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LIQUEFACTION IN KATHMANDU VALLEY DURING 2015 GORKHA (NEPAL) EARTHQUAKE

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Abstract

On 25 April 2015, an earthquake of magnitude 7.8 occurred in Gorkha, Nepal, an actively deforming central Himalayan mountain range. The epicenter was approximately 80 km northwest of capital city Kathmandu. Nepal lies on the boundary between the two massive Indian and Eurasian tectonic plates that collided to form the Himalayas. The continuous subduction of the Indian plate under the Eurasian plate caused the earthquake which resulted in widespread damage of civil infrastructure such as buildings, temples, bridges, highways and liquefaction occurred mainly in the central part of the country which includes Kathmandu, Lalitpur, Bhaktapur, Sindupalchowk, Dolakha and Gorkha districts. This paper compiles the occurrences of liquefaction and liquefaction-induced damage in various regions of the Kathmandu Valley during the 2015 Gorkha Earthquake and related aftershocks.

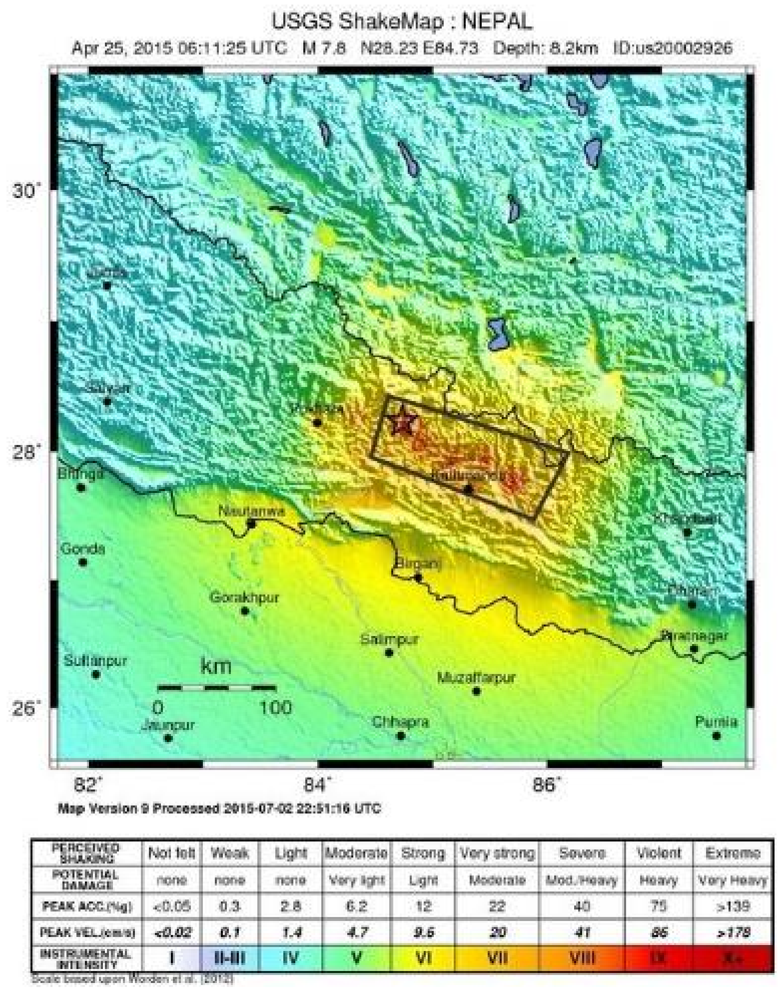
Kathmandu Valley was once a large lake and the ground conditions comprise of lake and river sediments known as lacustrine deposits which are susceptible to liquefaction. The lacustrine deposits are up to about 500 m thick and form interbedded layers of clay, silt, sand and gravel which are variable in extent and thickness. Liquefaction potential in these deposits has been studied and pointed out by many researchers in the past. Clear evidence of liquefaction in the form of sand boils, lateral spreading and ground failures were observed in many regions of the Kathmandu Valley following the Gorkha Earthquake. The location of ground failures induced by liquefaction was limited to edges of Kathmandu basin than that in the basin interior due to the basin edge amplification effects. However, no major ground failure occurred and the extent of damage due to liquefaction was rather limited. One reason might be the low intensity of the ground motion (PGA ranging from 0.16-0.2g) which may have generated cyclic stress ratios (CSR) marginally higher than cyclic resistance ratios (CRR) locally and therefore rather limited to “marginal” liquefaction. Other reason might be the groundwater level; which was substantially low due to the dry season and continuous groundwater extraction.

Keywords: Gorkha Earthquake; basin edge effects; Kathmandu Valley; liquefaction; sand boils

1. Introduction

On 25 April 2015, an earthquake of magnitude 7.8 occurred in Gorkha, Nepal, an actively deforming central Himalayan mountain range. The epicenter (28°14'24.0" N 84°45'00.0" E) was approximately 80 km northwest of Nepal's capital city Kathmandu (Fig.1). Nepal lies on the boundary of the Indian and Eurasian tectonic plates that collided to form the Himalayas as a result of the ongoing subduction of the Indian plate below the Eurasian plate. Nepal has suffered several large earthquakes in the past with at least ten destructive earthquakes since the 13th century. The 1505 Mw 8.8 Lo Mustang earthquake was one of the largest earthquakes in Nepalese history which killed approximately 30 percent of the Nepalese population at the time [1]. The 1833 Mw 7.7±0.2 earthquake occurred close to Kathmandu destroyed about 4600 houses [2]. Almost after a return period of 100 years, the 1934 Mw 8.1 Nepal-Bihar earthquake completely destroyed about 80,000 building and about 126,000 houses were severely damaged. Human casualties were about 8,500 [3]. The 1988 Mw 6.9 Nepal earthquake killed about 1000 people and 60000 buildings were damaged in eastern Nepal, including Kathmandu [4]. Prior to the Gorkha event, the most recent one was 2011 Sikkim earthquake [5] [6]. The 2015 Gorkha earthquake resulted in the intensity of shaking is shown in Fig.1. The main event was followed by 453 aftershocks with magnitude greater than 4.0 as of May 6, 2016 (according to National seismological center [7]). The occurrence of aftershocks (Mw 6.7 and Mw 7.3) in the Kodari district with epicenters approximately 120 km northeast of Kathmandu caused further additional damages and human casualties. As of 23 September 2015, the death toll reached to 8,800.

The 2015 Gorkha earthquake caused widespread damage to civil infrastructure such as buildings, temples, bridges and highways mainly in the central part of the country which includes Kathmandu, Lalitpur, Bhaktapur, Sindupalchowk, Dolakha and Gorkha districts. This event has also triggered several ground failures such as



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 1 – Intensity shakemap (USGS 2015 [5])

landslides, rock falls and liquefaction. After the devastating 1934 Nepal-Bihar earthquake, Rana (1935) reported about the occurrence of liquefaction at some of the places in the Kathmandu valley in his book entitled "Great Earthquake of Nepal" [8]. It has been reported that all the houses in the alluvial soil either tilted or buried and sand and water fountains were erupted at many places as a result of widespread liquefaction during 1934 Nepal-Bihar earthquake [9]. Extensive damages were observed in India due to liquefaction during 1988 Nepal Earthquake [9] [10]. However, no proper evidence of liquefaction has been reported in Kathmandu valley during that event.

A reconnaissance survey was carried out with the Geotechnical Extreme Events Reconnaissance Association (GEER) team from May 6 to May 20, 2015 to assess the geotechnical damages and failures in the Kathmandu Valley (Kathmandu, Lalitpur, Bhaktapur), Gorkha (epicenter region), Pokhara (western region), Sindhupalchowk, and Dolakha districts. This paper compiles the occurrences of liquefaction and liquefaction-induced damage in the Kathmandu Valley.

2. Geology and Ground motion

Kathmandu Valley was once a large lake and the ground conditions comprises of about 500 m thick of Pliocene-Quaternary fluvio-lacustrine deposits, some of which have the potential to liquefy [11]. The most recent sediments consist of heterogeneous fluvial-lacustrine deposits which comprises of muds, silts, sandy loams, fine to coarse sands and gravel to pebble conglomerates [12] and are variable in extent and thickness. The southern part of the valley comprises of black to grey organic mud with alternate sequence of gravel, fine sand and silty clay with carboancious mud on the top and the age of this formation is believed to be middle Pleistocene [11] [13]. The central part consists of mainly fluvial fine to medium sand and silt intercalated with clays and fine gravels in some places. This sediment lies on the top of thick sequence of dark grey to black highly plastic clay and silts (locally called Kalimati or black cotton soil which falls under montmorillonite clay group having more swelling and shrinking characteristics) which is rich in organic matter [11]. The age of this clay is placed in the Pliocene to Pleistocene time according to Yoshida and Igarashi (1984). It's thickness is greatest along the central part of the valley. The northern part of Kathmandu valley consists of poorly sorted, thin to medium-bedded highly micaceous coarse sands, gravel and silts interlayered with clays in some places. This deposits is the youngest among all other deposits. The norther part is considered as the marginal line of the lake. Besides this, the valley comprises of alluvial deposits in river channels, flood plains, and fans, which are of Holocene age [13].

Fig.2 shows the main active faults along the major tectonic boundary. These faults are produced by the continuous collision of the Indian plate with the Eurasian plate. The rupture which caused the Mw 7.8 Gorkha earthquake occurred near the main Himalayan thrust fault between the subducting Indian plate and the overriding Eurasian plate to the north at 28°14'24.0" N 84°45'00.0" E at a depth of about 8.2 km (Fig.2). The

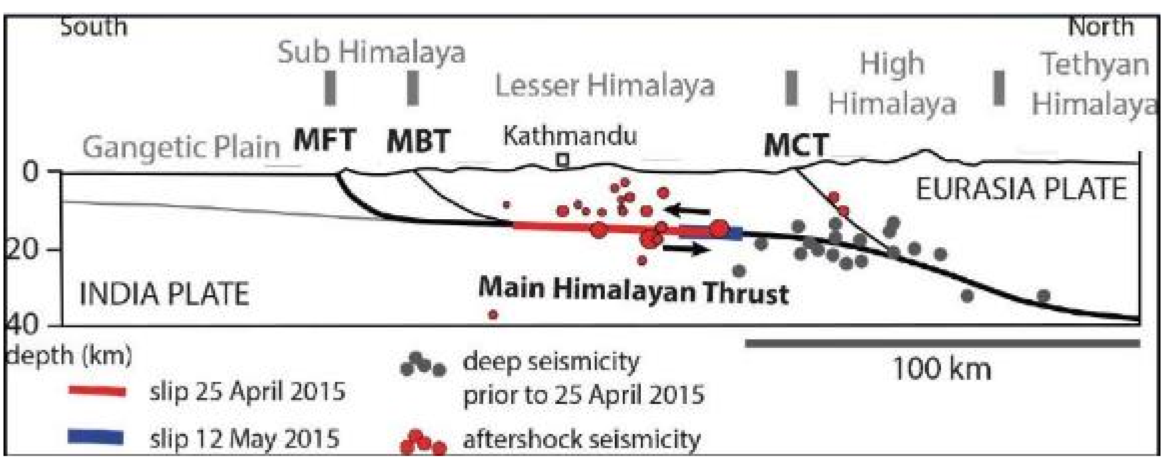


Fig. 2 – Cross section showing the approximate locations of slip during 25 April and 12 Many 2015 ruptures on Main Himalayan Thrust (USGS 2015 [14])

Indian plate is converging with the Eurasian plate at a rate of 45mm/year towards the north-northeast at about 80 km to the northwest of the capital city, Kathmandu and the city is bounded southwards by a tectonic ridge developed above the Main Boundary Thrust (MBT) (Fig.2). Fig.3 shows the mainshock slip direct was east from the hypocenter towards Kathmandu (USGS 2015 [14]). The rupture dimensions are approximately 120 km along strike and 120 km down dip. The maximum slip was about 4 m and occurred approximately 80 km ESE from the epicenter near the Kathmandu basin. The location of rupture during the mainshock and aftershocks is also shown in Fig. 3. The fault slip occurring to the entirely east of the epicenter suggests that there could be a strong directivity effect in the ground motion.

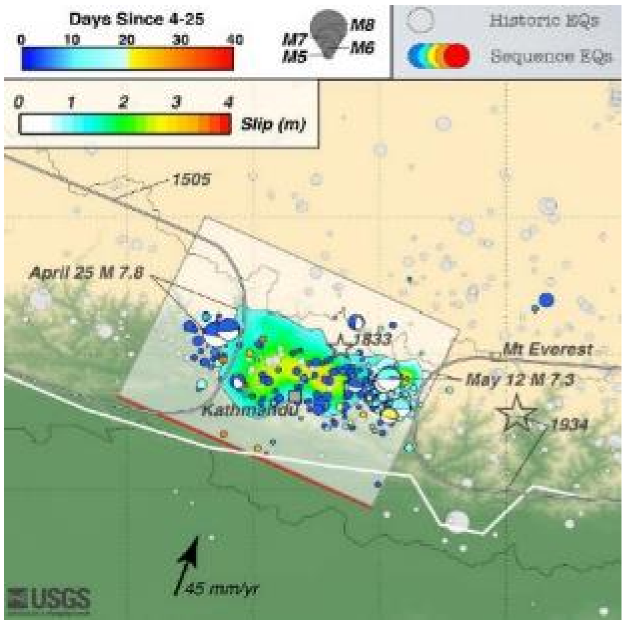


Fig. 3 – Mainshock slip directed east from hypocentre towards Kathmandu (USGS 2015 [14])

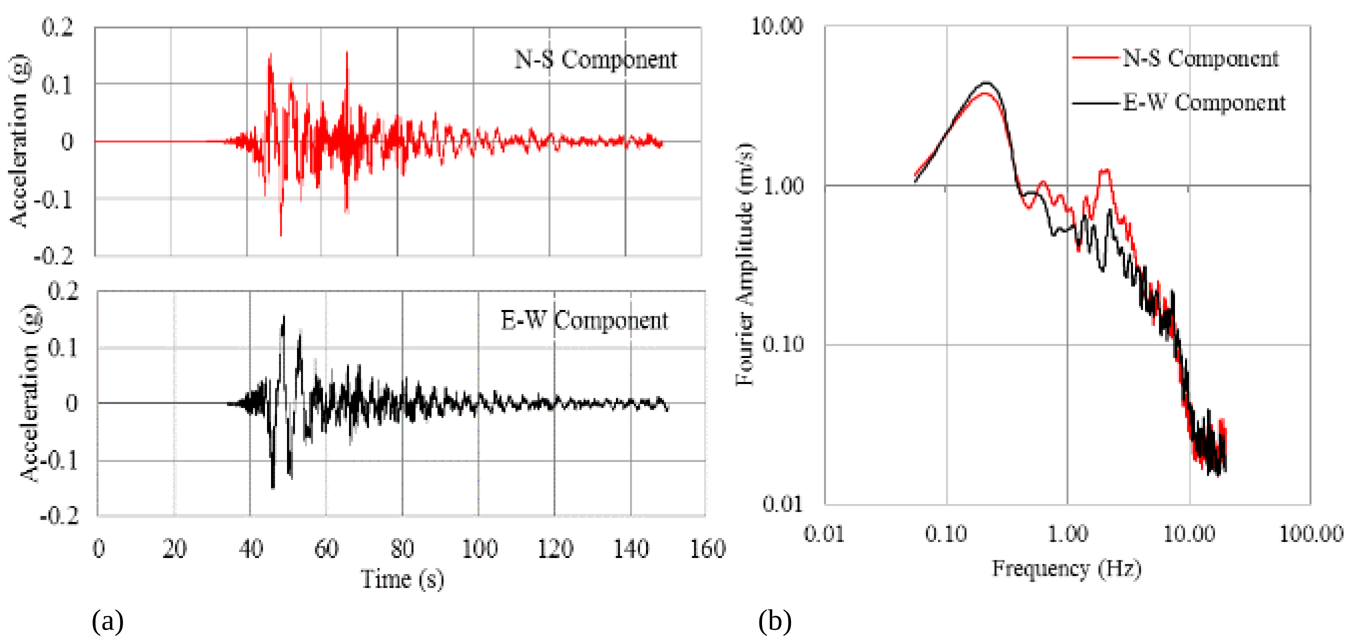
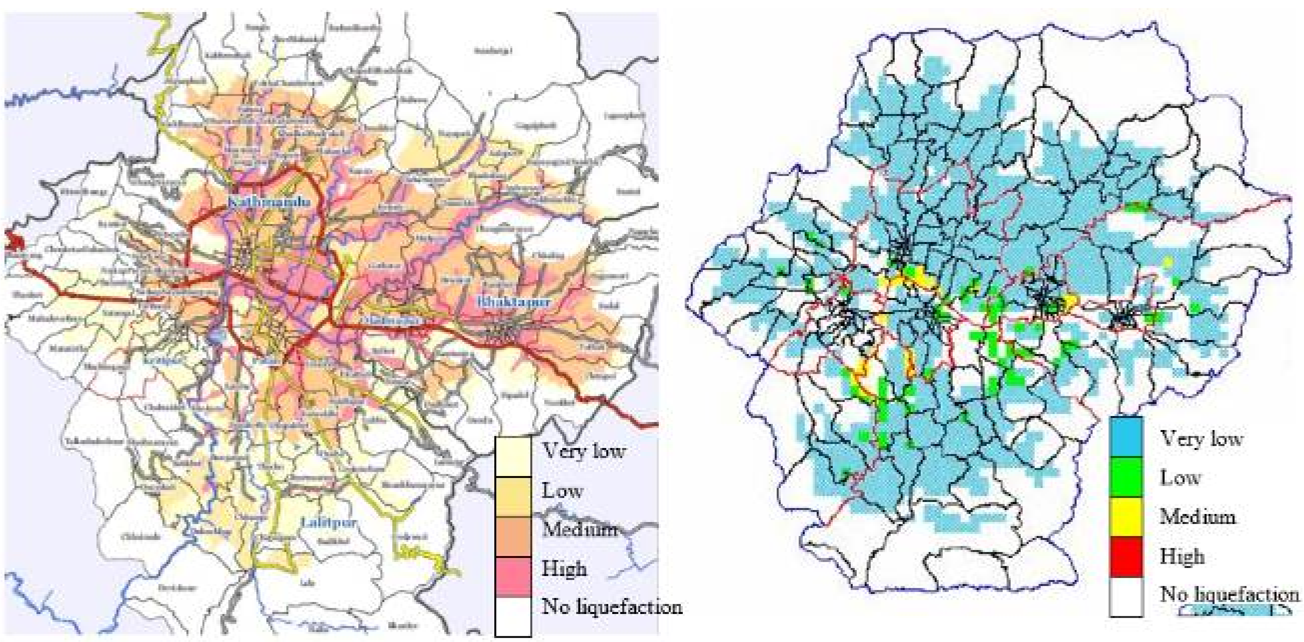


Fig. 4 – (a) Acceleration time histories and (b) Fourier Spectra of the Mw 7.8 2015 Gorkha Earthquake (Mainshock) [USGS (2015)]

Fig.4(a) shows the acceleration time histories of the mainshock event (N-S and E-W components) recorded at Kantipath, Kathmandu (Station KATNP, 27° 43' 48" N, 85° 20' 9.6" E). The ground motion has a very peak ground acceleration PGA=0.16g despite the larger magnitude of the M7.8 Gorkha Earthquake. Something about the Kathmandu valley has dampened the shaking and it might be due to non-linear effect and more research are required to see if this theory holds up. Fig.4(b) presents the Fourier spectra of both N-S and E-W components had predominant frequency of about 0.21 Hz. The presented ground motion was recorded in the middle of the Kathmandu basin and unfortunately, no strong ground motions data were available from other locations which could have provided more insights in to the understanding of this earthquake.

3. Liquefaction potential of Kathmandu Valley

Limited studies were carried out in the past to understand liquefaction hazard and potential in the Kathmandu Valley. The UNDP/UNCHS in collaboration with Government of Nepal conducted a seismic hazard mapping and risk assessment in order to develop the liquefaction hazard map of the Kathmandu Valley as shown in Fig.5a [15]. The map showed that about 25% of the area has high liquefaction potential. The liquefaction hazard assessment of Kathmandu Valley was also carried out using limited borehole data. Another collaborative liquefaction hazard assessment of Kathmandu Valley was carried by JICA and Government of Nepal in 2000-2002 [16]. Fig.5b shows the liquefaction potential map of Kathmandu Valley for mid Nepal earthquakes (except in mountainous areas, Modified Mercali Intensity (MMI) VII would be experienced in the Kathmandu Valley). According to the findings made by JICA [16], the liquefaction potential is very low in most of the areas and moderate potential was identified in some areas along the Bagmati river. Piya [6] compiled the available borehole data information for the Kathmandu Valley and developed the liquefaction susceptibility map of Kathmandu Valley using the qualitative and quantitative methods (Fig.6). This study showed high liquefaction potential in the core of the Kathmandu Valley, along the flood plains and in the eastern part of the Valley.



(a) (b)

Fig. 5 – Liquefaction potential map of Kathmandu Valley prepared by: (a) UNDP/UNCHS (1993) and (b) JICA (2002)

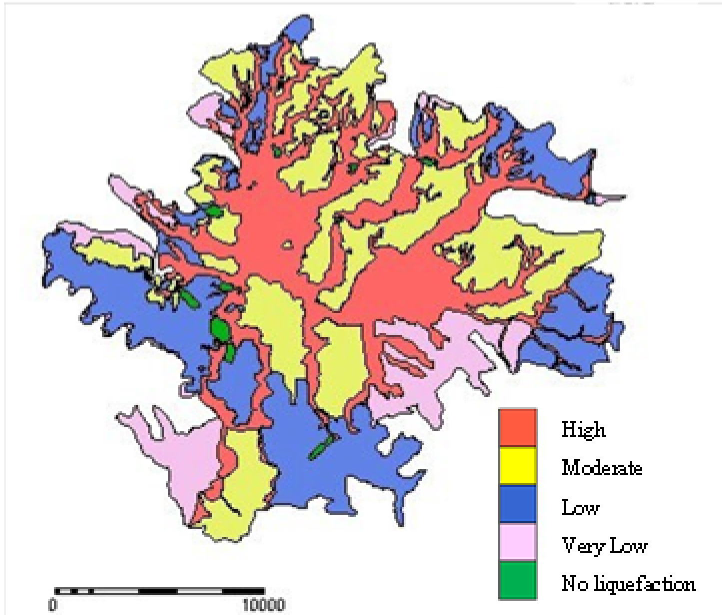


Fig. 6 – Liquefaction potential map prepared by Piya (2004)

It is worth noting that the ground water level assumed in these studies was significantly higher than that at the time of the Gorkha Earthquake. It is worth noting that the ground water level was approximately 5-9 m below the surface in the north-eastern part, 2 m deep in the western, central and eastern part and about 1 m deep in the southern part according to the Environmental Geology project of DMG (1998) [11]. The ground water level has declined by approximately 1-7 m at various regions of Kathmandu valley from 2000 to 2008 [17]. The reliable information on current ground water level of Kathmandu Valley is limited. However, according to the recently published article in the Nepal's national newspaper, the ground water level has decreased down by 8 m from 2008 to 2013 at the eastern part and 3-4 m in the southern part [18].

4. Liquefaction sites in Kathmandu Valley

The reconnaissance survey visited as listed in Fig.7 and Table 1. Confirmation of liquefaction was based on clear evidence, such as sand boils, lateral spreading, upliftment and settlement of structures. The main evidence observed was sand boils. The degree of liquefaction does not have been sufficient to cause extensive settlement of structures.

5. Evidences of liquefaction

Sand boils were observed at all the liquefaction sites except Lokanthali as shown in Figs.8-10. Fig.8a shows sand boils on open ground at Duwakot, Bhaktapur on the eastern edge of the Kathmandu Valley. A number of sand boils were observed in this floodplain area about 300 m from the Manohara river as shown in Fig.8a. The ejected soil was silty clay found in the banks of the river. The liquefaction site near Mulpani is located about 1 km south east on the same floodplain of Duwakot. Significant sand boils were observed in a potato field with fissures of about 5 to 15 cm width extending for a length of about 200-300 m (Fig.8b). Numerous sand boils in cropfields were also observed at the Imadol, Lalitpur and Hattiban sites. Both Imadol and Hattiban sites are located on the floodplain of Manohara river. Similar to the Duwakot area, sand boils occurred on the floodplain about 200 m from the Bagmati river at Bungamati site (Fig.9a).

Massive sand boils were observed at the Ramkot site at the western edge of the Kathmandu Valley. The site is on a steep terrace where liquefaction of very fine material was observed (Fig.9b). The site is about 100m northeast of a meandering Manamati river. Large volume of fine materials was ejected to the ground surface.

However, no lateral deformation of terraces was found. According to locals, the boils were ejected upto a height of 2 m for about 2 hours following the M7.8 earthquake.

The evidence of liquefaction was observed both in the open ground and under building foundations at the Manamaiju site. Sand boils of fine sand were observed in the open ground and some minor tilting of building was observed which might be possibly due to the lateral spreading along a free end (Fig.10). A large area

Fig. 7 – Liquefaction sites in Kathmandu Valley visited during field survey from May 6 to May20, 2015

Table 1 – List of liquefied sites in Kathmandu Valley

Site	Latitude	Longitude	Epicentral distance (km)	Evidence type
Duwakot	27°42'34.0"	85°24'50.3"	56.57	Sand boils
Mulpani	27°42'16.5"	85°23'58.6"	56.92	Sand boils
Ramkot	27°42'39.7"	85°15'44.2"	75.80	Sand boils
Manamaiju	27°44'43.9"	85°18'08.0"	70.35	Sand boils / Lateral spreading
Bungamati	27°37'43.1"	85°17'47.9"	81.22	Sand boils
Imadol	27°40'00.8"	85°20'16.4"	75.4	Sand boils
Hattiban	27°39'20.4"	85°20'03.9"	76.68	Sand boils
Lokanthali	27°40'29.3"	85°21'45.5"	73.42	Lateral spreading
Guheshwori	27°42'33.3"	85°21'27.2"	59.6	Sand boils

at Guheshwori site was flooded with sand and water during and after the earthquake shaking. According to the local residents, the area remained flooded for a day.

Lokanthali is the most interesting ground failure site from the earthquake which has drawn attention of researchers from all over the world. A section of the Araniko Highway extending from Lokanthali to Bhaktapur showed vertical offset. The section of highway which experienced failure was a newly constructed road embankment. This vertical dislocation ran across the highway diagonally but only extended a few meters away from the highway indicating failure to be localized. The vertical offset was approximately about 1m over about 200 m area (Fig.11). On the other hand, the horizontal offset extended over a large area (about 500 m). Large lateral cracks with 2-3 m deep fissures and width of 0.5m have occurred over a large area on or near sloping


(a)


(b)

Fig. 8 – (a) Sand boils in Duwakot, Bhaktapur (b) Sand boils observed in the potato field with the fissures in Mulpani.


(a)


(b)

Fig. 9 – (a) Sand boils observed on the floodplain about 200 m from the Bagmati river at Bungamati site (Photo courtesy: Diwakar Khadka) (b) Massive sand boils observed at Ramkot site in sloping terrace

(a) (b)

Fig. 10 – (a) Large sand boils of fine sand in Manamaiju (b) Tilting of building due to lateral spreading in Manamaiju

Fig. 11 – Ground deformation with vertical and horizontal offsets of approximately 2 m and 0.5 m respectively observed in Lokanthali region

grounds. The surrounding buildings and appurtenant structures of the highway also experienced an excessive amount of settlement. One of the sections of vertical offset extended near to the overhead pedestrian bridge located at the Kaushaltar bus stop. The pedestrian bridge had experienced damage due to this ground failure and was closed for repair during the period of field survey. The conclusive remark on the cause of this vertical and horizontal offsets is difficult due to lack of detail information on the type of soil present and the depth of the ground water table. Based on the observations, the length of fissures, and the past earthquake site investigations, this vertical and horizontal offsets of highway might be attributed to mass movement of soil at lower depth. These mass movements might have occurred due to weakening or liquefaction of soil. This failure mechanism might be attributed to cyclic shear softening of silty clay lacustrine deposits allowing the movement of overlying soil and resulting in the vertical and horizontal offsets observed at the surface. This deformation was exhibited at localized areas as the weakening soil might have been localized and the deformation diminished after extending to certain length. Vertical offsets mainly existed on the both sides of slightly depressed zone of the highway, so the soil at this zone might have weakened allowing the movement of opposite hill slopes and causing the vertical offset on the surface. According to the locals, the displacements were rather small from the main Mw7.8 earthquake and the displacements increased due to the first Mw6.7 aftershock. This site was revisited after the occurrence of M7.3 aftershock and it was found that the width and depth of fissures had increased since the main extent. This indicated that aftershocks can have pronounced effects on the deformation as suggested by Maharjan et al. [19].

The liquefaction potential map prepared by Piya [11] showed the high liquefaction potential in many areas of the Kathmandu Valley. Several factors may have reduced the soil liquefaction due to this earthquake. The main reason might be the groundwater level, which was significantly lower than that at the time when the liquefaction potential map was prepared. At all the liquefaction sites, liquefaction triggered but the damage was not severe. Additionally, the frequency and the intensity (low PGA of 0.16g) of the shaking appeared to be less than it would be expected for an event of the same magnitude. It suggests that some mechanisms or some factor are preventing amplification while propagating through the lacustrine deposits; further studies are required on it. The low intensity of the shaking (0.16-02g) was just enough to trigger the liquefaction but not strong enough to fully weaken the liquefiable materials exhibiting a “marginal” liquefaction as defined by Seed et al [20]. This makes the observations potentially valuable but could not induce large displacements due to the fact that the loading has been poorly quantified.

The location of liquefaction sites as shown in Fig.7 indicates that the location was limited to the valley sides (the basin edges) around the Kathmandu Valley after M7.8 Gorkha earthquake. This is due to the basin edge effects which resulted in ground motion amplification and change in the frequency content at the basin edge caused by the constructive interference of the direct shear waves propagating vertically through basin sediments and a horizontally propagating surface waves diffracted into basin. Such observation is relevant to the damage observed during 1994 Northridge and 1999 Kobe earthquake [21] [22].

6. Conclusions

On 25 April 2015, an earthquake of magnitude 7.8 occurred in Gorkha, Nepal, approximately 80 km northwest of capital city Kathmandu. A reconnaissance survey was carried out to assess the occurrences of liquefaction and liquefaction-induced damage in various regions of the Kathmandu Valley caused by the 2015 Gorkha Earthquake and related aftershocks. The liquefy action sites identified in the Kathmandu Valley and the possible causes of liquefaction have been summarized in this paper. Sand boils were the key evidence of liquefaction at most of the sites. The mixture of sand and water was ejected and flooded the ground at all the locations, except at the Lokanthali and Manamaiju areas where the lateral spreading was also observed.

The location of ground failures induced by liquefaction was limited to edges of Kathmandu basin than that in the basin interior due to the basin edge amplification effects. In the basin interior, the shaking generated rather low cyclic stress ratio (CSR), not enough to cause liquefaction which might be attributed to some mechanisms/factors which is damping out the shaking. Further studies are necessary to obtain velocity profiles, modulus reduction and damping curves of lacustrine deposits (black cotton soil) which is concentrated in the central and southern part of Kathmandu Valley, and rock outcrop records to establish a reference ground motion at higher frequencies. Nevertheless, at basin edges, the constructive interference of direct shear waves with basin-induced surface waves resulted in significant amplification in the surface ground motion. This edge effects generated cyclic stress ratio (CSR) marginally higher than cyclic resistance ratio of soil (CRR) locally and caused localized liquefaction along the edges of the Kathmandu valley. Moreover, because of the low intensity shaking, the soil failure was only limited to small/medium deformation in most cases. The shaking was just enough to trigger the liquefaction but not strong enough to fully weaken the liquefiable materials exhibiting a “marginal” liquefaction. The low groundwater level due to dry season and significant decline of groundwater level (approximately 10m in 10 years) by continuous extraction of ground water has also limited the occurrence of liquefaction and hence less deformation and damages.

It suggests that hazard maps need to recognize site response effects, factors preventing amplification, and the current ground water level. More studies on soil conditions and behaviors and the interpretation of strong motion records at several sites are necessary.

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