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Liquefaction of soil in Kathmandu Valley from the 2015 Gorkha, Nepal earthquake

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ABSTRACT

The Gorkha Nepal earthquake of moment magnitude M_w 7.8 occurred at 06:11 UTC on April 25, 2015, with the epicenter about 77 km northwest of Kathmandu Valley. Immediately following the earthquake, a field investigation was carried out in Kathmandu Valley to study the liquefaction and its consequences during the earthquake. Standard Penetration Test (SPT) was carried out at four liquefied sites. This paper provides first-hand observations of liquefaction and the associated effects. As the Kathmandu valley deposits are composed mainly of sand, silt and clay layers with a shallow ground water table, liquefaction is highly anticipated. This paper provides the observations of liquefaction case histories. Typically, most of these liquefactions were sand boils formed by freshly ejected sand forced out and spouting of groundwater from liquefiable sub-strata. Ejected soils at were collected and the particle size distributions of ejected soils were analyzed. SPT blow counts and the soil profiles at four liquefied sites were obtained. The factors of safety against liquefaction with depth at four sites were estimated and compared with observed liquefaction areas during Gorkha earthquake. The field observations along with results from liquefaction assessment were compared with the existing liquefaction hazard map. It was found that the existing hazard maps are unrepresentative and underestimate the liquefaction susceptibility in Kathmandu Valley.

Keywords: Gorkha Earthquake, Reconnaissance study, Liquefaction, Sand boiling, Case studies

INTRODUCTION

A megathrust subduction earthquake of moment magnitude M_w 7.8 occurred at 06:11 UTC on April 25, 2015, with the epicenter about 77 km northwest of Kathmandu at a focal depth of approximately 15 km [1]. Tremor was felt in Nepal, India, Bhutan, Bangladesh, and China. Two aftershocks of Mw 6.7 and 6.3 struck Nepal within 25 hours of the main shock. On May 12, another big aftershock of M_w 7.3, with epicentral location in the Northeast of Kathmandu, shook the region causing additional damage to Northern part of Central Nepal [2]. The spatial distribution of aftershocks, which extended 150 km to the east of the epicenter, suggests that the rupture propagated from west to east, thus producing severe destruction in Kathmandu, at approximately 80 km southeast of the epicenter. These seismic events in the central Himalaya were the strongest after the 1934 earthquake that was located northeast of Kathmandu [3, 4].

The deposition in the Kathmandu Valley is lacustrine and fluvial in origin with thickness up to 500 m [5, 6]. The deposited sediments are made up of clay, silt, sand and gravel. Areas with loose sand deposits have a greater chance of liquefaction after the earthquake. The peak ground accelerations of the 2015 Gorkha earthquake, recorded at various locations in Kathmandu valley, were approximately 180 cm/s^2. Although this acceleration was much smaller than expected (i.e. 300 cm/s^2), extensive soil liquefaction was observed at several locations in Kathmandu Valley. This highlights that soils in the valley are highly prone to liquefaction. Historical records indicate that great earthquake generally hits the region at an interval of about 80-100 years. Information of liquefaction in Kathmandu Valley during the previous major earthquakes except 1934 Nepal-Bihar earthquake is not found documented in the literature [7, 8]. Even the literatures regarding 1934 earthquake give limited insights into liquefaction [9, 10]. Liquefaction characteristic of soil in Kathmandu Valley and its consequences during previous historical earthquakes are poorly understood. The liquefaction potential assessment in the Kathmandu Valley is based on SPT blow counts and borehole data [11, 12]. In order to verify the liquefaction assessment method for use in the Kathmandu Valley, it is crucial to identify the field evidence of liquefaction induced settlement and lateral spreading and conduct specific liquefaction assessment. Field observation from the 2015 Gorkha earthquake provided a unique opportunity to understand the liquefaction potential in the Kathmandu Valley and verify the SPT-based method for the liquefaction assessment. The liquefaction potential of a soil deposit is an important aspect to access the stability of structure during earthquake. For example, an estimated 1,700 houses were consumed by the liquefaction during the very recent earthquake in Indonesia. Hundreds of buildings were collapsed as the ground slid beneath them [13]. Recently, researchers warned that an enormous stacking up of strain in the region portends at least one earthquake of magnitude 8.5 or more in the Nepal anytime in the future [14]. For this reason, post-earthquake reconnaissance activities that studies geotechnical aspect of the earthquake and provide case studies are of the same significance as research activities for researchers, engineers, policy-makers, and the society in general of Nepal and other countries [15, 16].

The present paper presents a summary of the field investigation with respect to the liquefaction cases in the Kathmandu Valley after the main shock of the earthquake. In addition, typical examples of liquefaction case studies triggered by the earthquake and the liquefaction-induced structural damages are briefly described. Standard Penetration Tests (SPT) were carried on liquefied sites and used for the liquefaction potential assessment using the SPT-based method [17]. The issues that need to be addressed to mitigate the liquefaction-induced damage or failure due to future destructive earthquakes are suggested.

GEOLOGICAL ASPECT OF KATHMANDU VALLEY

The surface of Kathmandu valley is generally broad and almost flat except towards the boundaries of the valley, where rivers are deeply incised. Well-developed flat terraces, formed by erosion from rivers, are common in the valley. The main rivers in valley are Bagmati, Bishnumati, Manohara, Dhobi Khola, Hanumate and Nakhu Khola. All tributaries drain towards the center of the basin in the Bagmati River, which cuts the Mahabharat hill range in the south and drains the river water to the southern plain through the Chovar gorge as the main drainage channel of Kathmandu Valley.

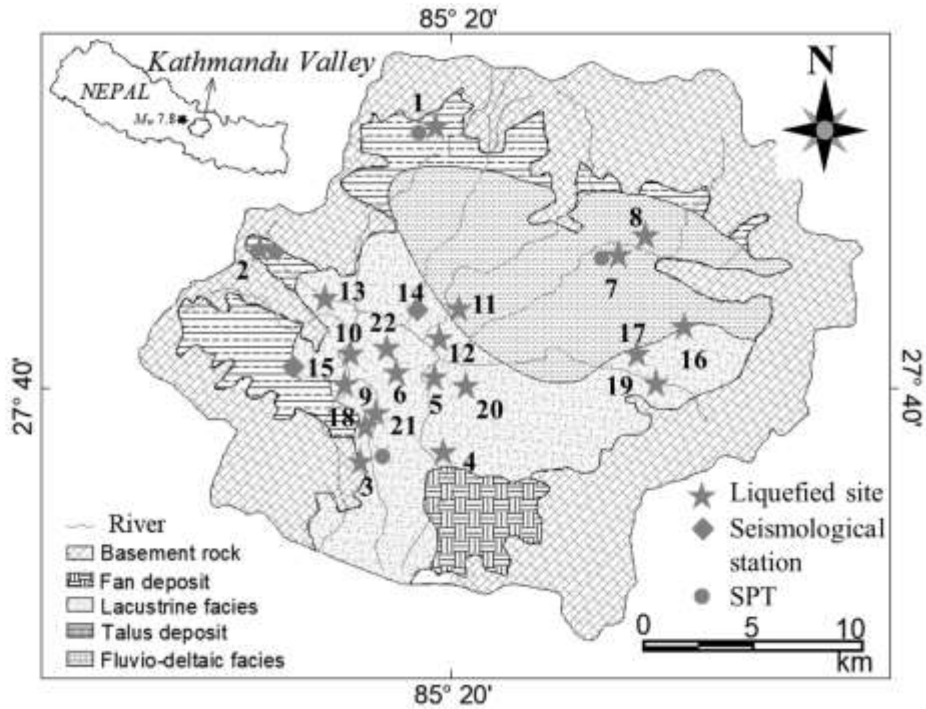

Figure 1 Surface geology of Kathmandu Valley with seismological stations (modified after Sharma et al. [12], Sakai [5]).

The Basement rocks of the Kathmandu valley is covered by thick semi-consolidated fluvio-lacustrine sediments originated from the Pliocene to Pleistocene epoch (Figure 1). These sediments are mainly derived from the surrounding hills by the river channel system. The sediment consists of arenaceous sediments composed of fine to coarse-grained sand with a small quantity of rock fragments, which are believed to have been supplied from the northern gneiss rocks. Argillaceous sediments composed of clay and silt resulting from the erosion of limestone and phyllite, which are exposed in the eastern, southern and western mountainous areas. Lignite and diatomite produced from the lake sediments. Agglomerate of boulders and gravel with a clayey and silty matrix in the southern basin de- rived as debris flow from the southern hills [5, 18]. The site investigation showed that most soils in the Kathmandu Valley are grey to dark silty sand and clayey silt. Organic clay, fine sand beds and peat layers are common in the surface 1 m layer [10, 19]. The shear wave (V30) velocity of the soft sedimentary deposits in Kathmandu Valley ranges from 160 m/s to 300 m/s and ground amplification may range from 2.0 to 8.0 [6].

GROUND MOTION

Strong ground motions recording at KTP and KATNP station are presented in this section. KTP station (N: 27.68216°, E: 85.27259°) located on the rock outcrop at 75.8 km from epicenter, was installed by Tribhuvan University, Nepal, and Hokkaido University, Japan [20]. KATNP station (N: 27.7120°, E: 85.3160°) was established by US Geological Survey (USGS) at Kanti Path, located on the top of a thick soil layer of 200 to 300 m thickness [1]. The KATNP station is 77 km southeast of main shock epicenter and 5 km northeast of KTP station. The E-W, N-S, and vertical components of the accelerograms of the main shock at KTP and KATNP are shown in Figures 3a and 3b respectively. The peak ground accelerations (PGA) of the main shock in horizontal direction are 241 cm/s^2 and 164 cm/s^2 at KTP (rock site) and KATNP (soil site) respectively. Time histories in Figure 3b clearly show that the horizontal accelerograms at KATNP had a long duration with conspicuous long-period oscillation at about 5 s. It is observed that the local site effects have contributed to the significant amplification of the motions and thus make the effects of the earthquake more influential in Kathmandu Valley. Details of the characteristics of ground motions recorded during the Gorkha earthquake can be found in Sharma and Deng [19], Takai et al. [20] and Parajuli and Kiyono [21].

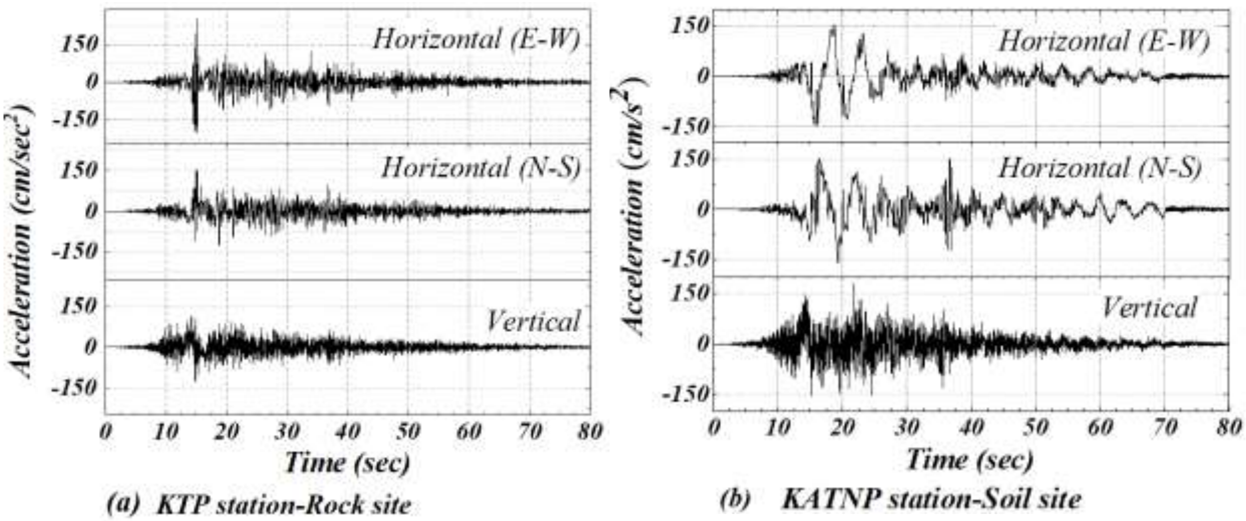

Figure 2. (a) Accelerograms at KTP [20] for the Mw 7.8 main shock, and (b) accelerograms at KATNP for the Mw 7.8 main shock [19]

OBSERVED LIQUEFACTION

The survey team travelled around the Kathmandu Valley during April 28 and 9 May 2015, and observed that the liquefaction triggered by the 2015 Gorkha earthquake appeared to be very limited and localized. The localized areas where liquefaction was observed in Kathmandu Valley during 2015 Gorkha earthquakes are shown in Table 1. Typically, most of these liquefactions were sand boils formed by freshly ejected sand forced out of over-pressurized sub-strata. At most site, sand was ejected to agricultural fields forming deposits that varied from thin veneers to sheets, a few centimeters thick. Although slight settlement and tilting were observed in buildings in Duwakot and Manamaiju, liquefaction induced damage to structures was not found. Brief descriptions of the four typical liquefied sites with soil profiles, SPT-N value and FS against liquefactions are presented in the following section.

The Manamaiju area is located on the north-west edge of the Kathmandu Valley. Some sand boils and traces were found in paddy fields on the right bank of the Bishnumati River (Figure 3). A number of fissures with openings up to 30 cm width were manifested on a flat plain along the river channel as shown in Figure 3. Some sand boils and traces were found in an empty plot (paddy fields) of land on the right bank of Bishnumati River. Other geotechnical problems and structural failure were observed in the surrounding area but were not associated with liquefaction except minor tilting of a building next to Bishnumati River. The soil in Manamaiju mainly consists of organic silt (OL) at the top, brownish grey silt (M) and poorly sorted, sub angular to rounded silty sand (SM) with occasional peaty clay and lignite layers. SPT-based method suggested by Idriss and Boulanger [17] was adopted to perform an analysis of the factor of safety (FS) with respect to liquefaction on each layer. Earthquake magnitude and peak ground acceleration from 2015 Gorkha earthquake were considered in this analysis. Details procedures of liquefaction analysis using Idriss and Boulanger [17] method can be found in Sharma et al. [12]. As shown in Figure 3, uncorrected SPT N values at each 1.5 m depth ranged from 6 to 28. The FS ranges from 0.7 to 1.6 at Manamaiju. It is clear that most of the liquefiable and marginally liquefiable samples are in the range of 3 to 10 m depth below the ground surface. All the liquefiable zones correspond to layers of silt (M) and silty sand (SM). However, liquefaction is not expected in sandy layers and layers of sand-gravel mixtures at greater depths (>10.0 m) due to their higher relative densities [12, 17].

Table 1List of observed liquefied areas in Kathmandu Valley [12, 19, 22]

Mark in Figure 2	Location	Northing (°)	Easting (°)	General description
1	Manamaiju	27.7453	85.3007	Fissures with openings of 20 cm width, sand boils and traces in an empty plot
2	Ramkot	27.7110	85.2622	Liquefied, large numbers of isolated blow sands
3	Bungmati	27.6286	85.2966	Sand boiling and fissures with openings of 5–35 cm width parallel to the river
4	Jharuwarashi	27.6151	85.3439	Ground fissuring of about 100 m long and 10 cm wide
5	Hattiwan	27.6656	85.3344	Sand boils on field, sand deposits up to few centimeters
6	Imadole	27.6668	85.3383	Liquefied, sand boils and traces of sand
7	Mulpani	27.7025	85.7007	Liquefied, ground fissures and sand boils
8	Duwakot	27.7094	85.4139	Sand boils and fissures, water well filled with sand, sand deposits up to few centimeters
9	Taudaha	27.6499	85.2829	Sand blows on agricultural field
10	Khadka Gaon	27.6950	85.2714	500m long ground fissure
11	Guheshwori	27.7093	85.3576	Sand boils on the field
12	Singh Durbar	27.6987	85.3200	Sand traces
13	Sitapaila	27.7200	85.2726	Sand boils
16	Pakune Pati	27.6969	85.4401	Sand boils and fissures along the river
17	Itapakhe	27.6792	85.4289	Ground fissures, sand boils on the field
18	Baghdol	27.6676	85.2980	Sand boils
19	Kamalvinayak	27.6785	85.4370	Traces of sand boils
20	Harisiddhi	27.6549	85.3352	Numerous sand boils
21	Malpokhari	27.6720	85.2958	Sand boils with GWT on surface
22	Syuchatar	27.6972	85.2740	Traces of sand

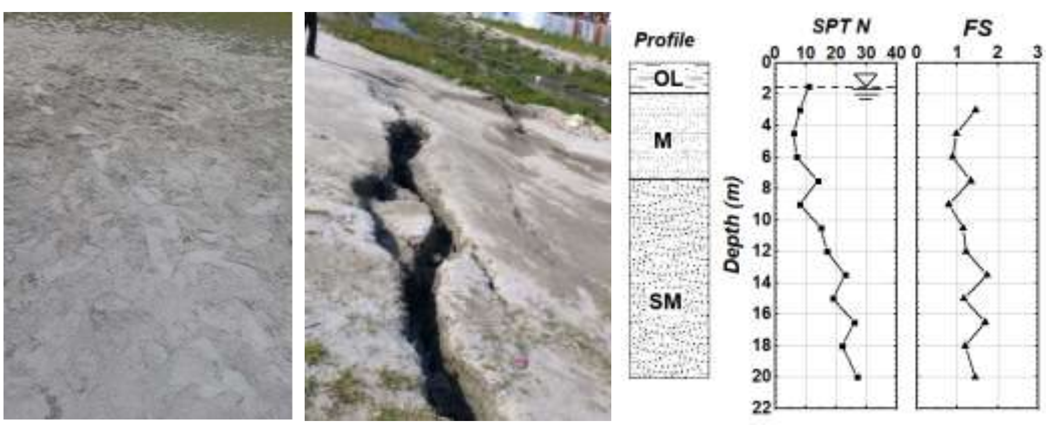

Figure 3 Manamaiju: observed liquefaction, soil profile, SPT-N value and factor of safety against liquefaction

Extensive liquefaction was found in the flood area of the Bagmati River in Bungamati, located on the south edge of the Kathmandu Valley. Sand boiling and fissures were seen on a flat plain along the river channel. Soils at this site were mainly new alluvium consisting of poorly graded sand (SP) and sandy silt (SM), which is approximately 100-300 m far from

Bagmati River. The ejected soil was poorly graded sand (SP) with a significant amount of non-plastic soil. The ground water table was at shallow depth (1.5-2.0 m) as the flood plain is close to the Bagmati River. The soil characteristics and high GWT significantly increased the potential of extensive liquefaction. Sand boiling and fissures with openings of 5–35 cm width parallel to the river were observed as shown in Figure 4. The uncorrected SPT N values at each 1.5 m depth ranged from 11 to 42 and the FS ranges from 0.6 to 1.9 at Bungamati. Most of the liquefiable and marginally liquefiable samples are in the range of 1.5 to 3 m and 6 to 8 m depth below the ground surface. All the liquefiable zones correspond to layers of poorly graded sand (SP) and silty sand (SM).

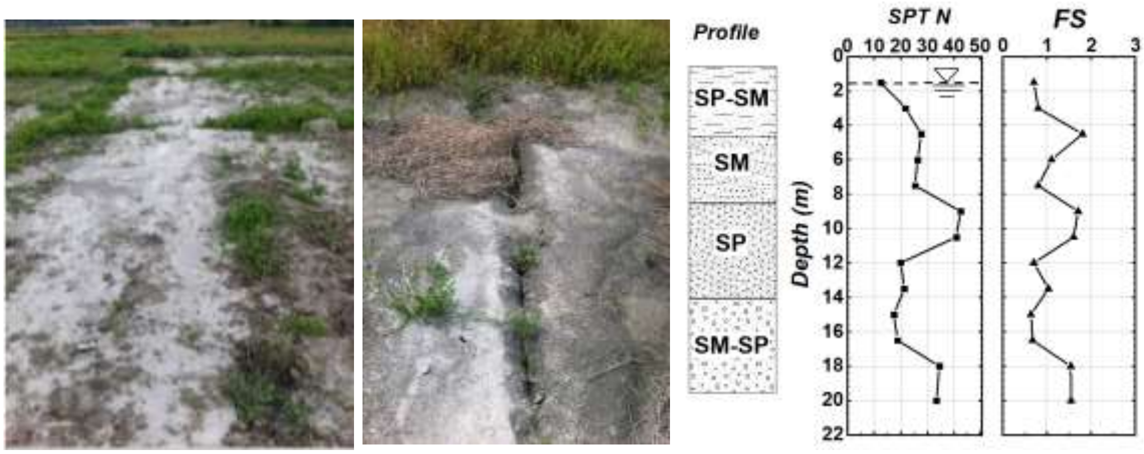

Figure 4 Bungmati: observed liquefaction, soil profile, SPT-N value and factor of safety against liquefaction

Extensive liquefaction was found in Duwakot near Nepal Engineering College on the left bank of Manohara River (Figure 5). This site is located on the east edge of the Kathmandu Valley. This is another site with clear liquefaction as indicated by sand boils. It is also famous for sand mining. Sand boiling and fissures were seen on a flat plain along the river channel. No significant damage due to liquefaction was found. However college building was reported to be subsided slightly [12, 23]. Numerous sand boils were also reported in Mulpani which is located on the same flood plain as Duwakot [12]. The soils in Duwakot consist of organic soil (OL) at the top of underlying sandy silt (SM). Poorly graded sand (SP) is seen underlain by well graded sand (SW) beneath the sandy silt (SM) as shown in Figure 5. The uncorrected SPT N values at each 1.5 m depth ranged from 4 to 38 and the FS ranges from 0.5 to 2 at Duwakot as shown in Figure 5. Most of the liquefiable and marginally liquefiable samples are in the range of 1.5 to 9 m depth below the ground surface. All the liquefiable zones correspond to layers of silty sand (SM) and well graded sand (SW) as shown in Figure 5.

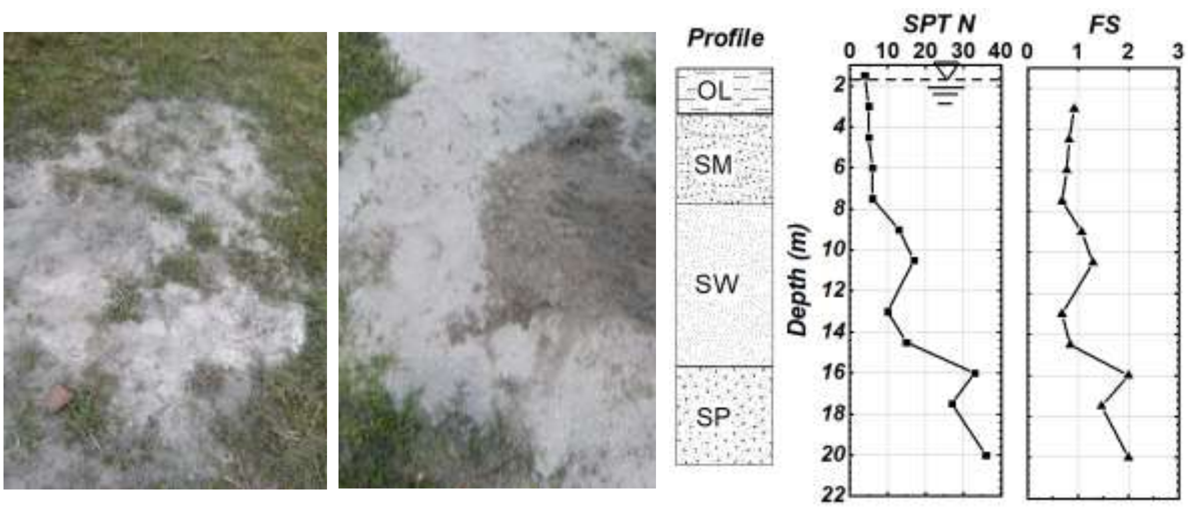

Figure 5 Duwakot: observed liquefaction, soil profile, SPT-N value and factor of safety against liquefaction

Ramkot is located on the western edge of the Kathmandu Valley. Liquefaction of very fine sand was observed on slope (Figure 6). However, no lateral deformation of slope was observed. The buildings on liquefied plain were intact. The soil in Ramkot consists of organic silt (OL) underlying the well graded sand (SW). Poorly graded sand (SP) and silt (M) are seen beneath the well graded sand (SW) as shown in Figure 6.The groundwater table (GWT) was at a depth of 2–2.5 m below the ground surface at the time of site visit. As shown in Figure 6, uncorrected SPT N values ranged from 5 to 26 and *FS* against ranges from 0.5 to 2 in liquefied sites. It is clear that most of the liquefiable and marginally liquefiable samples are in the range of 6 to 10 m depth below the ground surface. All the liquefiable zones correspond to layers of silt, silty sand, and a mixture of gravel and sand.

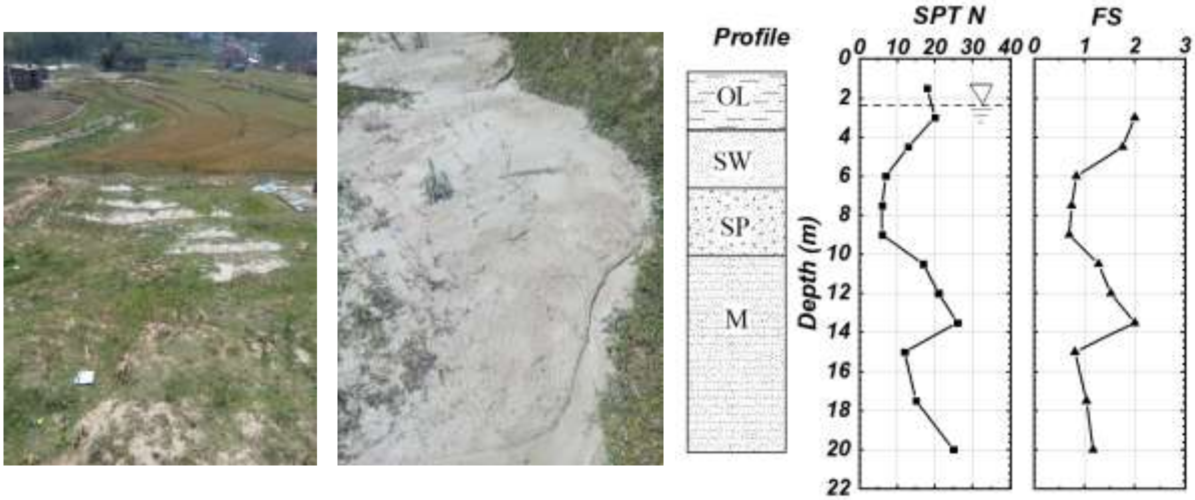

Figure 6. Ramkot: observed liquefaction, soil profile, SPT-N value and factor of safety against liquefaction

The typical particle size distribution of soil from each bore hole is shown in Figure 7. The fines content in the borehole logs were found between 10 and 42%. The particle size from all the bore holes falls within the range of most liquefiable soil defined by Tsuchida and Hayashi [24].

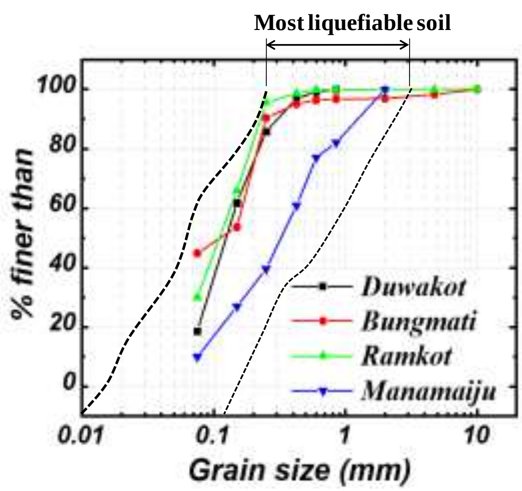

Figure 7.Typical particle size distribution of the soil at some liquefied sites. Range of most liquefiable soil after Tsuchida and Hayashi (1971).

Figures 8a and 8b show the liquefaction hazard maps prepared for the Kathmandu Valley by UNDP/MOHPP [24] and JICA [25] respectively. Most of these liquefied locations were indicated as the moderate to high liquefaction susceptibility zone by UNDP/MOHPP [25]. However, JICA [26] identified most of these locations as a non-liquefiable area even though the estimated ground motions in their research is higher than the observed ground motion in the Kathmandu Valley during the 2015 Gorkha earthquake. Both UNDP/MOHH [25] and JICA [26] considered magnitude of earthquake as 8.0 and the corresponding peak ground acceleration as 0.3g. While the observed peak ground acceleration in the Kathmandu Valley during 2015 Gorkha earthquake was about 0.18 g. The field observation clearly shows that the existing susceptibility maps are unrepresentative. In addition, this strongly indicates that soils in the Kathmandu Valley are highly prone to liquefaction and liquefaction assessment is of great importance to prepare for stronger earthquakes in the future.

The low liquefaction occurrence at the valley may be attributed to low amplitude of high-frequency shaking of the main shock. Peak ground motion observed in the Kathmandu Valley (about 0.18g) was lower than the estimated peak ground motion (about 0.3g) [25, 26] for these studies. Additionally, water levels were likely at their lowest levels because of dry season at the time of earthquake and/or rapidly sinking water table as a result of uncontrolled ground water withdrawal in the Kathmandu Valley which may have decreased the liquefaction potential. The lacustrine sediment might be insusceptible to liquefaction because of the fine grain-size distribution [12].

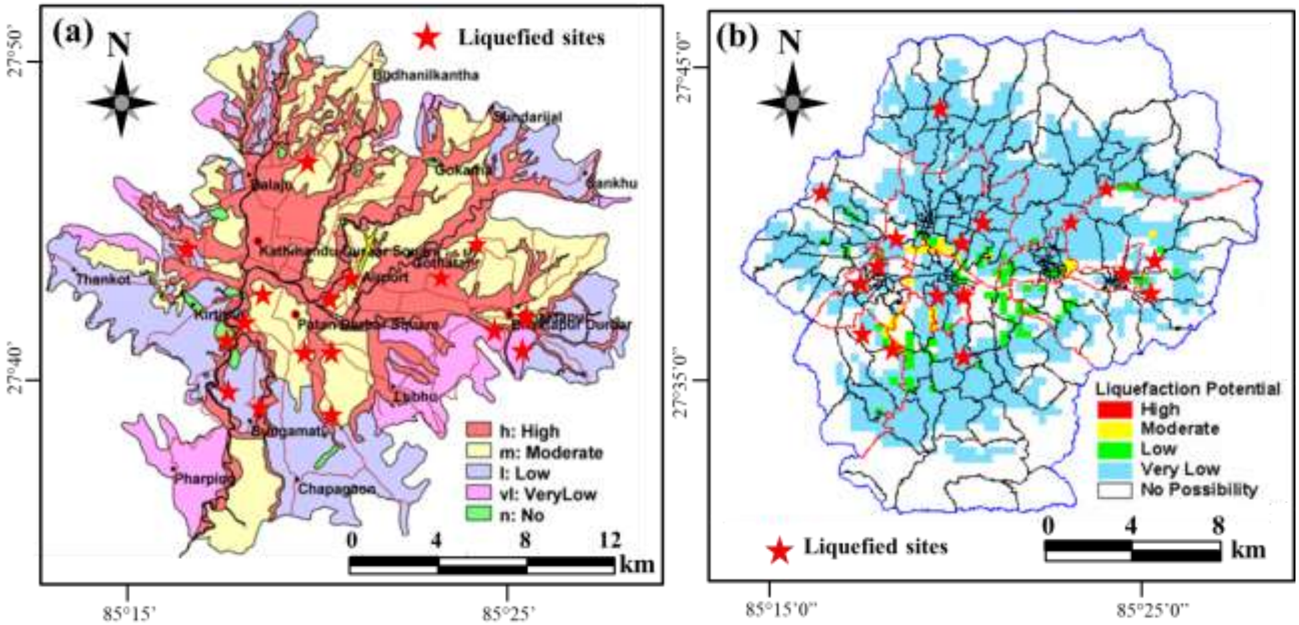

Figure 8. Liquefaction hazard maps with some typical liquefied site during 2015 earthquake (a) UNDP/MOHPP [25] and JICA [26].

CONCLUSIONS

The paper aims to investigate liquefaction phenomena in the Kathmandu Valley induced by the 2015 Gorkha earthquake. SPT site investigation at four liquefied sites were obtained and analyzed for the assessment of the liquefaction. The following conclusions can be reached.

1. At most sites, fine sand or non-plastic silts were ejected to agricultural fields forming deposits of a few centimeters thickness. Liquefaction-induced damage on building structures nearby the liquefied areas was not found except buildings on some places which tilted slightly.
2. Although the PGA observed during the earthquake in valley was much smaller than that expected (i.e. 300 cm/s^2), extensive soil liquefaction was observed at several localized area in the Kathmandu Valley. This highlights that the Kathmandu Valley is highly prone to liquefaction and liquefaction assessment is of great importance for seismic mitigation.
3. It was found from observations along with the results from liquefaction assessment that the existing hazard maps are unrepresentative and underestimate the liquefaction susceptibility in the Kathmandu Valley.
4. Liquefaction triggered by the M_w 7.8 Gorkha earthquake were limited and localized. This may be attributed to existing lacustrial soils, low-amplitude motions, and low ground water table at the time of earthquake.

Since the damage to buildings and other infrastructure in the Kathmandu Valley is linked with local ground conditions. Comprehensive geotechnical investigations should be carefully planned and executed in order to accurately characterize seismic response of soft sedimentary deposits and liquefiable soil deposits (seismic microzonation), and take it into consideration in the reconstruction works and development plan. Critical infrastructures such as hospitals, public buildings, police stations and life line services located on highly liquefiable area should be relocated or retrofitted to the meet functional requirement of those structures immediately after the earthquake.

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