Unearthed lessons of 25 April 2015 Gorkha earthquake ($M_W$ 7.8): geotechnical earthquake engineering perspectives

Dipendra Gautam

Structural and Earthquake Engineering Research Institute, Kathmandu, Nepal

ABSTRACT

Gorkha earthquake ($M_W$ 7.8) of 25 April 2015 struck central, eastern and western Nepal and neighbouring areas. Enormous losses during Gorkha earthquake were attributed to collapse of 498,852 buildings, 446 public health facilities and partial damage of 256,697 buildings, 765 health facilities as well as severely affected 2900 cultural and historical sites. Anomalies were in particular observed in terms of localized damage and recurrent damages during 1833, 1934, 1988 and 2015 earthquakes. This paper reports geotechnical earthquake engineering observations noted during field reconnaissance conducted in affected areas. Damage reports from historical as well as recent Gorkha earthquakes are mapped in this paper. To depict lessons, forensic interpretations are presented considering 1833, 1934, 1988 and 2015 earthquakes.

KEYWORDS

Gorkha earthquake; local site effects; topographic amplification; basin edge effect; Nepal

1. Introduction

Nepal lies in one of the most active seismic region in the world and seismic events occur frequently throughout Nepal. The Building Code Develop Project (BCDP) depicted the approximate recurrence interval of 81 years for earthquakes greater than 8 local magnitude (BCDP 1994). Similarly, recurrence intervals for the earthquakes of local magnitude 7.5–8, 7–7.5, 6–7 and 5–6 were estimated 40, 8, 5 and 2 years, respectively (BCDP 1994). Gorkha earthquake is the strongest event after the 1934 Bihar–Nepal earthquake ($M_W$ 8.1) in eastern Nepal both in terms of magnitude as well as losses. After 1934 earthquake in eastern Nepal, events like 1966 Bajhang ($M_L$ 6.0), 1980 Chainpur ($M_L$ 6.5), 1988 Udaypur ($M_W$ 6.8) and 2011 Sikkim–Nepal ($M_W$ 6.9) struck Nepal and losses were moderate both in terms of casualties as well as property and lifelines. Gorkha earthquake ($M_W$ 7.8) occurred in Barpak village of Gorkha district on 25 April 2015 at 11:56 local time. Until May 2016, more than 450 aftershocks of local magnitude greater than 4 occurred in Nepal and aftershocks are still continued. Aftershocks from 25 April 2015 ($M_L$ 6.7), 26 April 2015 ($M_L$ 6.9) and 12 May 2015 ($M_L$ 7.3) aggravated damage in affected areas. The main shock event of 25 April was located near Barpak village of Gorkha district ~78 km N–NE of Kathmandu valley; however, the aftershocks were concentrated in the bordering areas of Sindhupalchowk and Dolakha districts in the Himalayan Front. Gorkha seismic sequence caused 8790 casualties, 22,304 injuries, affected 8 million people and damaged ~755,549 buildings (NPC 2015). The shaking intensity in near-field region was estimated to be above 8 and for Kathmandu valley it was ~6–7 in the European Macro-Seismic Scale (EMS-98) (Martin et al. 2015). On the contrary, during field reconnaissance, some near-field regions like the Barpak village, the intensity was estimated ~10 in EMS-98 scale. A similar intensity level was estimated for Chuatara (Sindhupalchowk) and some other villages in Dolakha district during

CONTACT

Dipendra Gautam dipendra.gautam.seri@gmail.com

© 2017 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
field reconnaissance. Rapid dissemination of geological field investigation, accelerometric interpretation, some geotechnical effects, rapid seismo-tectonic characterization, structural performance and other aspects of Gorkha earthquake are reported by several researchers (e.g. Angster et al. 2015; Bhattarai et al. 2015; Hayes et al. 2015; Martin et al. 2015; Moss et al. 2015; Ahmad & Singh 2016; Dutta et al. 2016; Gautam & Chaulagain 2016; Gautam et al. 2016a; Rai et. al. 2016; Gautam 2017) and some site-specific reconnaissance reports can be found elsewhere.

To the best of author’s knowledge, detailed geotechnical aspects for 1833, 1934 and 1988 earthquakes are not available in literature. The latter event of 2011 earthquake caused damage in eastern Nepal including Indian state of Sikkim (for details, see Shakya et al. 2013; Dutta et al. 2015). Geotechnical aspects of earthquakes have paramount impact on performance of structures and lifelines at depicted by many earthquakes worldwide. However, Nepal lacks adequate database and recorded history regarding geotechnical earthquake engineering aspects of historical earthquakes. Detailed description of 1934 earthquake was presented by Rana (1935) that includes some description regarding the 1833 event too. Reports presented by Gupta (1988) and Fujiwara et al. (1989) also covered details of damage but these reports are largely confined to structural damage. In this context, Gorkha earthquake is the sole event to highlight the geotechnical earthquake engineering aspects and resulting damage mechanisms. In order to depict the geotechnical and structural damage scenario of Gorkha seismic sequence, three-month-long field reconnaissance was performed in central Nepal covering 21 districts including the 14 crisis hit districts. To fulfil the gap of earthquake geotechnical engineering observations, this study focuses on forensic interpretation of historical earthquakes and field observations during 2015 Gorkha earthquake.

2. Geology and seismicity

Gorkha earthquake occurred as a result of continuous convergence of Indian plate at the rate of ~45 mm/year towards NNE (USGS 2015) with the Eurasian plate. In general, all Himalayan earthquakes occur in the seismically active convergence zone regarded as Main Himalayan Thrust (MHT). Many devastating events have rocked the Himalayan region at a regular interval from Burma to Afghanistan, and Gorkha earthquake is also the result of the ongoing Indo-Eurasian convergence interaction. This earthquake is the result of the thrust faulting on or near the Main Frontal Thrust (MFT) which is believed to be most active thrust compared to Main Boundary Thrust (MBT) and Main Central Thrust (MCT). The MFT constitutes tertiary siltstones, sandstones and conglomerates, and it is situated in the southern boundary of Sub-Himalaya. Due to young fragile geology, landslides were historically noticed in this region during every earthquake. The MBT bounds the Lesser Himalaya and dominantly comprises the meta-sediments. The MCT occurring in the southern border of Higher Himalaya is believed to be inactive thrust fault and is composed of schist. Almost all large earthquakes in Himalaya are blind ruptures limited to the MHT and their rupture could be found along the MFT in Nepal Himalaya. Some of the urban areas like Kathmandu Valley in Nepal are situated in the alluvial deposits with highly interlayered clay and silts and sometimes gravels or mixture of all. These alluvial deposits are known to be the most affected sites in terms of damage concentration due to geological condition, population concentration and structural vulnerability (Gautam & Chaulagain 2016). The majority locations of Sub-Himalaya and Higher Himalaya have steep slopes leading to rock falls or landslides during earthquakes. Historically, almost all earthquakes have resulted in devastating landslides leading to massive environmental losses, wreckage of settlements and thousands of casualties. Gorkha earthquake is no exception in terms of enormous losses in environmental impacts, casualties and infrastructures. Details on geology and seismo-tectonics of Nepal Himalaya can be found in several literatures by Upreti and Le Fort (1999), Sakai (2001), Pandey et al. (1999), Dhital (2014), Hossler et al. (2016); Bollinger et al. (2016), Wesnousky et al. (2017) and others.
3. Geotechnical observations during Gorkha earthquake

Gorkha earthquake depicted many spectacular examples in terms of geotechnical earthquake engineering aspects in Nepal. Most of the observations presented in this paper could be insightful for future events in Nepal as well as other moderate- to high-seismicity regions. Past earthquakes were not reflective enough to disseminate proper geotechnical earthquake engineering features due to lack of extensive field observations and dedicated and proficient manpower in related fields. Even very loose records of 1988 earthquakes are available and classified observations did not exist in Nepal until 2015 Gorkha earthquake, although some of the descriptions presented by Rana (1935) clearly demarcate the significance of geotechnical aspects during historical earthquakes. After three-month-long field reconnaissance, the overall scenario of dominant geotechnical features observed during Gorkha earthquake is depicted in Figure 1. In order to interpret the geotechnical aspects of historical earthquakes, comparisons are made, and for this purpose, the geotechnical features extracted on the basis of description presented by Rana (1935) and others are depicted in Figure 2. In case of 1833 and 1988 earthquakes, relevant comparisons and descriptions are disseminated in the detailed description section of 2015 Gorkha earthquake.

3.1. Local site effects

In capital city districts of Kathmandu valley, localized damage was observed in some areas having deep alluvial soil layers. The loose soil sites regarded as Kalimati, Patan and Thimi formations witnessed severe damage than others. Some areas like Balaju (Figure 3(a)), Kathmandu, Bhaktapur, Patan and Durbar Square (Figures 4–6(a)) were severely affected by Gorkha earthquake. In these areas, even engineered reinforced concrete (RC) structures were collapsed. However, in other locations of Kathmandu valley, most of the non-engineered masonry buildings of around 100 years survived without any noticeable damage extent (Figure 7). These areas were also severely affected during 1934 Bihar–Nepal earthquake as depicted in Figures 3(b) and 6(b) (Rana 1935). Interestingly,
the clay obtained from excavation of drag well showed completely black, loose and saturated soil in Balaju.

During 1934 and 2015 earthquakes, localized damage was reported within Kathmandu valley. In addition to this, during 1988 Udaypur earthquake, Bhaktapur was affected somehow whereas other neighbouring towns remained unaffected. Apart from this, the devastating event of 1833 caused severe damage in Bhaktapur as reported by Bilham (1995). It is evident that all of the major earthquakes have affected particular areas recurrently depicting influence of soil stratigraphy within Kathmandu valley.

Figure 2. Geotechnical damage observation during 1934 earthquake.

Figure 3. (a) Severely damaged RC structures due to 2015 Gorkha earthquake in Balaju. (b) Ground failure in Balaju due to 1934 earthquake. (Courtesy: Rana (1935).)
The ground motion records of the far field event (~78 km) in two stations at ~500 m distance in Kathmandu valley show considerable discrepancy as shown in Figure 8. Previous study conducted by Gautam and Chamlagain (2016) also estimated wide variation in motion parameters and local amplification within the soft soil deposits. Considerable agreement is observed between the predictions of Gautam and Chamlagain (2016) and damages occurred due to Gorkha earthquake in the same area. In addition to this, recent study carried out by Gautam et al. (2016b) confirmed that the
local amplification and soil nonlinearity were the major causes of extensive damage in the areas having soft soils like Thimi and Bhaktapur when compared to the southern part of Kathmandu valley. Since 1255 earthquake, Bhaktapur is the most affected area by every earthquake and Thimi adheres with comparable damage scenario as that of Bhaktapur in every event.

The overall ground shaking in Kathmandu valley was ~2 minutes during the main shock of Gorkha earthquake, meanwhile Rana (1935) reported the ground movement was around 10–12 minutes during 1934 Bihar–Nepal earthquake. Unique ground motion in terms of the strongest vertical component was recorded towards the eastern part of valley during Gorkha
earthquake in Nepal (NSC 2015). During field reconnaissance in the epicentral area of Barpak, people confirmed strong vertical movement of their houses too. It is imperative to note that the combined effect of poor housing practices and ground motion parameters was the leading cause of widespread damage across central, eastern and western Nepal during Gorkha earthquake. Local soil amplification-based damage was distinctly noted in two neighbouring towns of Sindhupalchowk district. Khadichaur and Lamosaghu are two towns nearly 2 km apart, but only Lamosaghu was completely collapsed. On the contrary, Khadichaur did not reflect noticeable damage at all (Figure 9). Both of these towns were settled at the same time with similar substandard RC building stocks. Khadichaur is situated nearer to the river than Lamosaghu though Lamosaghu is on river terrace and Khadichaur is on bedrock, thus damage was discrepant in these neighbouring towns.

3.2. Topographic/ridgeline damage

In central Nepal, majority settlements were found to be concentrated on hilltops probably due to the fact that plain terrain is more useful for agricultural purposes. Such settlements on hilltops from Gorkha to Sindhupalchowk were among the severely affected regions (Figure 10). The downtown of Sindhupalchowk (Chautara) witnessed 100% collapse of stone masonry and ~98% collapse of RC buildings. Rest of the building stocks sustained serious structural damage (EMS grade 3). Apart from this, critical facilities like the hospitals and police office were also severely damaged and non-operable. Chautara is located on hilltop, thus topographic and ridgeline effects must be the prime cause of such devastation. In Dolakha, Ramechhap, Sindhuli, Gorkha, Rasuwa, Nuwakot, Dhading, Kavrepalanchowk, Sindhupalchowk, Kathmandu, Lalitpur, Bhaktapur and Makwanpur districts, damages due to topographic and ridgeline effects were widely noticed. Evidently, in Barpak village (near the epicentre), out of 1440 buildings, 1250 were completely collapsed and the rest of the buildings sustained serious structural damage so that none of the buildings were found to be operable during field reconnaissance in May 2015.

Topographic effect was also widely noticed during the 1934 earthquake. As reported by Rana (1935), two of the villages in Sindhupalchowk were totally collapsed and also severe damage occurred on hilltops of Bhojpur, Okhaldhunga, Sindhuli, Nuwakot, Rasuwa, Kavrepalanchowk, Kathmandu valley, Dhading, Makwanpur, Ramechhap and Dolakha districts in eastern and central Nepal. During Gorkha earthquake, damage in the settlements located on ridges was severer than that of the settlements located on flat topography. For instance, damage in case of Mankhu
Figure 9. (a) Completely collapsed Lamosaghu town. (b) Undamaged Khadichaur town along the Arniko Highway in Sindhupalchowk district.
(Dhading) and Mandre (near epicentre) depicted that new constructions across the ridgelines collapsed whereas old and poor constructions of flat topography survived appreciably (Figure 11). In case of Mandre neighbourhood, all of the 28 houses on ridgeline were collapsed (Figure 12(a)). Similar observations were made in case of Bungamati (Figure 12(b)), Swoyambhu and Khokana within the Kathmandu Valley. Apart from this, almost all of the ridgelines/hilltops in central and eastern Nepal witnessed relatively higher damage than the areas not in ridgelines. Virtually all Newari (Indigenous group native in Kathmandu and surrounding hills) settlements were established in ridgelines or hillocks since the thirteenth century, and dense row housing system was developed in all such settlements. It is evident that the Newari settlements on the ridgeline were severely affected by every earthquake and consistent damage scenario was observed during 2015 earthquake too.
3.3. Basin edge effects

Kathmandu valley is a deep alluvial basin; the depth of soft soil at the valley edge is relatively less (~60–70 m) when compared to the central part of valley (~550 m). Almost all historical earthquakes have depicted severe damage in valley periphery probably due to basin edge effects (Figure 13). Basin edge effects were also noted in significant world earthquakes in the past as reported by Tertulliani and Maramai (1998), Tertulliani (2000), Hallier et al. (2008), Tertulliani
et al. (2012) and others. Neighbourhoods in Kathmandu Valley like Harisiddi, Sanagaon, Lubhu, Sankhu, Padma Colony, Sitapaila, Kapan and Balaju (Figure 14) are situated at the edge of basin and were among the severely damaged during 1833 (Bilham 1995), 1934 (Rana 1935) and 2015 earthquakes. In addition to the damage reports, Rana (1935) estimated higher surface velocity at the edge of basin than central valley. Surface velocity at central valley was estimated ~285 cm/sec, whereas in case of basin edge (Harisiddi, Lubhu, Sanagaon), it was ~345 cm/sec (Rana 1935). In case of Gorkha earthquake, the surface velocity for central Kathmandu valley was estimated ~107 cm/sec (USGS 2015) and no database was available for valley periphery, thus exacting comparisons cannot be made. This author also experienced the main shock and the strongest aftershock.
of May 12 in the outskirt of Patan and the aftershock of 26 April \((M_W 6.9)\) in Bhaktapur; the shaking in Bhaktapur was stronger than the other two events.

### 3.4. **Liquefaction**

Liquefaction-induced foundation sliding was observed in Balaju area during field reconnaissance in the same area where ground failure was reported by Rana (1935) during 1934 Bihar–Nepal earthquake (see Figure 3). Several engineered buildings constructed in Balaju area along the river stretch were either completely collapsed or severely damaged in terms of foundation sliding. The peak ground acceleration (PGA) during the 25 April 2015 earthquake was recorded \(\sim 0.25g\), thus surface manifestations of liquefaction are justified according to the PGA threshold criteria set by Santucci de Magistris et al. (2013, 2014). Partly the damage was also attributed to structural deficiencies (details can be found in Gautam & Chaulagain 2016; Gautam et al. 2016b; Gautam 2017) however, many failure evidences were related to foundation slides in Balaju. Immediate vicinity of tributaries, shallow depth of groundwater table and prevalence of sand in upper 30-m strata undergird the possibility of liquefaction, thus surface manifestations were not observed in Balaju. Few more cases of liquefaction were observed during the field reconnaissance within Kathmandu Valley (Figure 15(a, b)). In addition to this, some cases of liquefaction and sand blows in southern and north-western fringes of Kathmandu Valley were particularly observed.

Due to directivity effects, Gorkha seismic sequence was confined towards the east of the epicentre (Grandin et al. 2015) and shaking was not intense in the southern plains of Nepal. Thus only one liquefaction surface manifestation was reported in Chitwan district in case of plains. During 1934 event, almost all districts of eastern and central Nepal situated in Indo-Gangetic Plain were observed liquefaction including Chitwan (see Figure 2). Shallow depth of groundwater table and dominant occurrence of sand in stratigraphy may have facilitated such liquefaction occurrence in the southern plains during 1934 earthquake. In case of strong shaking, some hundreds of liquefaction may occur in the southern plains as in the case of 1988 earthquake. Liquefaction-induced damages in plains like the foundation settlement of \(\sim 0.9 \text{ m}\) was reported in Biratnagar (Rana 1935) during 1934.
earthquake; similar cases of liquefaction-induced damages from eastern and central plains were also reported by Rana (1935) during 1934, and Fujiwara et al. (1989) during 1988 earthquakes.

### 3.5. Landslides

Around 3600 landslides of various scales were reported by National Planning Commission of Nepal during Gorkha earthquake (NPC 2015). Small- to large-scale landslides were observed in affected areas from Gorkha to Okhaldhunga due to Gorkha seismic sequence. In addition to this, landslides in Sindhupalchowk, Dolakha, Ramechhap, Sindhuli, Kavrepalanchowk, Gorkha, Nuwakot, Dhading, Makwanpur, Rasuwa, Nuwakot and Lalitpur were observed during field reconnaissance (Figure 16 (a–c)). Due to large landslide events in central Nepal, some of the ongoing hydropower and water supply projects were affected and damage in site office was observed. The landslide observed in

Figure 14. (a) Severely devastated Harisiddi area. (b) Complete collapse of masonry and severely affected RC buildings in Sankhu.
Tatopani bazaar (Nepal–China border) in Sindhupalchowk District destroyed the commercial centre including custom office, thus obstructing the trade for several months (Figure 17(a)). In addition, some gabion walls and bridge damage due to landslide were observed in Sindhupalchowk District (Figure 17(b)). An avalanche was reported in the Langtang region in central Nepal that devastated the entire neighbourhood. Several other avalanches were reported by the mountaineers in the mountains of central and eastern Nepal.

3.6. Ground failures

Many secondary ground failure cases were observed in almost all affected districts of central Nepal. However, primary surface rupture was not observed as reported by Angster et al. (2015). Ground failure affected the local road networks in Kathmandu and Lalitpur (Figure 18(a,b)). Moreover, the Araniko Highway that connects Nepal with China was obstructed by large-scale ground fissure in Bhaktapur and Sindhupalchowk districts. Ground failure occurred along the Araniko Highway in Bhaktapur was ~1.5 km long with a depth of ~1.28 m at most (for details, see Angster et al. 2015) and affected hundreds of residential buildings (Figure 18(c)). Ground fissures in Dhading district were found to be occurring in many villages and the depth was measured to ~3 m at most. During 1934 earthquake, Jaleshwor and Hanumannagar neighbourhoods in the eastern plains observed...
ground fissures of ~50 m depth and several kilometres length (Rana 1935). Rana (1935) reported that the ground fissures occurred in Balaju and Shankhamul area within present-day Kathmandu metropolitan city were ~0.3 m deep. The depth of ground fissure in the easternmost part of Nepal (Jhapa) was reported ~0.6 m that was accompanied by sand boiling and turbulent springs for several hours. Similar events were reported in Biratnagar area (adjoining town of Jhapa) by Rana (1935). During reconnaissance and consultation with local people, a discontinuous sequence of ground failure was identified from Gorkha to Sindhupalchowk (Figure 19).

3.7. Other geotechnical features

Apart from several significant geotechnical features that caused or aggravated the damage, some other geotechnical problems in few places were noticed during the field reconnaissance. Soil creep was observed in Sindhupalchowk wherein an RC building was found to be settled around 2 m below the ground surface. The soil was saturated and the building was constructed on river terrace comprised unsettled cobbles and gravels. In addition to this, poor foundation construction practice and lack of adequate ductility may have contributed in this case (Figure 20(a)). In Figure 20(a), interestingly, a poorly engineered building which is not in the direction of stream flow is intact. Foundation settlement was also observed in some buildings constructed along the river stretch in Sindhupalchowk district (Figure 20(b)). During 1934 Bihar–Nepal earthquake, foundation settlement in eastern and central plains was observed to be around 0.9 m as reported by Rana (1935). Apart from this, one case of displacement of bridge abutment was observed in Gorkha district near the epicentre due to combined action of mudslide and ground displacement. Otherwise almost all highway

Figure 16. (a) Landslide near the epicentre in Gorkha; (b) rock fall in Gorkha; (c) debris flow in Sindhupalchowk.
bridges were found to be intact or slightly damaged and remained operable. During 1934, the Bishnumati River Bridge was reported to be damaged in the north-western part of Kathmandu Valley (Figure 21(a)). During Gorkha earthquake, liquefaction surface manifestation was found in the same location (Figure 21(b)). Thus the damage would have been attributed to liquefaction even in the case of 1934 earthquake.

In the central and southern parts of Kathmandu Valley, groundwater level increased largely (~2 m in some areas) and many of the stone spouts that were not discharging were found to
Figure 18. Ground fissure in urban road of (a) Kathmandu (b) Lalitpur and (c) ~1.5-km-long ground fissure along the Arniko Highway in Bhaktapur.

Figure 19. Tentative discontinued sequence of ground failure identified during field reconnaissance.
be activated after Gorkha earthquake. One stone spout in the southern fringe of Kathmandu Valley started to discharge after 12 years, and in some areas of northern and north-eastern Kathmandu Valley, the groundwater table was reported to be declined sharply. In Makwanpur district, some of the springs were observed to be dried after the earthquake on the contrary. Sharp lowering of groundwater in the northern valley suggests possible movement of groundwater towards the central or southern parts of valley, hence demands further investigation to reach in conclusion.

Figure 20. (a) Foundation settlement in a single-storied RC building, meanwhile a poorly engineered two-storied building stands intact nearby. (b) Ground movement and settlement governed separation of foundation with superstructure.
3.8. Juxtaposition of geotechnical aspects identified during 1833, 1934 and 2015 earthquakes

Gorkha earthquake that occurred after 82 years of the devastating event of 1934 caused massive destruction in terms of casualties, lifelines, environmental and economic losses. Gorkha earthquake thus can be understood as recurrence of 1934 event due to its damage characteristics; however, the duration, magnitude and motion parameters of Gorkha earthquake are relatively lower than that of
1934 event. For instance, Rana (1935) estimated the velocity $\sim 285$–$345$ cm/sec, whereas the velocity during the main shock event recorded in National Seismological Center depicts 80 cm/sec (NSC 2015). Some of the geotechnical features are repeatedly being noticed in Nepal in the case of major earthquakes like the 1833, 1934 and 2015 events. Thus, such historical interpretation and associated consistency could be instrumental to infer some of the basic geotechnical aspects that may affect the damage in future earthquakes too. For this purpose, common observations for 1934 and 2015 Gorkha earthquakes are summarized in Table 1. Due to lack of extensive damage reports, only few aspects of 1833 earthquake can be disseminated. The $M_L$ 7.7 earthquake of 1833 damaged 18,000 buildings in central Nepal of which 4000 buildings were damaged within Kathmandu Valley and neighbouring towns (BCDP 1994). Rana (1935) and Bilham (1995) reported that severe damage occurred in the areas like Bhatgong (Bhaktapur), Lubhu, Sanagaon, Harisiddi and others. The parities presented in Table 1 depict that it would not be difficult to identify the areas sustaining higher damage due to geotechnical problems in the case of future strong to major earthquakes. The lessons learned and future way forwards are disseminated in the following section in order to highlight the significance of geotechnical earthquake engineering aspects as the existing construction regulations do not consider this aspect adequately. The existing building codes in Nepal and recommendations are accompanying primarily the structural robustness and do not incorporate geotechnical earthquake engineering aspects. Same case is applicable for road standards being used in Nepal. Recent discussions for post-earthquake reconstructions are found to be focusing only on structural integrity keeping aside the geotechnical problems; however, it would be imperative to consider geotechnical aspects for safety and serviceability of structures in case of multi-hazard resilient construction frameworks.

Figure 22. The nine-storied (62 m) Dharahara Tower in Kathmandu (a) after 1934 Bihar-Nepal earthquake (extracted from National Seismological Center website); (b) after 2015 Gorkha earthquake; (c) before Gorkha earthquake. (Courtesy: Bibek Rupakhety.)
Table 1. Highlighted geotechnical damage during 1934 and 2015 earthquakes in Nepal.

| Location                  | Geotechnical features                                      | 1934 Bihar–Nepal earthquake (Rana 1935)                        | 2015 Gorkha earthquake                                                                 |
|---------------------------|-------------------------------------------------------------|---------------------------------------------------------------|----------------------------------------------------------------------------------------|
| Lubhu, Sanagaon,          | Basin edge effect                                           | ~99% structures collapsed                                     | ~90% of adobe masonry structures were collapsed and severe damage in other structures   |
| Harisiddi, Sankhu         |                                                             | 70% buildings damaged in Kathmandu Valley                     | ~30% buildings damaged in Kathmandu                                                   |
| Khokana, Bungamati        | Ridge effect                                                | ~99% structures collapsed                                     | ~90% of adobe masonry structures were collapsed and severe damage in other structures   |
| Bhadgaon [Bhaktapur]      | Local soil amplification due to prevalence of loose black   | ~95% adobe masonry buildings damaged                          | ~60% of adobe masonry buildings damaged                                               |
|                           |     cotton soil                                             | Some areas with relatively older and fragile buildings still intact | Some areas with relatively older and fragile buildings still intact                     |
| Kirtipur, Pashupati       | Rock site                                                   | Intact                                                        | Intact                                                                                  |
| Balaju                    | Liquefaction                                                | Ground failure                                                | Foundation sliding was observed because the liquefied areas during 1934 event are nowadays converted to heavily constructed areas |
| Panga                     | Local soil amplification due to prevalence of loose black   | Severe damage occurred though this site is located around 1 km from Kirtipur | Severe damage even in engineered RC constructions                                       |
| Sindupalchowk, Okhaldhunga, Rasuwa, Bandipur | Topographical amplification                              | Severe damage in hilltops, almost all houses were severely damaged however survival of houses in plain areas was noticed | Structural collapse even in engineered RC construction was observed                      |
| Sundhara                  | Possibly due to vibration resonance                         | 9 storied Dharahara tower collapsed (Figure 22(a))            | The downtown of Sindupalchowk, Cahutara, on hilltop was the worst hit                   |
| Sindupalchowk, Okhaldhunga, Rasuwa, Nuwakot, Gorkha | Earthquake induced landslides and slope failures              | Earthquakes of small to mega scale occurred in steep slopes   | 90% structures collapsed                                                               |
|                           |                                                             | Few cases of river blockage due to debris were reported       | Other hills were deserted due to collapse of structures in all areas                    |
| Bishnumati River          | Liquefaction induced damage                                 | Bridge damaged                                                | Nine-storied Dharahara Tower collapsed (Figure 22(b))                                  |
| Kathmandu Durbar Square   | Local amplification (loose soil)                            | Severe damage in monumental constructions of greater height   | Other high-rise structures in vicinity were also affected; however, some marginal      |
|                           |                                                             | (4–5 storied)                                                | constructions of 2–3 storied remained intact                                           |
| Patan Durbar Square       | Local amplification (loose soil)                            | Some monuments damaged                                        | ~3600 earthquakes of small to mega scale                                              |
| Thimi                     | Local amplification                                        | Severe damage in monumental constructions of greater height   | Road networks were severely affected basically towards Chinese border of Nepal         |
| Durbar high school        | Local amplification                                        | Some monuments damaged                                        | Severe damage in monumental constructions of greater height (4–5 storied)            |
|                           | Ridge effect                                                | ~90% buildings damaged                                        | Some monuments damaged                                                               |
|                           |                                                             | Severely damaged                                              | ~70% adobe masonry buildings damaged                                                 |
4. Insights of Gorkha earthquake

With the help of forensic interpretation of some past earthquakes and detailed field reconnaissance in 21 districts affected by Gorkha earthquake, some of inferences are drawn as follows:

(1) Areas within Kathmandu Valley do not reflect the unanimous behaviour during earthquakes, thus localized damage was prevalent in every earthquake. In addition, engineered or well-constructed buildings are sometimes more affected than the substandard and highly vulnerable buildings located in stiff soil. Kathmandu, Patan and Bhaktapur Durbar squares were severely affected by earthquakes, thus adequate seismic provisions are required for such heritage sites (for details, Gautam 2017). Limited works regarding site characterization exist in the case of Kathmandu Valley (e.g. Gautam 2016); however, exhaustive studies regarding microzonation and implication of site-specific design and construction guidelines are urgent for Kathmandu Valley. Apart from this, site sub-classification as suggested by Forte et al. (2017) may be important to address the seismic demand in local scales within and outside Kathmandu Valley.

(2) Geologically, areas dominated by Kalimati, Gokarna, Patan and Thimi formation are found to be more affected than areas with other formations and rock sites. Insignificant damage during each earthquake in Kirtipur unrelenting severe damage in Panga (settlement nearby Kirtipur with loose soil) reflects the effect of local amplification mechanism within small spatial variation. During Gorkha earthquake, even engineered RC buildings collapsed in Panga and very old adobe masonry buildings in Kirtipur survived. Such damage mechanism depicts necessity of site-specific consideration for building construction in Kathmandu Valley.

(3) Kathmandu Valley has many hillocks and ridges wherein most of the traditional row housing settlements exist. Damages are concentrated in such settlements in every earthquake. Thus, improvement in construction technology is needed in such areas like Bungamati, Khokana and other ridges according to higher seismic demand. Widespread ridgeline damages were noticed throughout the affected areas in central Nepal. This suggests immediate need of identification of safer settlements in local scale as most of the people in rural areas cannot afford sophisticated housing types and rely on local materials that may be detrimental in the case of strong to major earthquakes.

(4) Harisiddi, Balaju, Sankhu, Lubhu and Sanagaon were severely affected in every earthquake due to stronger shaking than in other areas and partly due to dominantly occurring traditional masonry structures. Thus special considerations are needed in construction guidelines or building codes in case of basin edge. The surface velocity at basin edge was ~60 cm/sec more than the central valley during 1934 earthquake (Rana 1935). Such higher extent of velocity parameter may be due to refraction and superposition of seismic waves, thus detailed studies regarding basin effects and basin edge effects are required for Kathmandu Valley.

(5) Nepal is a mountainous country with only 17% of land areas as plains and most of the population is located on hilltops. During Gorkha earthquake, the most affected were the hilltops and ridgelines due to topographic/ridgeline effects. Similar observations were reported during 1934 earthquake too. Detailed studies regarding topographic and ridgeline damages are needed in Nepal to insure seismic performance of rural building stocks in particular.

(6) Many buildings were found to be constructed along the river courses; such poor site selection practice caused serious damages in terms of foundation failure and settlement of buildings in some areas. River terraces should not be used for housing construction as depicted by the total collapse in Lamosaghu and no damage in Khadichaur neighbourhoods along the Arniko Highway in Sindhupalchowk.

(7) Landslides and associated slope failures are common in mountains of Nepal. It would be imperative to develop probabilistic landslide hazard maps and plan settlement locations. Slope instability, dry landslides and rock falls may occur even after several months of earthquake like in the case of 1934 event. Even a weak aftershock may trigger such movements,
thus identification and management of landslide risk are needed across Nepal because the entire Nepal Himalaya lies in seismically active region.

(8) The Indo-Gangetic Plain of Nepal is highly susceptible to liquefaction due to sand deposit and shallow groundwater level. Surface manifestations were observed during 1934 and 1988 earthquakes, but the effect of Gorkha earthquake was not significant in this region, thus only one event of liquefaction occurred in previously liquefied area. Structures and lifelines will be severely affected by liquefaction in case of future earthquakes, thus bridges, road, buildings and other infrastructures should be constructed assuring adequate provisions against liquefaction. Nepal Building Code does not have any provisions to incorporate liquefaction effect for design and construction of buildings and other infrastructures. Apart from this, the effect of liquefaction in highways and bridges is not incorporated by Nepal Road Standard. The consequence would be detrimental if liquefaction aggravates the damage as in the case of 1988 earthquake.

(9) Vibration resonance may have occurred in Kathmandu Valley during Gorkha earthquake as depicted by damage on specific high-rise structures like the Dharahara Tower and other high-rise apartment buildings. This is partly reinforced by satisfactory performance of Clock Tower during 2015 Gorkha earthquake and the failure of Dharahara, as both of these towers were rebuilt after the 1934 earthquake. Similar observations were made in the case of residential buildings too as most of the substandard buildings up to three stories performed very well, while many well-designed and detailed high-rise structures sustained substantial damage. This reflects necessity of adequate and representative seismic code that considers soil-structure interaction.

(10) Infrastructures like highways and bridges are vital for connectivity to earthquake-affected areas. Construction of bridges in landslide or mass movement prone areas will be detrimental like the dysfunctionality of Araniko Highway in central Nepal during Gorkha earthquake for several months. Slope protections for strategic highway networks as done in Banepa–Bardibas Highway (which passes along the crisis-hit areas) is must to ensure uninterrupted operation.

5. Concluding remarks

A three-month-long reconnaissance was performed after the devastating Gorkha earthquake in central Nepal. Field identification of geotechnical features confirmed that significant damage was also attributed to geotechnical phenomena. Topographic and ridge effects, local site effects and basin edge effects were widely noticed in central Nepal. Furthermore, liquefaction, earthquake-induced landslides, lifeline damages and drastic variation of soil response within small distance are identified as major geotechnical problems reinforcing enormous losses along with structural vulnerability and ground shaking. Historical earthquakes had reflected similar geotechnical problems in the same areas, thus it is concluded that during every major earthquake in Nepal, particular areas are suffered from specific geotechnical problems. Need of microzonation studies, identification of safe settlements, site selection and development of adequate guidelines for buildings and lifelines are the key issues to be considered immediately for assuring seismic safety in Nepal. Forensic analysis suggests that there is high probability of recurrence of similar damage mechanism in the case of future earthquakes. Insights of this study can be crucial for ongoing reconstruction efforts; however, detailed studies are needed to downscale seismic risk in Nepal.

Acknowledgments

The author would like to acknowledge Krishna Devkota, Krishna Bhetwal, Pramod Neupane, Bipin Gaire, Niraj Raj Thapa, Jastara Koju, Janette Lauza-Ugsang, Liesl Clark, Mukunda Bhattari, Lok Bijay Adhikari, Soma Nath Sapkota for information and support during field work.
Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Dipendra Gautam http://orcid.org/0000-0003-3657-1596

References

Ahmad R, Singh RP. 2016. Attenuation relation predicted observed ground motion of Gorkha Nepal earthquake of April 25, 2015. Nat Hazards. 80:311–328.

Angster S, Fielding E, Wesnousky S, Pierce I, Chamлагain D, Gautam D, Upreti BN, Kumahara Y, Nakata T. 2015. Field reconnaissance after the April 25, 2015 M7.8 Gorkha earthquake. Seismol Res Lett. 86:1506–1513.

Bhattarai M, Adhikari LB, Gautam UP, Laurendeau A, Labonne C, Hoste-Colomer R, Sibe O, Hernandez B. 2015. Overview of the large 25 April 2015 Gorkha, Nepal, earthquake from accelerometric perspectives. Seismol Res Lett. 86:1540–1548.

Bilham R. 1995. Location and magnitude of the 1833 Nepal earthquake and its relation to the rupture zones of contiguous great Himalayan earthquakes. Curr Sci. 69:155–187.

Bollinger L, Tapponnier, P, Sapkota SN, Klinger Y. 2016. Slip deficit in central Nepal: omen for a repeat of the 1344 AD earthquake? Earth Planets Space. 68:12. doi:10.1186/s40623-016-0389-1.

[BCDP] Building Code Development Project. 1994. Seismic hazard mapping and risk assessment for Nepal. Kathmandu: Ministry of Housing and Physical, Planning, Government of Nepal. (UNDP/UNCHS (Habitat) Subproject: NEP/88/054/21.03).

Dhital MR. 2014. Geology of the Nepal Himalaya: regional perspective of the classic collided Orogen. Cham: Springer; Dutta SC, Mukhopadhyay Saha R, Nayak S. 2015. 2011 Sikkim Earthquake at Eastern Himalayas: lessons learnt from performance of structures. Soil Dyn Earthq Eng. 75:121–129.

Dutta SC, Nayak S, Acharjee G, Panda SK, Das PK. 2016. Gorkha Nepal Earthquake: actual damage, retrofitting and of April 2015 and prediction by RVS for atypical structures. Soil Dyn Earthq Eng. 89:171–184.

Forte G, Fabbrocino S, Fabbrocino G, Lanzano G, Santucci de Magistris F, Silvestri F. 2017. A geolithological approach to seismic site classification: an application to the Molise region (Italy). Bull Earthq Eng. 15:175–198. doi:10.1007/s10518-016-9960-1.

Fujiwara T, Sato T, Murakami HO, Kubo T. 1989. Reconnaissance report on the 21 August 1988 Earthquake in the Nepal-India border region. Tokyo: Japanese Group for the Study of Natural Disaster Science.

Gautam D, Chamлагain D. 2016. Preliminary assessment of seismic site effects in the fluvo-lacustrine sediments of Kathmandu Valley, Nepal. Nat Hazards. 81:1745–1769. doi:10.1007/s11069-016-2154-y.

Gautam D, Chaulagain H. 2016. Structural performance and associated lessons to be learned from world earthquakes in Nepal after 25 April 2015 (MW 7.8) Gorkha earthquake. Eng Fail Anal. 68:222–243. doi:10.1016/j.engfailanal.2016.06.002.

Gautam D, Forte G, Rodrigues H. 2016a. Site effects and associated structural damage analysis in Kathmandu Valley, Nepal. Earthq Struct. 10:1013–1032. doi:10.12989/etas.2016.10.5.1013.

Gautam D, Rodrigues H, Bhetwal KK, Neupane P, Sanada Y. 2016b. Common structural and construction deficiencies of Nepalese buildings. Innov Infrastruct Solut. 1:1. doi:10.1007/s41062-016-0001-3.

Gautam D. 2016. Empirical correlation between uncorrected standard penetration resistance (N) and shear wave velocity (V_S) for Kathmandu Valley, Nepal. Geomatics Nat Hazards Risk. doi:10.1080/19475705.2016.1243588.

Gautam D. 2017. Seismic performance of world heritage sites in Kathmandu valley during Gorkha seismic sequence of April–May 2015. J Perform Constr Facil. doi:10.1061/(ASCE)CF.1943-5509.0001040.

Grandin R, Vallée M, Satriano C, Lacassin R, Klinger Y, Simoes M, Bollinger L. 2015. Rupture process of the M_w = 7.9 2015 Gorkha earthquake (Nepal): Insights into Himalayan megathrust segmentation. Geophys Res Lett. 42:8373–8382.

Gupta SP. 1988. Report on Eastern Nepal earthquake 21 August 1988, damage and recommendations for repairs and reconstruction. Bangkok: Asian Disaster Preparedness Center.

Hallier S, Chaljub E, Bouchon M, Sekiguchi H. 2008. Revisiting the basin-edge effect at Kobe during the 1995 Hyogo-ken Nanbu earthquake. Pure Appl Geophys. 165:1751–1760.

Hayes GP, Briggs RW, Barnhart WD, Yeck WL, et al. 2015. Rapid characterization of the 2015 M_w 7.8 Gorkha, Nepal, earthquake sequence and its seismotectonic context. Seismol Res Lett. 86:1557–1567.

Hossler T, Bollinger L, Sapkota SN, Lave J, Gupta RM, Kandel TP. 2016. Surface ruptures of large Himalayan earthquakes in western Nepal: evidences along a reactivated strand of the Main Boundary Thrust. Earth Planet Sci Lett. 434:187–196.
Martin SS, Hough SE, Hung C. 2015. Ground motions from the 2015 M7.8 Gorkha, Nepal, earthquake constrained by a detailed assessment of macroseismic data. Seismol Res Lett. 86:1524–1532.

Moss RES, Thompson EM, Kieffer D, Tiwari B, et al. 2015. Geotechnical effects of the 2015 magnitude 7.8 Gorkha, Nepal, earthquake and aftershocks. Seismol Res Lett. 86:1514–1523.

[NPC] National Planning Commission. 2015. Post disaster need assessment. Vol. A and B. Kathmandu: Government of Nepal.

[NSC] National Seismological Center. 2015. Recent earthquakes. Available from: http://seismonepal.gov.np/index.php?listId=162

Pandey MR, Tandukar RP, Avouac JP, Vergne J, Heiritier T. 1999. Seismotectonics of the Nepal Himalaya from a local seismic network. J Asian Earth Sci. 17:703–712.

Rai DC, Singhal V, S BR, Sagar SL. 2016. Reconnaissance of the effects of the M7.8 Gorkha (Nepal) earthquake of April 25, 2015. Geomatics Nat Hazards Risk. 7:1–17.

Rana BSJB. 1935. The great Earthquake of Nepal. Nepali. Kathmandu: Bookhill Publication. (Reprint 2015).

Sakai H. 2001. Core drilling of the basin-fill sediments in the Kathmandu Valley for paleo-climatic study: preliminary results. J Nepal Geol Soc. 25:9–18.

Santucci de Magistris F, Lanzano G, Forte G, Fabbrocino G. 2013. A peak acceleration threshold in liquefaction occurrence. Soil Dyn Earthq Eng. 54:17–19.

Santucci de Magistris F, Lanzano G, Forte G, Fabbrocino G. 2014. A peak acceleration threshold for soil liquefaction: lessons learned from the 2012 Emilia earthquake (Italy). Nat Hazards. 74:1069–1094. doi:10.1007/s11069-014-1229-x.

Shakya K, Pant DR, Maharjan M, Bhagat S, Wijeyewickremaa AC, Maskey PN. 2013. Lessons learned from performance of buildings during the September 18, 2011 earthquake in Nepal. Asian J Civil Eng (BHRC). 14:719–733.

Tertulliani A, Leschiutta I, Bordoni P. 2012. Damage distribution in L’Aquila city (Central Italy) during the 6 April 2009 earthquake. Bull Seismol Soc Am. 102:1543–1553.

Tertulliani A, Maramai A. 1998. Macroseismic evidence and site effects for the Lunigiana (Italy) 1995 earthquake. J Seismol. 2:209–222.

Tertulliani A. 2000. Qualitative effects of local geology on damage pattern. Bull Seismol Soc Am. 90:1543–1548.

[USGS] United States Geological Survey. 2015. M 7.8-36km E of Khudi, Nepal. Available from: http://earthquake.usgs.gov/earthquakes/eventpage/us20002926#general_summary

Upreti BN, Le Fort P. 1999. Lesser Himalayan crystalline nappes of Nepal: problem of their origin. In: Macfarlane A, Quade J, Sorkhabi, editors. Colorado: Geological Society of America; p. 225–238. (Special Paper 328).

Wesnousky SJ, Kumahara Y, Chamlangain D, Karki A, Gautam D. 2017. Geological observations on large earthquakes along the Himalayan frontal fault near Kathmandu, Nepal. Earth Planet Sci Lett. 457:366–375.