites, schists and marbles while overlain Nawakot complex constitutes low grade metamorphic rocks of

Fig. 11. Nyatapola (Basantapur tower) (a) inner premises of the former royal palace, a recent museum (Courtesy: Wikipedia) and (b)damages occurred at the roof and adjacent parts.

Fig. 12. Trailokya Narayan Mohan temple (a) before the quake (Courtesy: http://hanumandhoka.gov.np/) and (b) collapsed all three-stories after the quake.

Fig. 13. Maju Deval temple built in 1690 A.D. (a) before the quake (Courtesy: http://hanumandhoka.gov.np/) and (b) collapsed all three-stories after the quake.

Fig. 14. Damages at (a) Hanumandhoka and (b) around Hanumandhoka.

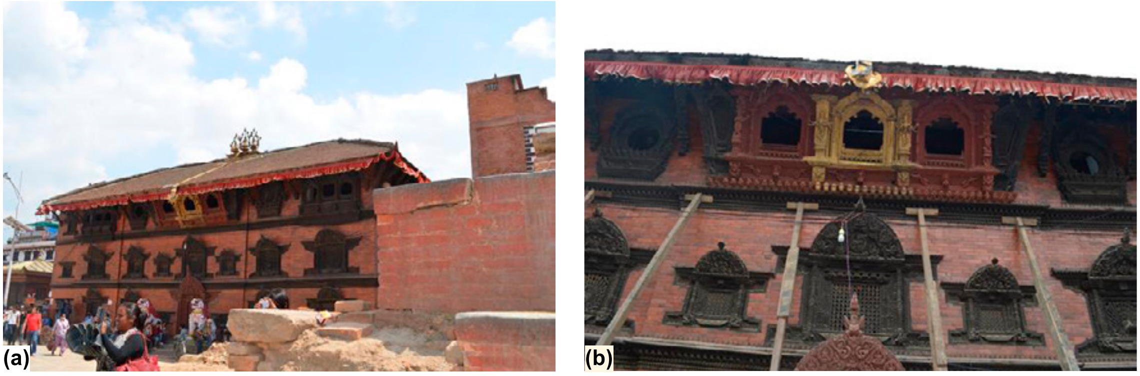

Fig. 15. Kumari House (a) first survey in the month of May 2015 without support and (b) the survey of July 2015 after wooden bracing support was added.

Fig. 16. Bhimsen Tower also called Dharahara (a) before the quake (Courtesy: http://www.nytimes.com/) and (b) collapsed after the quake.

slates, phyllites, dolomites and limestones which are susceptible to physical as well as chemical weathering. On the other hand, there exists a regional-scale antiform fold structure passing through the earthquake rupture zone. This Great Antiform (Hagen, 1969; Dhital, 2015) controls the distribution of mass movements and landslides. Generally, the region of antiform structures incorporated with low grade metamorphic rocks are highly susceptible for the formation of several joints and cracks easily due to physical and chemical weathering. As a consequence, slope failures are common in these areas. In the case of Araniko Highway of Sindhupalchowk district, numerous landslides, mass movements and debris flows occurred every year in rainy season. When a tremor passes through these zones, several shallow slides occur across the entire area. Most of the landslides are controlled by major drainage in the vicinity and exacerbated by improper road construction along the cut sections also accelerating mass movements during strong earthquake shaking.

Furthermore, Kathmandu Basin is composed of fluvio-lacustrine soft sediments formed in the Plio-Pliestocene age (alternative layers of clay, silt and sand) of more than 550 m thick unconsolidated sediment at valley center (**Fig. 30**). The lower fluvial granular sediments (gravel, sand and silt) of about 200-250 m thick is overlain by lacustrine clay sediments of about 200-300 m thick (Sakai et al., 2002). When seismic waves pass through rocky terrain and encounter the soft sediments (soils), the seismic waves amplify more. Closer to the epicenter the effects will be higher. Consequently, the frequency of seismic amplification is responsible for damages to frequency matched buildings and other infrastructures.

Figure 31 (a) and **(b)** represent the recorded ground motion data (USGS seismological section at KATNP) for 25 April mainshock (M_w = 7.8) and 12 May aftershock (M_w = 7.3) respectively. The accelerograms measured three horizontal (E-W), horizontal (N-S) and vertical components for both quakes. The Peak Ground Acceleration (PGA) of the ground motion was determined to be in the range between 150-170 cm/s^2 and 70-80 cm/s^2 for the 7.8 and 7.3 magnitude events respectively. It is notable that the PGA of 7.3 magnitude aftershock produced the most significant shaking at the recording station. The overall values for both quakes did not exceed the PGA estimates with 10 % probability of exceedance in 50 years for the recording station site, based upon current regional seismic hazard studies (JICA, 2002; Nath and Thingbaijam, 2012; Ram and Wang, 2013). Since the accelerograms demonstrated long period motions, shaking of the ground was primarily shown to include soft soil long period amplification attributable to the deep semi-unconsolidated fluvio-lacustrine Pleistocene sediments. The causative factor of

Fig. 17. Damages in Patan Durbar Square (a) Chyasim Deval Krishna Mandir and (b) toppling of the temple top in the east direction.

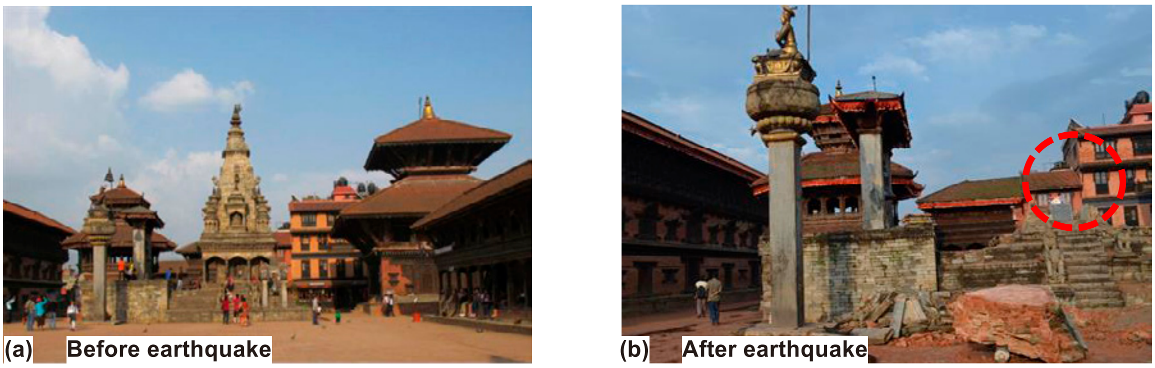

Fig. 18. Bhaktapur Durbar Square premises (a) Vastala temple, before the quake (Courtesy: http://www.nytimes.com/) and (b) collapsed after the quake.

Fig. 19. Fasidega Temple in Square (a) before the quake (Courtesy: https://commons.wikimedia.org) and (b) collapsed after the quake.

structural damage on many buildings of the Kathmandu Basin is the presence in some locations of large peak accelerations in the short period vibration. It is also notable that the presence of predominantly long-period ground motions prevented severe damages in most buildings, since they are medium to short period structures.

9. Geotechnical causes

One of the major causative factors of severe damages in Kathmandu Valley is the geological/geotechnical behavior where building foundations have been constructed improperly.

Fig. 20. Tilted RCC building at Machhapokhari, Ringroad, Kathmandu. Tilted towards the east direction.

Fig. 21. Toppled RCC building at Anand Nagar, Sitapailai, Ringroad, Kathmandu. Tilted towards the east direction.

Fig. 22. Tilted RCC building near Sitapaila, Ringroad, Kathmandu. Tilted towards N-S directions.

Fig. 23. Toppled RCC building in Gongabu area,, Kathmandu. Tilted towards the south direction.

Fig. 24. Toppled RCC building at Balkhu, Kathmandu. Tilted towards the east direction.

Fig. 25. Tilted RCC building at J.P. Marg, Kathmandu. Tilted towards the east direction

Bhandary et al. (2012) selected about 300 logs from the existing 700 borehole logs in the Kathmandu Basin to create a geotechnical database. According to the database, the maximum depth of soil strata contact with bedrock is more than 600 m in some locations.. The N-S section indicates the predominance of sand and gravel layers in northern part of the Kathmandu Basin extending through the central part of Kathmandu and enriched with clay deposits in the southern part. According to Okamura et al. (2015), based on eleven shallow boreholes in the depth between 10-30m, relative low SPT values (I <15) are typical in western part of the Kathmandu Basin near Tahachal in which the shallow soil stratum constituted chiefly of clay. At the middle part of the boreholes around Tribhuvan International Airport, the SPT values increased more than 15 with chiefly distributions of sandy gravel, coarse medium sand and silty sand. Further towards Bhaktapur, the shallow sub-surface soil characteristic is occupied with coarse to fine sand followed by clay at the bottom layer. The groundwater table is controlled by six major rivers such as Bishnumati River, Tukucha River, Dhobikhola River, Bagmati River, Manahara River and Hanumante River, producing a general phreatic surface within a depth of 1-3 m. For instance, the Gongabu-Samakhusi area of Kathmandu began to urbanize a little more than twenty years ago when developments lacked proper treatment of sub-soil conditions. Before urbanization, the area was a swamp and rice paddy fields.

Fig. 26. Intact house shattered by earthquake triggered landslides along the Araniko Highway.

Fig. 27. Houses were at the toe of the slope was demolished completely by earthquake induced landslides along the Araniko Highway.

Fig. 28. Culvert and retaining structure on the bank of the of the river along the highway was severely affected.

Fig. 29. Damages on column of the Sunkoshi Hydropower due to release of sudden landslide dam triggered by the earthquake.

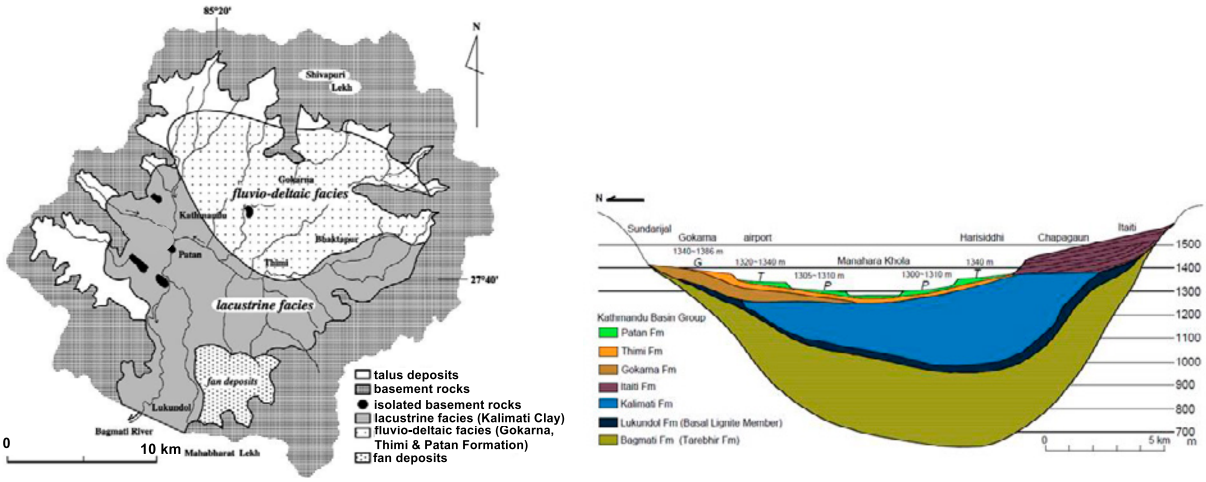

Fig. 30. Representation of geological map of Kathmandu Basin and its cross-section (Reference: Sakai et al., 2002).

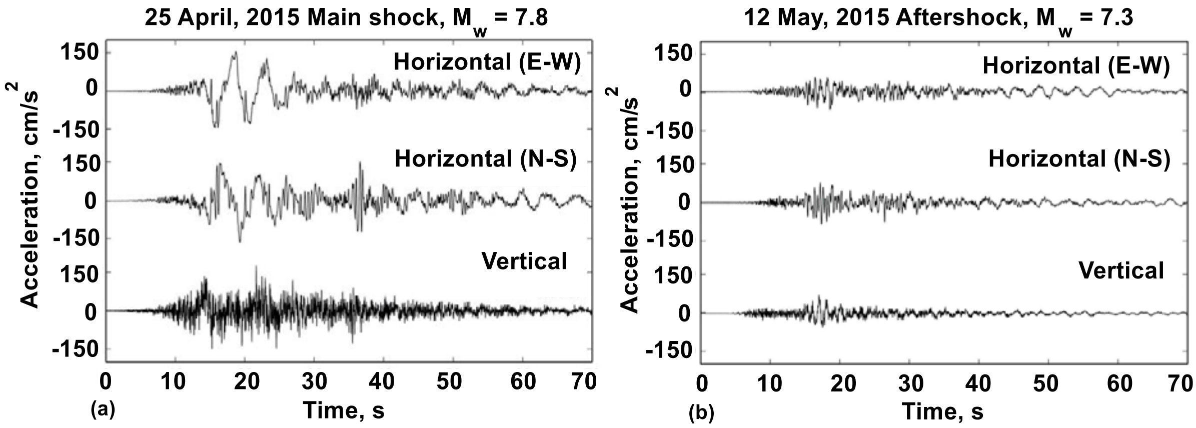

Fig. 31. Recorded ground motion data for (a) 25 April main shock and (b) 12 May afterschock (Reference: USGS, 2015).

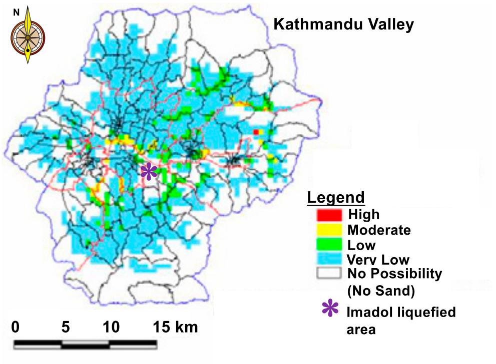

Fig. 32. Liquefaction potential map of the Kathmandu Valley (Source: JICA, 2002) and liquefaction observed area at Imadol, Lalitpur district.

Fig. 33. Observed local scale liquefied white colored fine silty sand at the agricultural field in Imadol area.

During the 2015 earthquake and aftershock, differential settlement of sub-surface layers in this area has led to damages. This reflects not only geotechnical/geological causes but also improper structural designs producing severe vulnerability causing greater damages compared to other city core areas.

9.1 Liquefaction

Kathmandu Basin deposits are classified as highly susceptible to potential liquefaction due to its loose, saturated, recent fluvio-lacustrine sediment nature. Juang and Elton (1991), UNDP/MOHPP (1994), Shrestha et al. (1999), JICA (2002), Piya (2004), Subedi et al. (2012), Dixit et al. (2013), Mugnier et al. (2011), Gautam and Chamlagain (2015) and Subedi et al. (2016) have carried out research on potential for seismic liquefaction. However, in contrast, the April 25, 2015 strong earthquake caused only local effects in some parts of the valley. The moderate to high potential zones of liquefaction as predicted by UNDP/MOHPP (1994) and Piya (2004) for conditions of high ground motion did not exhibit liquefaction except in Jharuwasi as reported by Subedi et al. (2016). During the 2015 earthquake, other local effects were seen at Manamaiju, Ramkot, Bungmati, Jharuwarasi, Hattiban, Imadol, Mulpani and Duwakot, in predominantly agricultural settings. **Figures 32** and **33** show the liquefaction potential map developed by JICA (2002) and some liquefied photos in the vicinity of Imadol agricultural field. White fine silty sand boils were observed in a small scale. Since the effects are confined to paddy fields, there was no known liquefaction related damage to the buildings.

9.2 Cause of failure on gabion structures

Use of in-situ material is the main cause of failure of gabion structures along the Araniko Highway. Geologically low grade metamorphic rocks of phyllite, schist which constitute chlorite minerals can be easily crumbled with your finger. These weak local materials when used to construct gabion structures, result in voids occurring in the middle part of filling materials, while their weathering reduces the shear strength of the structure. Another vulnerability from, improper construction of higher gabions is toe-bulging. Rupture of gabion wire due to rusting of wire is another cause. However, the total failures or collapses due to the earthquake tremor were very few, indicating a significant degree of residual strength of the gabion structures.

9.3 Cause of failure on retaining wall of JICA road

The Kathmandu-Bhaktapur Road is the part of the Arniko Highway that connects Kathmandu district with the ancient cities of Bhaktapur situated in the eastern part of the Kathmandu valley. The Kathmandu-Bhaktapur section starts at Tinkune in Kathmandu and ends at Suryabinayak in Bhaktapur, also called Nepal-Japan friendship road, has been improved by the Japan International Cooperation Agency (JICA). The road was upgraded to six-lanes in order to reduce the traffic congestion and improve the public transportation system which will be beneficial to the link road with Sindhuli and Araniko Highway for trade between China and with future phases, possibly with India (JICA, 2007).

A longitudinal crack appeared at the Lokanthali intersection where the built embankment was damaged due to differential settlement. Several buildings along the highway were tilted with an apparent longitudinal crack of about 40 cm which passed through the bridge towards the direction of Bhaktapur. Several houses and garages were tilted. Moreover, the pedestrian foot bridge was severely settled and police checkpoint was tilted due to slope failure. A depression about 1 m deep appeared to be due to differential settlement. As a result, cracks extended up the retaining walls. The joint between two types of reinforced soil retaining wall and gravity wall experience significant damaged. Ground fissures also passed through the gravity wall and continued to the opposite side of the bridge towards a residential area. **Figure 34** shows ground fissures, cracks on the wall, heaving and settlement of the area.

10. Building structural failure causes

It is notable that a buildings structural frame plays a vital role to prevent structural failure especially when strong tremors impact it. In the two surveys, failures of modern buildings in the city area have been attribute to building toppling due to improper practices of building codes. Major examples can be observed in comparing failure cases with adjacent buildings. At the same site/location, we found a sound building without any damages, while a neighboring building was toppled completely. In general, high-rise buildings are vulnerable in locations of soft soil deposits while low-rise buildings are highly susceptible in rocky terrain.

Generally, the minimum design of columns (pillars) for typical low to mid rise buildings in Kathmandu should be 30 cm X 30 cm and minimum requirement of steel rod reinforcement should be 2 % by area. The shear stirrups spacing should be at least 10 cm apart and the anchorage value of standard bend shall be incorporated as 4 times the diameter of the bar for each 45º bend subject to a maximum value of 16 times the diameter of the bar. The anchorage value of standard U-type hook shall be 16 times the diameter of the bar (Punmia et al., 2001).

Furthermore, shorter development lengths were observed on failed columns and beams. The lap lengths were insufficient for reinforced bars. The shear stirrups spacing were measured to be around 15 cm which do not follow the Nepal design code limitation of 10 cm (**Fig. 35**).

It is noteworthy to mention here that the Gongabu-Samakhushi area has built buildings leaving more space from business perspectives mainly renting to the people in terms of local business to sustain daily living. However, the subsequent upper floor's external wall rested on cantilevered beams making the structure wider at the upper height of the building. As a result, the overloaded ground floor collapsed first and the remaining structures toppled sequentially. Meanwhile, some cases of lower floors with inadequate shear walls on several buildings collapsed with remaining with upper stories intact, which is called soft-story failure. In this case, ground floor spaced lacking reinforcement is typically used for parking and local businesses such as l restaurants, offices, and retailers. As a result, lower floor pillar with no shear wall reinforcing bend easily and collapsed. In some cases failures between pillar and beam can be easily observed. As an engineering practice, rods extended from the upper section of the beam should be bent at 90º and inserted into the pillar maintaining the development length. Conversely, rods at the bottom section of beam should also be bent at the similar pattern. In the failure region, rods of beam were not inserted far enough inside the pillar and left at the joint only with shorter development of length. As a result, during the 2015 strong shaking column edges of the pillars easily yielded, spalled and released.

11. Caused owing to non-engineered renovation

Old structures, especially houses built with the combinations of brick and local clay mixed with lime are remnants of 1934 AD earthquake (8.1 Magnitude) or were renovated after being damaged in that historic event. Most of houses have walls made of sun-dried/fire bricks or local stones utilizing mud mortar, not only in rural areas but also in core areas of city. Most of the frames are made up of wood with flexible roofs and floors. Due to inadequate connections, many buildings could not bear the strength and damaged heavily during the strong quake. Also, renovations have been carried out with cement brick walls without considering proper engineering reinforcement. As a result, fissures and wide cracks often appeared between mud mortar wall and cemented walls (**Fig. 36**).

Furthermore, many renovations of old buildings were performed without considering even basic engineering designs. For example, reinforced concrete for one to three story additions were placed on top of old buildings with brick wall with mud mortar which overloaded the buildings producing severe damage. Similar phenomena were found along the Arniko Highway in Sindhupalchowk districts.

12. Directional movements of infrastructure

Frequent tremors occur in the Himalayan territory due to tectonic collision of the Indian plate and Eurasian plate at the rate of 5 mm per year. The continuous subduction of Indian plate below the Eurasian plate is the mechanism of evolution of Himalaya, which is observed to increase at the rate of 2 cm every year. The subducted Indian plate when interlocked at some places, accumulates stress and then enormous energy is released in the form of quakes in surrounding regions. According to Bilham (2004), the interlocked portion of the plate interface is situated at the depths of 4-18 km interf-

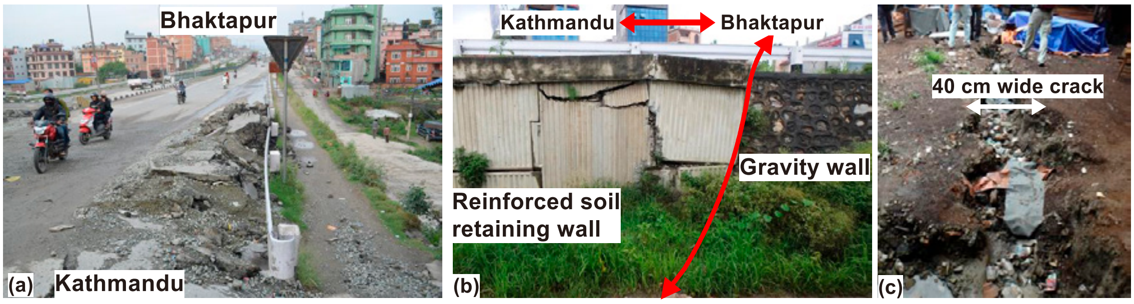

Fig. 34. Nepal-JICA road (a) road subsidence (b) cracks appeared on reinforced soil retaining wall and (c) 40 cm wide crack appeared. A longitudinal crack appeared at the joint of two embankment walls and runs along the another side of the bridge. Photos of (b) and (c) are adopted from Dr. H. Nakazawa from NIED, Japan.

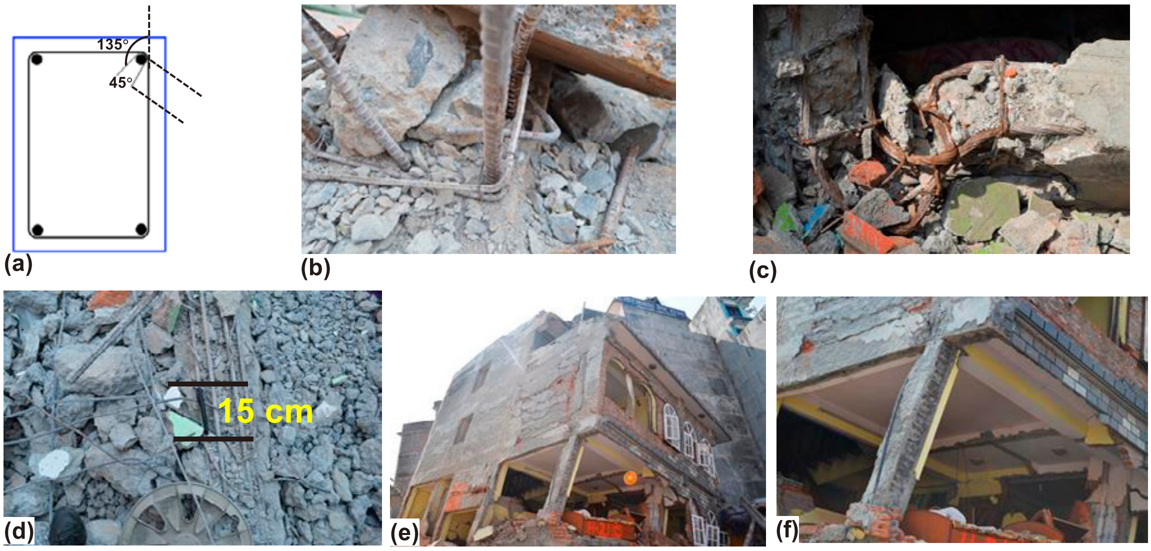

Fig. 35. (a) Indian standard of stirrup, (b) in appropriate anchorage bend, (c) column joint failure, (d) stirrup spacing is approached 15 cm or greater and (e and f) soft-storey failure due to undersized column.

Fig. 36. Figures from (a to d) represent non-engineered practices of renovation and (e) left house renovated one year before the quake without considering engineering design, as a result base shear formed and leaned towards next house. Meanwhile, the right side of the house was also renovated 30 years ago with completely replaced mud + brick with cement + brick and withstood the main shock and aftershock with only minor cracks inside the house. This house is older than 82 year and existed during the 1934 EQ.

acing with a low-dip angle. The Himalayan seismic release during the April 25 2015 magnitude 7.8 event ruptured the Main Himalayan Thrust Fault (MHT). The earthquake created about 1 m of uplift in the Kathmandu Basin (Elliott et al., 2016). The rupture propagated from west to east at the interface along the Indian and Eurasian plates at shallow level (Seeber and Armburster, 1981; Pandey et al., 1995; Bilham et al., 1997; Pandey et al., 1999; Avouac, 2003; Ader et al., 2012; USGS, 2015). As a result massive shaking was experienced between Gorkha, western part of Kathmandu to the eastern part of Kathmandu towards the border of China. This was the second largest modern tremor next to the 1934 AD. Nepal-Bihar earthquake of magnitude 8.1 (Ambraseys and Douglas, 2004; Bilham, 2004). The 2015 earthquake ruptured a 150 km long section of the Himalayan décollement terminating close to Kathmandu (Avouac et al., 2015; Hayes et al., 2015; Lindsey et al., 2015; Galetzka et al., 2015). The earthquake failed to rupture the surface of Himalayan frontal thrusts, raising concern that a future Mw ≤ 7.3 earthquake could break the un-ruptured region to the south and west of Kathmandu. However, Mencin et al. (2016) mentioned that 70 mm of aftershock slip occurred locally north of the rupture, and fewer than 25 mm of aftershock slip occurred in a narrow zone to the south. Historical earthquakes in 1803, 1833, 1905 and 1947 also failed to rupture the Himalayan frontal faults, and were not followed by large earthquakes to their south. So this issue will continue to be analyzed and debated.

Figure 37 shows the placement of April 25, 2015 main shock and May 12, 2015 aftershock on the resolved MHT geometry illustrated by Elliott et al. (2016). High-frequency seismic sources are represented with diamond-shaped symbol which run through the hinge line between the ramp and flat. The 7.3 magnitude aftershock occurred at the eastern end of the rupture zone. In the figure, directions of rupture with their corresponding magnitudes are represented together with the locked tectonic interface zone.

Gualandi et al. (2016) incorporated a variational Bayesian ICA (vBICA) method introduced by Choudrey (2002) to eliminate the seasonal and post-seismic signals. The analysis of post-seismic deformation after the main shock showed it to be 76.7±1.0 % aseismic. The measured deformation is consistent with the rate-strengthening frictional sliding on the MHT mostly downdip of the rupture. The afterslip reaches farther south and to shallower depth at the end of the eastern rupture zone. Mencin et al. (2016) mentioned that no discernible afterslips occurred on the combined main shock and/or aftershock rupture or on the surrounding MHT to the east or west. Although, after the main shock, <25 mm minor afterslip occurred between Kathmandu and the MDT, their models show that the maximum 70 mm afterslip occurred north of rupture below 20 km as shown by **Fig. 38** (Annotated figure received by Roger Bilham to use in this paper).

On the basis of several models and research conducted by revered seismologists, we implicate by our observations, the effects of directional movements of seismicity during the 2015 main shock and aftershock at infrastructures directly. During the two-surveys, the authors collected selected data in the Kathmandu Basin and along the Araniko Highway in Sindhupalchowk district. It was obvious that the April 25, 2015 strong tremor detached the zone along the western part from the epicenter of Barpak, Gorkha towards eastern direction delineating 150 km long rupture zone. As a result, buildings, historical monuments including temples and infrastructures either collapsed completely or tilted with partially to severely damage. The toppled and damaged sections have followed the direction of wave propagation showing the direction towards east. In addition, the shear marks visible in structures also delineate the wave propagation direction.

Proceeding, the major aftershock on May 12, 2015 does not reflect the direction of collapsed/tilted structures in the direction as with the main shock towards east. Overall affected structures have leaned towards a southern direction with occasional tilting towards a northern direction. **Figures 37 (b** and **c) and 39** distinctly represent the contrasting directions of the April 25 main shock and the May 12 aftershock (**Figs. 17b, 20-25**).

In this reference, authors have re-examined the previously surveyed areas and confirmed orientation of the observed structures. We collected data in the Kathmandu Basin and along the Araniko Highway in Sidhupalchowk district. In the Kathmandu district, samples were collected in the vicinity of Kathmandu Durbar Square at Basantapur-Jhochhe area, Thamel-Chhetrapati-King's Way area, Gongabu-Sitapaila area and Sankhu area. In Lalitpur district, Bungmati area was chosen as a typical historical and heritage area. In Bhaktapur district, in the vicinity of Bhaktapur Durbar Square at Naagpokhari area and Khala area were selected.

The data collection procedure was restricted to distinctly visible structures only. We did not survey directional movements of each building which were not visible from outside. Collected data were plotted in a rose diagram to interpret the directional movements. **Fig. 37 (b)** and **(c)** represent the overall directional movements of Kathamandu Basin and Sindhupalchowk district along the Araniko Highway. In figure, Legend A and B distinctly represent the directions of east and south respectively.

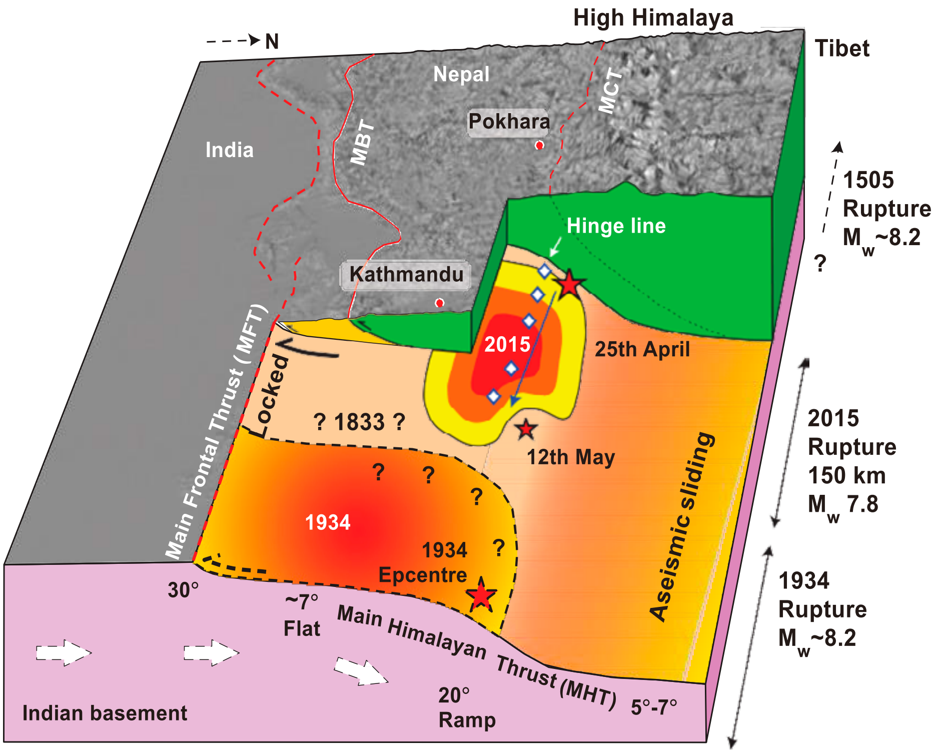

Fig. 37a. Representation of April 25, 2015 main shock and May 12, 2015 aftershock on the resolved MHT geometry. Aftershock occurred at the eastern end of the rupture zone (Reference, Elliott et al. 2016). The infrastructures tilted due to this aftershock in the N-S direction, mostly in southern direction. Below rose diagrams reveal the directions of tilted/collapsed buildings, historical monuments, temples and other infrastructures in the study area.

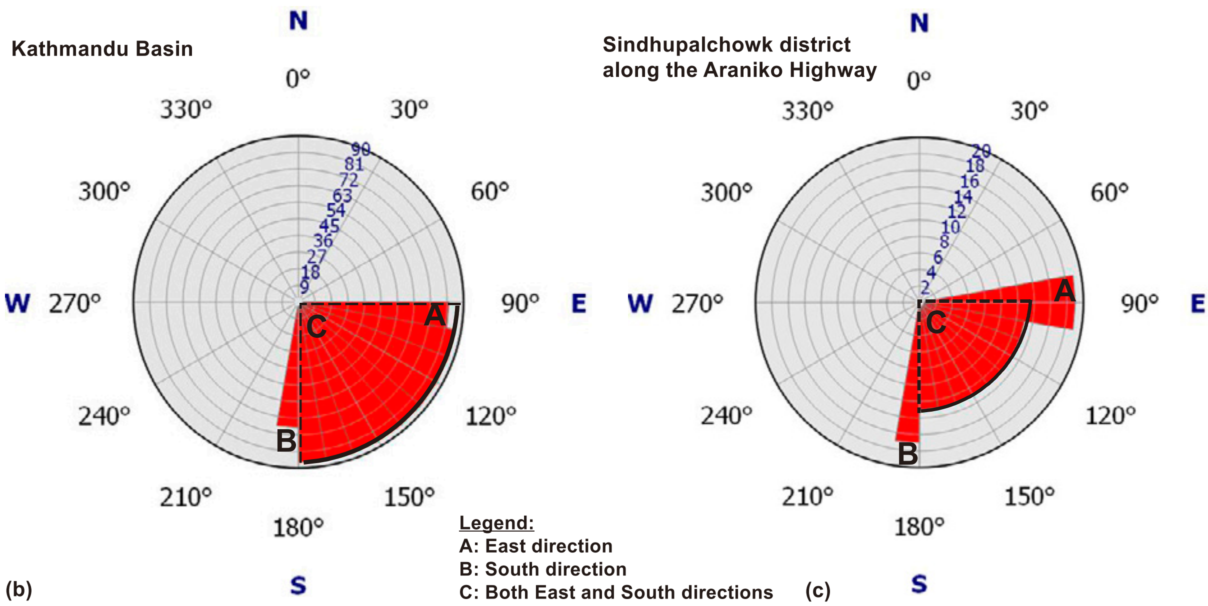

Fig. 37. Rose diagram showing tilted/collapsed directions (b) in Kathmandu Basin and (c) in Sindhupalchowk district along the Araniko Highway.

Legend B illustrates the structures affected with both quakes, main shock and aftershocks.

Care should be noted in the rose diagrams that authors have not measured the exact azimuth of the trend of the collapse direction, instead, tentative directions were noted. Moreover, the Legend 'C' outlined with a black-colored solid curve and dotted line is the representation of a combined/mixed direction which defines the majority of this part tilted and/or collapsed in

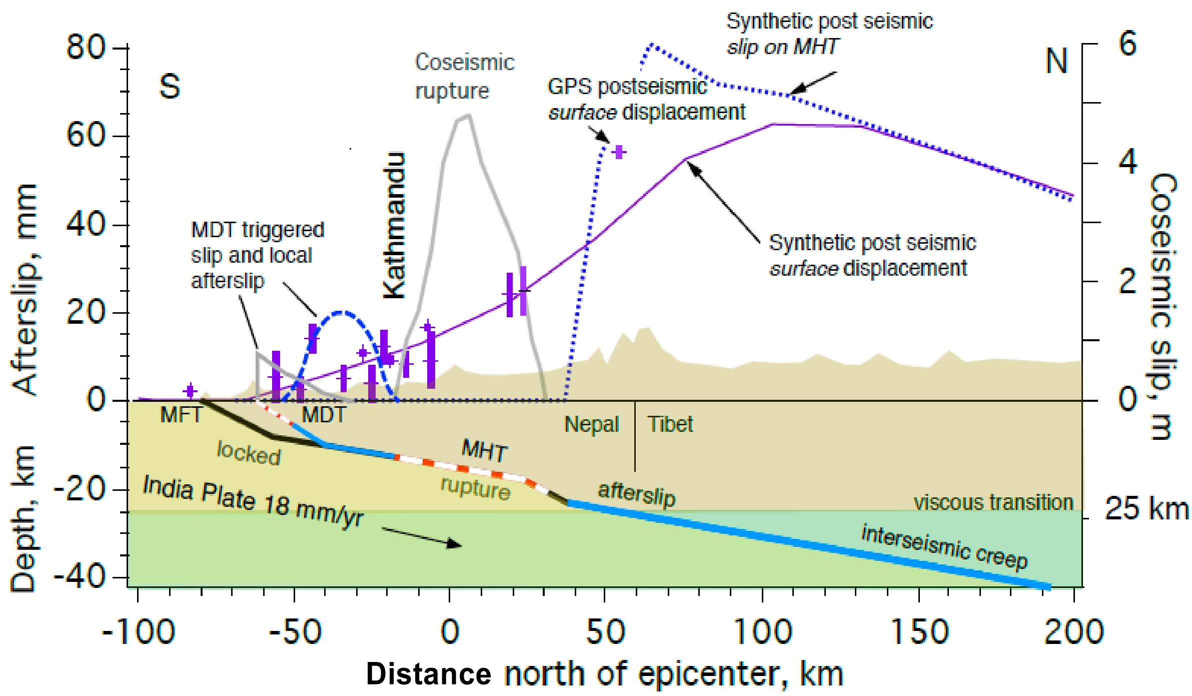

Fig. 38. Representation of N-S cross-section for the comparison of afterslip and observed post-seismic displacement. The figure illustrates that the minor afterslip occurred on the MHT south of Kathmandu and most of the afterslip in 2015 occurred on the region of interseismic creep below the base of rupture (annotated Figure 3 from the publication of Nature Geosciences, 13 June, 2016; received courtesy Prof. Roger Bilham).

both east and south directions. Furthermore, numbers from the center of the diagram towards the radius along the NE direction demarcates the number of selected representative data collected in the field.

Similarly, rose diagrams were plotted and represented in **Fig. 39** from the Kathmandu Basin. In this case also, similar procedures of representation of rose diagrams have been incorporated.

13. Discussions

Main shock of magnitude M_w = 7.8 on April 25, 2015 and aftershock of magnitude M_w = 7.3 on May 12, 2015 impacted mostly old/traditional buildings, historical monuments of World Heritage areas and triggered earthquake induced landslides along 150 km long rupture zone from the hypocenter of main shock at Barpak, Gorkha towards east passing through central part, Kathmandu Basin. Near the end of the rupture, aftershock of magnitude 7.3 originated at Bigu, 18 km southeast of Kodari and about 30 km east of Kathmandu. Wave propagation of the main shock revealed collapse and damage of structures towards the easterly direction. In contrast, the aftershock caused most of the structures to collapse and tilt toward southern direction. Regionally surveyed areas distinctly show the direction of structures leaning towards the east, the south and a combination of both (east and south). Published finding of leading international researchers thus far have not discussed detailed reasoning behind the directions of tilts brought by May 12, 2015 aftershocks. With reference to Gualandi et al. (2016), afterslip occur towards south direction at the end of rupture zone which interrupts the rate-strengthening barrier. As a consequence, this afterslip triggered the May 12, 2015 intensive aftershock which is reflected on the structures founded on the surface of the earth. Careful additional research should be undertaken at this zone to determine if this afterslip has contributed this intensive aftershock, or if there might be the chance of formation of a new fault plane along N-S direction from the end of the rupture zone of main shock.

Rose diagrams represent the directional movement of structures due to quake towards east, south and combinations of both directions around the rupture zone. **Figure 40** shows the percentage distribution of movement direction in the Kathmandu Basin. The Kathmandu Basin showed around 35 % of buildings and historical monuments tilted and collapsed towards east due to main shock. On the other hand, 29 % contributed towards south direction due to intensive aftershock. Remaining 37 % revealed structures were tilted in both east and south direction. Similarly, in Sindhupalchowk district along the Araniko Highway, 39 % of observed

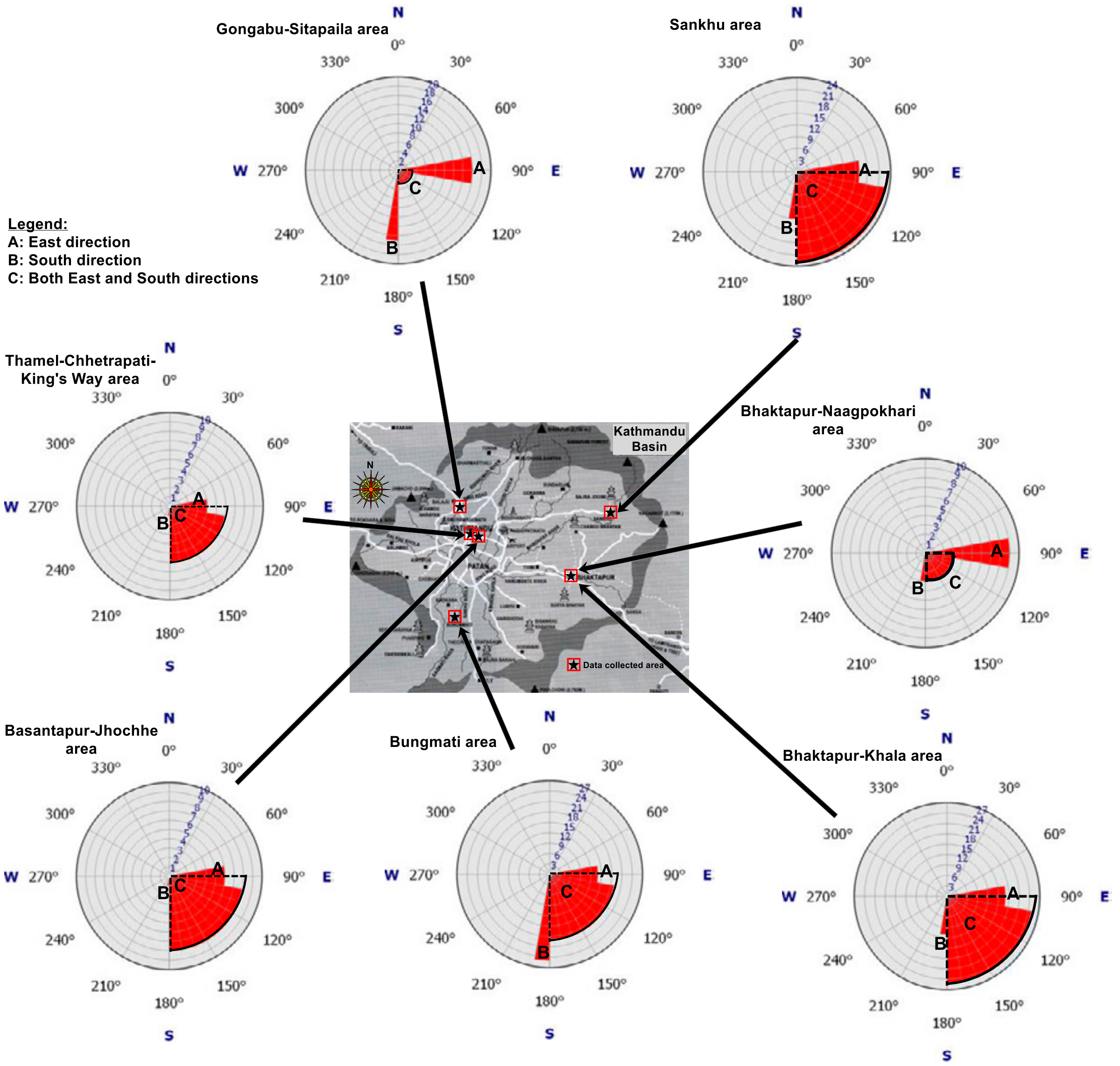

Fig. 39 . Representation of Rose diagram of tilted/collapsed buildings, historical monuments including temples of the Kathmandu Basin during April 25, 2015 main shock (M_w = 7.9) and May 12, 2015 aftershock (M_w = 7.3). It is noteworthy that the major shock affected the overall infrastructure, deforming toward the east direction while the major aftershock deformed in the north-south direction. Legend A and B denote the single tremor (main shock and after shock) events whereas Legend C denotes the effects of both tremors and tilting in both directions.

houses revealed to south direction. Remaining houses intensively affected with both quakes and tilted both in east and south directions (26 %) as shown by **Fig. 41**. Since the data collections are not specified to the conditions of each and every house and other structures, the percentage distributions of directional movements may vary accordingly. However, the effects of both shocks preserved the direction unless and until the structures are either completely demolished to build new ones or renovated with necessary improvements adopting specified codes.

The PGA values in Kathmandu Basin are significantly smaller with compared to the estimates of 10 % probability of exceedance in 50 years from the recent studies and brought damages owing to the large peak in the short period of vibration. The most of the buildings are less affected with long-period ground motions since they lack harmonic resonance at long periods. Care should be taken when constructing high-rise buildings at the central part of the Kathmandu Basin to study and model site response spectra effects and perform dynamic design modeling of the structures to incorporation long periods ground motion effects (Takewaki et al., 2011).

Due to seismically uninformed traditional construction practices and lack of adequate knowledge by local contractors and homeowners renovating old remnants and monuments, these structures suffered intensive and extensive damage. With reference to Chaulagain et al. (2015), about 44 % of buildings are constructed with mud mortar brick or stone masonry. On the other hand, 25 % wooden buildings, 18 % cement brick and 10 % cement concrete are common in Kathmandu Basin. The walls constructed with mud mortar with sun-dried or fired bricks incorporated with wooden frame bear low strength which is insufficient to maintain seismic load and subject to failure. Aftermath earthquake scenario shows the lack of training in local and micro levels to renovate and build new earthquake resistant buildings. Local people have started to build their houses adopting the similar method with slight improvements even in urban areas.

During the Rana regime, the construction materials used to build palaces and tower (Bhimsen Tower) were called Vajra, which is a type of reinforced material constitutes Surki (brick dust), Chuna (lime), Mas ko Daal (Black lentil) and Chaku (caramel). These typical architects have surrounding walls reflected to the European style. The Dharahara (Bhimsen Tower) was formed in the Mughal architecture to maintain the religious harmony between Hindu, Islam and Christ with the formation of the Hindu god, Shiva at the top floor. These structures were subjected to damage intensively in past earthquakes as well. Therefore, new historical monuments should be built with the adaptation of advanced engineering structures maintaining the historic architecture of the previous structures. Similar phenomena should be implemented for old historical and World Heritage temples, shrines, monasteries and monuments. A general awareness program should be conducted from the grass roots level.

Since the rupture zone passes through the great antiform and low grade metamorphic rocks of slate, phyllite, schist, limestones and dolomites, the regional area is highly susceptible to landslides in rainy seasons. The earthquake further adds several shallow slope failures along the Araniko Highway and in the vicinity which intensively damaged houses, roads and hydropower stations. Therefore, sound geotechnical design incorporating accurate geological conditions understanding of lithological control are most important to prevent and mitigate natural hazards in the future. In addition, gabion structures can be used robustly to prevent or reduce slope failures. Improvements to existing gabion structures can be formed by increasing geometric dimensions of the completed system by more than 1 m. For instance, gabion dimensions can be increased as L X H = 1.25 m X 1 m; 1.5 m X 1 m; and 1.75 m X 1m using geosynthetics. The results might be effective with improving the resistant breccia or round-shaped alluvial gravels used to construct retaining structures. In the case of soft sediments such as in Kathmandu Basin, heterogeneous soil properties, recent

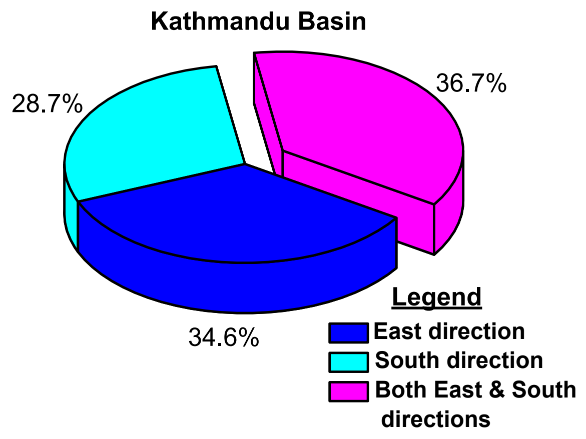

Fig. 40. Pie chart representing percentage distribution of directional movements in the Kathmandu Basin due to main shock and aftershock.

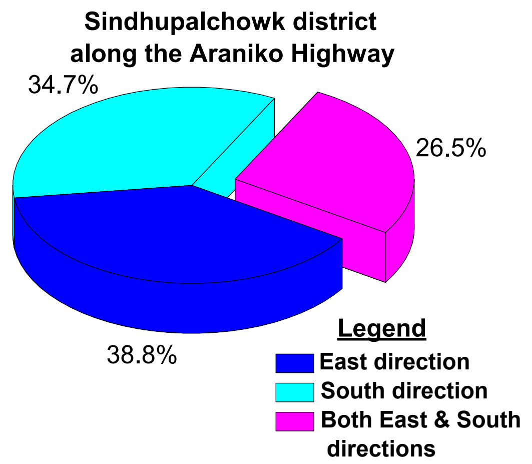

Fig. 41. Pie chart representing percentage distribution of directional movements in the Sindhupalchowk district along the Araniko Highway due to main shock and aftershock.

alluvial shallow deposits, shallow groundwater table controlled by major drainage system and lower SPT values will continue to post potential for liquefaction, land subsidence and large differential settlement during further earthquakes. Although the current disaster shows the local effects to be constrained to agricultural fields, care should be taken in the future to develop urbanization together with high-rise multiple buildings and city centers for the potential case of a more direct hit with an earthquake epicenter in Kathmandu. Detailed geotechnical study of soil dynamic properties should be carried out and proper seismic resistant international building code provisions should be implemented in order to reduce risk of possible failures in the future.

14. Conclusions

The strong earthquake on April 25, 2015 (7.8 M_w) and intensive aftershock on May 12, 2015 (7.3 M_w) cost the lives of 8,659 people, 21,150 people injured and huge economic losses across the nation including vast damages to eight World Heritage sites. Our two-surveys during May and July, 2015 aided understanding of the damages to traditional towns, historic monuments, and modern buildings. Causative factors associated with geological, tectonic, seismic, geotechnical and improper building construction of practices combined to bring huge damages during the quakes. Directional movement of wave propagation inflicted on structures due to both the main shock and aftershocks have been understood by observation of the mechanisms within the rupture zone. The main results from the survey can be drawn as follows:

1. Regional damages on buildings are confined to the old/traditional structures which are remnants of or renovated after the 8.1 magnitude 1934 AD earthquake. Renovations are blended with old and new methods without considering any standard engineering practices. For instance, top-story additions with concrete/cement structures over old unreinforced mud or cement mortar buildings with wooden frames.
2. World Heritage monuments and shrines are intensively damaged due to their aging weak condition.
3. Some RCC buildings were mostly collapsed and severely damaged around Gongabu-Sitapaila area due to strong base shear failure together with soft-story failures. Field studies showed that these newer buildings do not follow minimum current international standards with provisions to minimize failures. Conversely, in cases where the ground motion was not so intense, the RCC buildings remain intact.
4. Localized liquefaction effects were seen due to presence of semi-consolidated Pleistocene deposits controlled by major river drainage basins with shallow ground water and low bearing capacity of shallow sandy deposits followed by alternating layers of clay and sand fluvio-lacustrine deposits. The observed damages due to liquefaction are confined to agricultural fields in this disaster.
5. Presence of low grade metamorphic rocks and regional control of an anti-form structure contributed to many earthquake induced landslides affecting buildings roads and bridges along the Araniko Highway.
6. The M_w7.8 main shock and M_w7.3 aftershock produced eastward and southward tilted and collapsed structures. The main shock detached a 150 km long rupture zone propagating towards the east. The aftershock rupture zone was oriented south and to shallower depth initiating near the end of the eastern rupture zone. As a result, the aftershock produced a southern direction of shaking and damage to structures. Thus, care should be taken to further research whether this direction is due to aftershock directivity or if it reveals a new fault origination.

Acknowledgements

First our special thanks goes to Prof. Roger Bilham to provide his annotated figure of cross-section with topography and viscous transition from his publication of Nature Geosciences (June 13, 2016). We are equally thankful to USGS permitting to use the data base for the academic purpose.

We express sincere gratitude to the esteemed Thai PBS TV media and Nepal 1 TV media for the initial May 2015 survey. Proceeding, we are thankful to Prof. Tadashi Hara (Kochi University), Dr. Daisuke Suetsugu (ILMR, Saga University), Dr. Hiroshi Nakazawa (NIED, Japan), Mr. Kentaro Kuribayashi (Eight Japan Engineering Consultants), Mr. Tsuyoshi Nishi, Mr. Takuya Sakuraba (Construction Project Consultants), Mr. Takafumi Kariya, Mr. Yuki Kochi (K's-Lab.), Prof. Hemanta Hazarika (Kyushu University), Mr. Navindra Shrestha and Mr. Anil Ratna Tuladhar for their valuable advice during the follow-on July 2015 survey with special attention to formulate the integrated workshop in Nepal. We also express special thanks to Mr. Sushil Aryal, news coordinator of News 24 TV who edited and uploaded video proceedings of C2015NEIPDM to YouTube: (https://www.youtube.com/watch?v=oSxABPFHXeM).
Further appreciations proceed to Prof. Hiroyuki Araki, Director of Institute of Lowland and Marine Research and Prof. Keiko Kitagawa, Seitoku University for necessary financial supports to conduct the survey and successfully accomplish the C2015NEIPDM workshop on October 08, 2015. At last, we express our gratitude to people of Saga, Japan and ModChaNaPhai Foundation, Thailand for their kind supports with collecting donations to support aftermath earthquake victims.

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Symbols and abbreviations

KATNP	Seismological Center of USGS at Kantipath (Code for USGS)
MHT	Main Himalayan Thrust Fault
MCT	Main Central Thrust
M_w	Moment magnitude
PGA	Peak Ground Acceleration
*Pati	small public place for people to take rest
RCC	Reinforced Cement Concrete
SPT	Standard Penetration Test
USGS	United States Geological Sciences