Field evidence of Gorkha earthquake of 25 April (7.8 M) and Kodari earthquake of 12 May 2015 (7.2 M) in Nepal

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ABSTRACT
25 April 2015 Gorkha Earthquake (Mw 7.8) and 12 May 2015 Kodari Earthquake (Mw 7.3) have been considered as devastating earthquakes with a heavy toll of lives and loss of properties. The present study envisages the visit of the various damaged sites affected by the recent earthquakes. The existing attenuation relationship from various existing models fails to explain the observed ground motion parameters. The Gorkha earthquake occurred as the result of thrust faulting near the Main Frontal Fault and Kodari earthquake occurred due to thrust faulting near the decollement associated with the Main Himalayan Thrust, which defines the interface between the underthrusting Indian and the overriding Eurasian Plates. The Kodari earthquake is located beyond the eastern end of that of Gorkha earthquake, but, it is not considered as aftershocks. These earthquakes caused considerable damage to life and properties and induced many mass movements in mountainous areas, which could be another cause of secondary disasters. The assessment of existing infrastructure damages on intensity scale ranging VII-IX classes. The maximum damage is in Sindhupalchok district of Nepal. It is necessary to develop a new attenuation model especially for the Himalayan region to predict the ground motion parameters.

KEYWORDS
Earthquake; Nepal; damages and faulting

Introduction
An earthquake of magnitude 7.8 Mw was triggered on 25 April 2015 near Gorkha village, located 80 km NW of Kathmandu in Nepal. It is known as Gorkha earthquake. A massive building and property destruction and heavy death toll (over 8000 people) were reported after the earthquake from epicentre (28.147° N and 84.708° E) to surrounding areas even up to Kathmandu. Two aftershocks (6.6 and 6.7 Mw) were triggered within an hour of the main shock and were followed by a large number of aftershocks within its rupture area. Another large aftershock of magnitude Mw 7.3 (Kodari earthquake, 27.837° N and 86.077° E) was triggered on 12 May 2015 located at 150 km east of Gorkha earthquake. Sindhupalchok district was the worst affected district after the Kodari event, which was located within the same district. The absence of aftershocks in Kathmandu indicates that the rupture has not propagated southward of HFT. As per the United States Geological Survey (USGS), the earthquake ruptured area along with shallow dip of fault suggests that the main event is a reactivation of a sub-horizontal part of the Himalayan Frontal Fault (HFT).
The Gorkha and Kodari earthquakes in Nepal present themselves as the two major post-instrumentation era events in the Himalayan region and they provide an opportunity to study the earthquakes in relation to the ground motion as well as seismotectonics of the Himalayan terrain. The existing attenuation relations (Abrahamson & Silva 2008; Boore & Atkinson 2008; Campbell & Bozorgia 2008; Chiou & Youngs 2008) fail to predict the observed ground motion parameters. Therefore, it is required to develop a local attenuation model for predicting the ground parameters.

In order to define the key priorities in complex emergencies and crises after the Gorkha earthquake in Nepal, it is necessary to plan judiciously for meeting goals such as severity of needs, geographic and sectoral gaps, vulnerable groups and communities. We also learn lessons from the past earthquakes such as Indonesia, Turkey and Haiti ones to find out to prioritize the strategies to cope with earthquake hazards as well as the rehabilitation programmes and other attendant activities.

**Brief geology of Nepal**

Nepal is located in the centre of the Himalayan mountain belt, and is almost rectangular in shape with about 870 km length in the NWW-SEE and 130–260 km in N-S direction. Geologically Nepal Himalayas is subdivided into four tectonic zones from south to north which are separated by E-W trending thrusts (figure 1). Geologically the youngest Siwalik Group lies between Main Frontal Thrust (MFT) in south and Main Boundary Thrust (MBT) in north. It is a narrow belt of 20–30 km width and 5–6 km thickness that runs E-W of middle Eocene age. Geologically this zone is composed of loose to consolidate north dipping sedimentary rocks (conglomerate, and stone, silt stone, mudstone and marls) with fossiliferous horizons. These sedimentary foreland basin deposits form an archive of the final stage of the Himalayan upheaval and record the most recent tectonic events in the entire history of Himalayan evolution since ~14 Ma.

Lesser Himalayan Zone lies to the north of the Siwaliks. The northernmost thrust sheet of the MFT is truncated by the Lesser Himalayan sequence and overlain by un-metamorphosed to weakly metamorphosed rocks of the Lesser Himalaya, where the Lesser Himalayan Zone is thrusted over the Siwalik Group along MBT. This composed of low-grade metamorphic rocks like slate, phyllite,
schist, quartzite, marble and sedimentary rocks limestone and dolomite, shale, etc. in the south. The Lesser Himalayan Zone generally forms a duplex above the mid-crustal ramp (Decelles et al. 2001; Schelling & Arita 1991; Srivastava & Mitra 1994).

The Higher Himalayan Zone overlies the Lesser Himalayan Zone in north and is separated by Main Central Thrust (MCT). It consists of high-grade rocks, e.g. kyanite—sillimanite gneiss, schist and quartzite and is mostly characterized by ductile deformation. This zone is characterized by extremely high relief, steep topography, rocky cliff and outcrops with little soil cover terrain. Tibetan-Tethys Zone lies north from the Higher Himalayan Zone. This zone is composed of fossiliferous sedimentary rocks like shale, limestone, sandstone, etc. It attains a lower relief and ruggedness than Higher Himalaya.

**Seismotectonics**

The east-west trending plate boundary between India and Eurasia comprises several major and minor faults distributed on a roughly 200 km wide strip between the Himalayan front and the MCT to the north (figure 1). The seismic activity is caused by the convergence of the Indian tectonic plate to the north towards the Eurasian Plate with a relative rate of an approximately 40 mm per year. The shortening is accommodated by several parallel faults and therefore it is recognized as a diffuse plate boundary. The plate boundary at the foot of the Himalaya is one of the most active continental boundaries worldwide and host of the largest earthquakes in the region. Many active faults are distributed along the major tectonic boundaries (Nakata & Kumahara 2002), which were produced by the collision of the Indian Plate with the Eurasian Plate (figure 2). These active faults in the SW part the Kathmandu basin (Saijo et al. 1995; Yagi et al. 2000) cut the Late Pleistocene sediments and have a vertical displacement rate of 1 mm/yr. Several large to great earthquakes occurred during the last century along the Himalayan front.

**Historical earthquakes**

It is necessary to discuss the Great Himalayan Earthquakes triggered in the past. Among the four Great Himalayan Earthquakes (Shillong earthquake of 1897, Kangra earthquake of 1905, Nepal—Bihar earthquake of 1934 and Arunachal—China earthquake of 1950) within the last 100 years (figure 3), the great Nepal—Bihar earthquake (M 8.0) of 1934 severely damaged the Kathmandu Valley. Various workers such as Richter (1958), Singh and Gupta (1980), Chen and Molnar (1977), Seeber and Armbruster (1981) developed an improved understanding of a slip that occurred.

![Figure 2](image-url). Major faults in the Himalayan region and rupture zones of earthquakes of 25 April 2015 and 12 May 2015 as shown by Lisa Wald 2015 on a generalized cross section after Lavé and Avouac (2000) and Kumar et al. (2006) (MFT: Main Frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust).
The earthquake of 1934 was the most devastating earthquake ever occurred in the territory of Nepal with casualties of more than 16,000 people including from Nepal and India put together. The earthquake of 1255 has been reported to destroy many houses and temples and killing one-third to one-fourth population of the Kathmandu Valley. The earthquake of 1408 AD has been reported to destroy the Machhendra Nath temple of Patan. Similarly the earthquakes of 1681 and 1810 have been reported to occur but the exact locations of these earthquakes are not known. Recent research on historical data has well constrained on the source size, magnitude and possible location of the 1833 event (Bilham 1995) which devastated Kathmandu Valley.

There has been no great earthquakes of magnitude $>8.0$ M in the gap between the earthquakes of 1905 and 1934 with the available data and there is a real threat that a major earthquake may occur in this gap that will affect western Nepal. Another historical earthquake in 1505 at Lo Mustang is one of the seismic gaps from the last 500 years, where a magnitude larger than 8 M earthquake was expected to happen in the future due to ongoing stress accumulation, which has not been released by the recent earthquakes in Nepal. The M 7.3 earthquake of 12 May 2016 shows a similar spatial pattern as the sequences of 1905 during the Kangra event, in 1991 and 1999 during the Uttarkashi and Chamoli earthquakes; 1916–1926, 1926–1945 in Uttaranchal. The record of historical earthquake is not complete, which becomes a problem in assessing the recurrence period of great earthquakes.

The 12 May 2016 event is believed to be induced by slow static triggering of the M 7.8 earthquake (figure 4). It is also inferred that the strain was built up and part of its energy was released in these recent earthquakes (figure 5). Therefore, the remaining strain energy might trigger another event in future. The Gorkha and Kodari are the only two events in Nepal, which were triggered at the Indo-Eurasian subduction boundary and therefore, the seismological analysis will reveal more
Figure 4. Historic earthquake locations along the Himalayas showing the seismic gaps as well as the patterns of temporal seismicity (after Bollinger et al. 2014).

Figure 5. Red arrow: tectonic convergence. Black lines: local stress orientation (WSM, World Stress Map). Additional literature: Avouac (2003), Bollinger et al. (2006, 2014). To view this figure in colour, see the online version of the journal.
understanding of seismotectonics of the Himalayan subduction boundary between Indian and Eur-

Asian plates.

**Gorkha earthquake**

A large earthquake of magnitude Mw 7.8 occurred in central Nepal on 25 April 2015 (figure 6). Two aftershocks of 6.6 and 5.7 M were recorded within an hour of the main event. There are a large num-

ber of aftershocks recorded after the main event of Gorkha earthquake. Most of the aftershocks are close to the edges of the ruptured zone as it may be approximately delineated from seismological observations. Geological cross sections, crustal structure model, and the preliminary seismological data available few days after the main shock reveal that the earthquake has ruptured a part of the Main Himalayan Thrust (MHT).

Gorkha earthquake was triggered as the result of thrust faulting on or near the MFT between the subducting Indian Plate and the overriding Eurasian Plate to the north (figure 7). The rupture started at the epicentre, about 80 km to the northwest of Kathmandu and propagated eastward for about 130 km. The 25 April 2015 M 7.8 main shock had approximate dimensions of $\approx 120 \times 80$ km from its hypocentre to eastwards. The slip of 3 feet was observed in the present studies at the area directly located under the Kathmandu city (figure 10). The focal mechanism derived from the analyses of seismological data shows a fault plane striking N143°E, with a very shallow dip of 7° towards the north.

The Gorkha earthquake induced many mass movements in mountainous areas and resulted in landslide lakes, which could be another cause of secondary disasters in the part of Gorkha, Balua, Nuwakot, Sindhupalchok, Dolakha, Ramechhap, and Kavre along the road sides in Sindhupalchok district. The mass movements are the main causes of the collapse or heavy damage to buildings and

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**Figure 6.** Damaged areas around epicentral of 7.8 M and 7.3 M earthquakes in Nepal Laprak village (7.8 M earthquake) and Singati village (7.3 M 26 earthquake).
heavy casualties in mountainous areas. The earthquake also triggered a major avalanche on the south slopes of Mt. Everest, located approximately 160 km east-northeast of the epicentre. Many base camps were destroyed due to avalanche.

**Kodari earthquake**

12 May 2015 M 7.3 Kodari earthquake (SE of Zham, China) occurred as the result of thrust faulting on or near the decollement associated with the MHT, which defines the interface between the underthrusting India Plate and the overriding Eurasia Plate to the north. At the location of this earthquake, approximately 80 km to the east-northeast of the Nepalese capital of Kathmandu, the India Plate is converging with Eurasia at a rate of 45 mm/yr towards the north-northeast, a fraction of which (18 mm/yr) is driving the uplift of the Himalayan mountain range. The 12 May 2015 event was located 150 km to the west, and which ruptured much of the decollement between these two earthquakes (figure 6). Events of the size of the 12 May 2015 earthquake are typically about 55 × 30 km in size. The 12 May 2015 earthquake is located just beyond the eastern end of that rupture (NOAA 2015). It is not considered as aftershocks of 7.8 M. Sindhupalchok district was the worst affected district besides neighbouring regions after the Kodari event, which was located within the same district. It also induced several mass movements in the hilly terrain, particularly the highway was blocked, which is connected from Tibet. It also affected the supply of emergency relief materials from China.

**Aftershocks of Gorkha earthquake**

The aftershocks are distributed in an area roughly 150 km long and 50 km wide, with the majority of the aftershocks located in the eastern part of the ruptured area. At first order, the area defined by the bulk of aftershocks corresponds to the ruptured area on the fault plane. The location of the ruptured
area, together with the shallow dip of the focal mechanism, suggests that it is most probably the sub-horizontal part of the MHT that has ruptured, mostly the deeper part of it. The absence of aftershocks to the south of the valley of Kathmandu suggests that the rupture has not propagated southward to reach the surface along the MFT. There were 14 aftershocks more than 5 M magnitudes up to 11 May 2016 and within an hour of the main event, two aftershocks of 6.6 and 5.7 M were triggered. The aftershocks of 7.8 M earthquake continued with reduced magnitudes. The rupture of the Gorkha earthquake was extended towards east which is evident from the 158 aftershocks with 29 June 2016. The Kodari earthquake of 7.3 M was triggered on 12 May 2016 outside the rupture area of Gorkha event. Kodari earthquake was the new rapture and continued further in the SW and NE directions (figure 7). The epicentre of Kodari earthquake was located 90 km east of Gorkha earthquake. It was also located outside of the rupture of Gorkha earthquake. The Kodari earthquake formed its own rupture, distinctly separated from the rupture caused by the Gorkha earthquake. The aftershocks are normal occurrences after the main shock and are expected to decrease in frequency and magnitudes in days and weeks after the main shocks. Even if we consider Kodari earthquake as an aftershock of Gorkha earthquake, its probability is not possible. It seems that rupture of both the earthquakes was on HFT and MBT in Kathmandu Himalaya but the 7.3 M earthquake was not the aftershock of 7.8 M earthquake. Kodari earthquake was clearly a consequence of the Gorkha earthquake, most likely caused by redistribution of stress on the tectonic plates, as it was not the aftershock of Gorkha earthquake.

Intensity of 7.8 M earthquake

The intensity of an earthquake differs greatly from place to place and distance from its epicentre. The intensity of damage is the result of seismic-wave attenuation, which is the reduction in wave amplitude and wave energy as they travel away from their source. The peak acceleration was recorded as 0.74 g for Gorkha earthquake as per USGS. The intensity classes are based on the field visits and information from the secondary sources for the affected area. The intensity is classified as class IX (Kathmandu), VIII–VII (Bhaktapur, Lalitpur, Gprkha, Sindhupalchok and Hetauda) and VI (Birganj, Raxual and Sitamanrhi) (figure 7). Kathmandu is a densely populated city and surrounding localities Bhaktapur and Lalitpur also have more populations compared to other cities in Nepal. The large aftershock triggered in Nepal (Kodari earthquake) after a couple of days and damages was again severe in the neighbouring regions of the epicentre. The intensity at Sindhupalchok district was mapped at class VII after the main shock as it was located 180 km east of the main shock and further mapped in class IX after Kodari earthquake which further caused an increase of death toll to 100 persons in the same district. The intensity maps of Gorkha and Kodari earthquakes were superposed and compared to find out the severe damages at Sindhupalchok (Class IX), which was either mapped in class VIII after the main shock (figure 8). It was observed that a large aftershock of 7.2 M (Kodari earthquake) was triggered in Sindhupalchok district. This is one of the reasons that maximum damage was observed in Sindhupalchok after the Kodari earthquake. It is also an important observation which leads to the inappropriate modelling of ground motion in Nepal Himalayas. It is quite clear that Kodari earthquake may not be considered as the aftershock of Gorkha earthquake.

Ground motion

It is necessary to carry out ground motion studies to improve the understanding of damaging ground motion produced by earthquakes to develop the seismic hazard assessment and mitigations. The epicentral distance is not a very relevant parameter for the determination of the ground motion, because a large portion of the affected area lies directly within the rupture zone in case of large earthquakes. Seismic waves arrive at a given point from the whole of the rupture zone and not just from the epicentre. This explains why the damage caused by the main shock of 25 April 2015 did not
decrease with an increasing epicentral distance, as evident from the intensity map shown in figure 7.

The ground acceleration was computed using the USGS data for the Nepal earthquake which ranges from 0.02 to 0.74 g. (figure 7). The maximum peak ground acceleration (PGA) was estimated at 0.4 g (figure 8) of the Kodari earthquake. The maximum damage and loss of lives occurred in the Sindupalchok district, which is located 100 km to the east of the epicentre of the main event. The Sindupalchok district was again affected by the Kodari earthquake on 12 May 2016 as the epicentre was located within the same district.

A quick comparison of various international attenuation relations with observed and estimated ground motion parameters using existing models (Abrahamson & Silva 2008; Boore & Atkinson 2008; Campbell & Bozorgnia 2008; Chiou & Youngs 2008) for the recent Nepal earthquakes fails to predict the observed ground motion parameters. Site effect can always alter the ground motion and change the damage pattern of large earthquakes (Ahmad & Singh 2015). It is thus clear that the attenuation laws employing the epicentral distance as a parameter should not be used in an earthquake hazard analysis in the Himalayan region, as the rupture zone of a strong seismic event in this region tends to be large and almost horizontal. It is necessary to resort to a more modern attenuation law that uses the minimum distance from the causative fault as a parameter. There could still be a research need to develop or refine a representative attenuation model suitable for an earthquake hazard analysis in this region.

**Observations on earthquake damage**

There are a number of damages observed in Kathmandu Valley and surrounding hill side regions. The majority of new construction in Nepal utilizes various forms of unreinforced masonry consisting of solid brick, concrete block or stone with either cement or mud mortar. Older buildings are made of unconfined unreinforced brick masonry with either wood or masonry lintels at door and window opening and wood framed floors supported heavy mud floor and roof slab, or sloped wood.
framed roof or canopies with corrugated galvanized iron or clay/stone tile finishing. The lack of adequate foundation for steep hill side type construction contributed to many collapsed and damaged structures. The stone rubble is used instead of masonry foundation, which was damaged during the recent earthquakes.

**Building typology**

Most of the buildings were also built of unreinforced masonry and that has caused high fatality rates in Nepal. Daniell et al. (2015) in their CEDIM Report 3 compared the similar Sichuan earthquake in China with a fatality of 65,000 out of 1.7 million destroyed houses. The average ratio is 1 death per 250 destroyed houses, where as it is in the order of 1 death per 350–400 destroyed houses in Nepal. However, it is important to take the time of day difference into account. Thus both earthquakes have similar ratios. It appears in low quality building and construction materials (i.e. concrete strength), additional rebar and other safe reinforcement practices saved many catastrophic collapses, thus reducing the death toll in Kathmandu city.

**Earthquake damage to temples and heritage structures**

A devastating effect was observed on the ancient temples and heritage structures in Kathmandu Valley after the Gorkha earthquake. Some of them are included in the UNESCO World Cultural Heritage sites. Disproportionately high rising structures collapsed during the earthquake shaking as compared to the brick masonry and reinforced concrete (RC) frame buildings in their immediate neighbourhood. Most of them suffered from only minor visible damages. Various possible explanations for the high damages to the temples and the heritage structures are the age of the heritage structures and inadequate maintenance. There is an unusual structural design such as higher flexibility and larger masses. The existing damage and cracks could not be retrofitted earlier which were caused by past strong earthquakes (1833 and 1934). The natural frequencies of these monumental structures usually differ significantly from those of normal brick masonry buildings. Therefore heritage sites became more vulnerable to the ground motion of the main shock dominated by long-period motions.

It is interesting to note that some old temples that have survived the 2015 earthquake are also known to be those that suffered the least damage in the 1934 earthquake disaster, for example the Akash Bhairav Temple at Indrachowk, Kathmandu, the Pashupatinath Temple in Kathmandu and the Nyatapole Temple at Taumadhi Square, Bhaktapur (Shakya 2000). In the Nyatapole Temple, the highest pagoda temple in Nepal, only the uppermost storey shows externally visible damage, which could be a re-run of the 1934 earthquake damage to this temple, as recalled by some elderly people in Bhaktapur. An investigation of the possible reasons (e.g. more robust structural system, better maintenance, etc.) for the apparent earthquake resilience of these temples could provide valuable hints for the earthquake-resistant redesign of the collapsed temples.

**Earthquake damage to stone rubble masonry houses**

In the hilly regions of Nepal, a majority of houses are made of stone rubble masonry held together with mud mortar. Such structures are inherently vulnerable to sudden brittle failure when subjected to strong earthquake shaking. Most of the stone masonry buildings collapsed during the recent earthquake. This is the main factor for the high death toll in the Sindhupalchok district, where 3423 deaths were confirmed as of 17 May 2015, accounting for about 40% of the total number of 8567 people killed in the 2015 Nepal earthquake disaster. Many stone rubble masonry buildings collapsed causing numerous injuries and deaths in other hill districts (such as Nuwakot, Dhading, Rasuwa, Gorkha and Kavrepalanchok) of Nepal. To minimize losses of lives and property in the hilly areas
during inevitable future earthquakes, it is necessary to spread the knowledge about cost-effective means to improve the earthquake resistance of stone masonry buildings.

Numerous landslides triggered by the earthquake have also proven to be deadly in the mountainous regions with unstable slopes. Hence, it is necessary to make detailed geological hazard surveys to identify zones particularly vulnerable to rock falls and landslides. Such locations have to be officially declared as danger zones where building activities should no longer be permitted.

**Earthquake damage to reinforced concrete buildings**

Concrete buildings are relatively new and have been built mainly after 1960. These buildings consist of an RC skeletal frame with brick infill walls. The performance of the RC frame buildings in the recent earthquake was not much better to that of well-constructed traditional brick masonry structures. Many newly built, modern-looking structures also collapsed during the earthquake. Some of the recently built apartment blocks and shopping malls also suffered heavy damage, leading in some cases to a total loss of substantial investments of the owners of these expensive structures. The RC structures were built in Nepal in many cases without performing proper structural analysis and design by a qualified structural engineer. Poor concrete quality and deficient reinforcement detailing are also important factors that make the reinforced concrete structures in Nepal vulnerable to earthquake damage. This is due to the fact that an RC skeletal frame efficiently supports the static vertical gravity forces, it is not suitable to resist the substantial horizontal shear forces occurring during a strong earthquake. Many buildings in Nepal have been built without proper shear walls and became vulnerable to the recent strong earthquakes.

**Damage to bridges**

Few bridges collapsed along the Arniko Highway near Lokanthali Bus stand at Kathmandu (figure 9). The bridge in Kathmandu city is a two-span simply supported RC structure. The bridge appears to be functional despite a nearby RC building collapsed in a pan-cake mode. We suspect that the E-W trending lineament in Kathmandu Valley is responsible for the damage of the bridge. Most of the bridges were not damaged after the Gorkha earthquake. The bridge in Gorkha district is a single-span truss bridge. This bridge is safe despite its location within the epicentral area. We also noticed that in Balua village the newly constructed bridge was intact, although it is also very near to the epicentral area.

**Observations on the damage to the district of Sindhupalchok**

Sindhupalchok is one of the worst affected districts after the Gorkha earthquake. Buildings in these areas are less damaged than in other parts of the district (figure 10). In the belt to the north of this well-accessible area including Chautara, the district capital, damages are greater. In these areas there is higher population density and major landslides have blocked roads. Most of the buildings have been rendered uninhabitable (80%–90%) and remaining were razed to the ground (10%). The pillared concrete buildings (5%) appeared to be intact. No stone/brick/mortar buildings are now inhabitable. Many village roads, asphalt and cinder, have long cracks 3″–6″ wide. Many roads are blocked by rock landslides. Sections of roadway will be pried away by the coming monsoon rains.

The aim of the lesson learnt from the earthquake hazards is to improve the post response of the Gorkha and Kodari earthquakes and encourage positive action by decision makers in Nepal. The lessons learned are the product of the analysis of main findings and lessons from evaluations of past earthquakes, with similar characteristics and features of Nepal. We also learned lessons from the past earthquakes such as Indonesian, turkey and Haiti ones to find out to prioritize the strategies to
cope with earthquake hazards as well as the rehabilitation programmes and other attendant activities.

The building code is a living document, which requires periodical review and update to reflect current understanding of the regional and local site seismicity, structural earthquake performance and latest design and technology (Lo & Wang 2012). The high cost of re-building collapsed, demolishing unsafe, and retrofitting damaged buildings has caused some re-examination of the main objective of building code, i.e. to protect life safety of occupants and minimizing their injury. Beyond the life-safety objective, each jurisdiction may find its own optimal economic balance between the cost of initial design and construction, versus the cost and delay of re-construction after an earthquake. Schools and emergency response facilities, including fire and police stations, and hospitals, especially those located on weak sub-soils prone to liquefaction, or sites subject to geologic hazard

Figure 9. Severe cracks developed over a road bridge in Kathmandu after the 7.8 M earthquake. A vertical slip of 1 m along the E-W trending fault in Kathmandu Valley, which seems to be activated after the 7.8 M earthquake and damaged the bridge.
(landslides, rock falls, etc.), should be relocated or retrofitted to meet the requirement of maintaining their function after an earthquake.

Major lifelines that are either co-located and/or interdependent with respect to maintaining their proper function should have specific performance requirements in order to avoid multiple and/or cascading lifeline failures. Emergency response and resilience plans for the region, and local jurisdictions should be developed and exercised. These plans should focus on robustness, redundancy, resourcefulness and rapidity (John 2008). These may improve the effectiveness during emergency response facilities after comparing with the experience gained from the past damaging earthquakes.

Conclusions

The Gorkha and Kodari earthquakes, followed by a number of aftershocks are caused by the dip slip movement along the Himalayan Thrust Belt HFT and MBT where the Indian Plate is subducted below the Eurasian Plate at a very shallow depth. It is a rare evidence in Himalayan terrain, where epicentres are located within these thrust planes. The post-earthquake survey in Nepal provides a wealth of information on the intensity and damage patterns as well as the reasons for collapse of houses, infrastructures and heritage buildings. The damages of these earthquake areas do not decrease with the epicentral distance from the earthquake. It is due to the triggering of another 7.3 M earthquake to the east of 7.8 M earthquake. Damage patterns of many villages of Sindhupalchok district have been effected worst due the second earthquake. The ground acceleration (0.02—0.74 g) was computed using the USGS data for the Nepal earthquake. The comparison of intensity maps of these earthquakes suggests a new finding for damage assessment that can become more severe, if the large aftershock is away from the rupture area of the main shock, as in the case of these earthquakes. Lesson learned from the past earthquakes may be an ideal strategy for planning the earthquake response system for the decision makers for the effected people and damaged infrastructures. Gorkha and Kodari earthquakes provide a wealth of seismological data which will be quite useful for attenuation model for an earthquake hazard analysis in this region. We suggest developing a new attenuation model especially for the Himalayan region to estimate the ground parameters.
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