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Liquefaction Susceptibility Mapping of Kathmandu Valley

Ashish Bastola [1], Indra Prasad Acharya [2]

[1, 2] *Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal*
Corresponding Email: [1] bastola.ashish@gmail.com

Abstract

Kathmandu valley has been established as being under high risk of liquefaction hazard during several studies by previous researchers. Eyewitness accounts and visitors log during the 1934 Nepal-Bihar earthquake mentions observations that may be attributed to liquefaction related phenomena. Furthermore, sand boils were observed at various places in Kathmandu valley during the 2015 Gorkha earthquake as well. This study attempts to identify the susceptibility of Kathmandu valley to liquefaction in light of recent development in this field. SPT based probabilistic model has been used for evaluation. Sixty borehole logs are evaluated taking reference of earthquake of magnitude 7.8 M_w and peak ground acceleration of 0.16 g. Probability of ground failure is computed, based on liquefaction potential index adjusted for probabilistic model. The probability of ground failure for various has been plotted in ArcGIS to prepare liquefaction susceptibility map for Kathmandu valley. The findings are found to be in agreement with observations made during the 2015 Gorkha, Nepal earthquake.

Keywords

Liquefaction Hazard – Susceptibility – Probabilistic Model

Introduction

The term liquefaction was originally coined by Mogami and Kubo (1953). It is defined as "transformation of solid to a liquefied state as a consequence of increased pore water pressure and reduced effective stress [1]. Increased pore pressure is caused by tendency of granular material to compact when subjected to cyclic loading.

Liquefaction has been proven to be one of the primary cause associated with destruction during earthquake. Its strength was realized for the first time during 1964 Niigata, Japan earthquake and Prince William Sound, Alaska Earthquake. It led to large scale failure of buildings and other structure such as bridges. During the 1971 San Fernando and 1989 Loma Prieta earthquake in California, the 1995 Kobe earthquake in Japan, 1999 Koceali earthquake in Turkey and 1999 Chi-Chi earthquake in Taiwan, similar effects due to liquefaction were be observed. Widespread liquefaction related ground failure were observed during 2010-2011 Christchurch, New Zealand earthquake inflicting financial loss worth 25-30 million NZ dollars [2].

Kathmandu lies in the center of the long Himalayan chain. It occupies active seismic zone with Indian Plate in south undergoing subduction beneath Tibetan plate in north at the rate of 20 mm per year. This region has experienced several big earthquakes in the past and at regular interval. There have been numerous devastating earthquake in the past such as in 1934, 1960, 1988 and 2015. Earthquake of magnitude greater than 8 have occurred every 80 years on average (NSET, 2008).

The deposit of Kathmandu valley is lacustrine and fluvial in origin with thickness up to 500m in the central region, formed during Holocene era. The explained evidence after the 1934 earthquake in the book entitled "Nepal Ko Mahabhukampa" indicates widespread liquefaction occurrence in Kathmandu valley (Rana, 1934). Water is said to have poured out from nine to fifty meter cracks in the fields and road, as rivers, including Bagmati and Bishnumati, flooded, some reaching as high as seven to ten feet. In Balaju and Sankhamul, parts of road caved in by a couple of feet [3].

During 2015 Gorkha earthquake, with main event measuring 7.8MW in magnitude [4], liquefaction was triggered at several places in the valley. Surface manifestations of liquefaction were clearly visible at several places in the form of sand boils, cracks on ground surface and bearing capacity failure in buildings. Locals stated that sand boil was ejected up to 1 m above the ground surface in Manmaiju. Similarly, large lateral cracks with 2 m deep fissure and up to 1.2 m vertical offset had occurred over a large area on or near sloping ground.

Figure 1: Large sand boils in a field at Manmaiju during the 2015 Gorkha, Nepal earthquake [4]

"UNDP/UNCHS/Habitat project for seismic hazard and Risk assessment for Nepal" had prepared liquefaction hazard map of Kathmandu valley in 1994. The work was based on the methodology of Juang and Elton (1991) using scoring system. They used surface geological map and lithological information from 123 borehole logs collected within the valley. According to the study, 25 percent of total study area possesses highly susceptible soil, about 11 percent has low, 35 percent has moderate and 29 percent has very low susceptible soil.

[5] studied 185 well logs, over 30m deep, and 328 shallow borehole logs with few reaching up to 30m depth, using Seed and Idriss (1971) and Iwasaki (1984) methods. Piya found that over 32 percent of total area was under high susceptible zone, which included most of the flood plain and some core city area. About 30 percent occupied moderate susceptibility zone, 25 percent low and 12 percent of land had very low susceptibility. The low to very low region was found to be distributed along southern part of the valley, including Kirtipur and Chobhar.

Out of 66 borehole logs studied by Marasini and Oakmura (2014), only 18 boreholes were found to have factor of safety higher than 1 with rest having factor of safety less than one in almost all layers of soil deposit.

1. Methodology

The evaluation of liquefaction potential was done in two stages. The first step was to determine whether the site of interest contained soil layer(s) that are capable of liquefying or not. The aim in this stage was to seek for indications of low potential for liquefaction failure. The first such indicator is plasticity index: soil having plasticity index higher than 12 is considered not to participate in liquefaction [6]. The second indicator is ground water table. Soil strata below 15 m are not considered to have major influence on ground surface condition [7], even if they undergo liquefaction. So, the aim was to identify locations having ground water table below 15 m depth and label them as not susceptible. Sandy soil with SPT more than 30 is considered too dense to liquefy [1]. So, soil strata having SPT value more than 30 are excluded from further analysis. The above mentioned steps comprises 'Screening Evaluation'. The next step in liquefaction evaluation is quantitative evaluation of liquefaction potential.

1.1 PGA and Magnitude of Earthquake

The 2015 Gorkha Nepal earthquake scenario has been used as model earthquake scenario. According to Gorkha Earthquake Report [4], peak ground acceleration was measured 0.16 g in Kathmandu valley and the earthquake had magnitude of 7.8 M_w.

1.2 Selected Model and Analysis Procedure

The quantitative evaluation in this study is based on probabilistic model suggested by [8]. It is an SPT based liquefaction evaluation procedure. The model was suggested by Cetin in 2000 in his dissertation.

SPT values were first normalized as per the recommendations of 1996, 1998 and 2003 NCEER/NSF workshops [1].

$$N_{160} = N_m C_N C_E C_B C_R C_S \tag{1}$$

where, C_N is overburden correction factor, C_E is hammer energy correction factor, C_R is rod length correction factor, C_B is correction factor for borehole diameter and C_S is sampler correction factor.

Eqn 2 is the summarized equation for the evaluation of probability of liquefaction [8].

$$P_L = \phi\left(-\frac{N_{1,60} * (1+0.004*FC) - 13.32*\ln CSR_{eq} - 29.35\ln M_w - 3.7*\ln\left(\frac{\sigma'_v}{P_a}\right) + 0.05*FC + 16.85}{2.7}\right) \quad (2)$$

where, P_L is probability of liquefaction, FC is fines content, ϕ is standard cumulative normal distribution,, $N_{1,60}$ is corrected SPT value, CSR_{eq} is equivalent cyclic stress ratio and P_a is atmospheric pressure (100 kPa).

To evaluate CSR_{eq}, total overburden stress σ and effective overburden stress σ' upto the required depth were evaluated. Magnitude scaling factor MSF and depth reduction coefficient r_d were also calculated based on [1].

$$CSR_{eq} = 0.65\frac{a_{max}}{g}\frac{\sigma_v}{\sigma'_v} r_d * MSF \quad (3)$$

The effect of liquefied soil upon ground surface featutes decreases with increase in its depth. To account for such bias due to depth of liquefied soil strata, liquefaction potential index was suggested in 1982 by Iwasaki [9]. The model proposed by Iwasaki was for deterministic method of liquefaction evaluation, based on factor of safety. However, it was modified by [10] in 2006 to account for probabilistic model as well.

$$LPI = \int_0^{20} F w(z)\, dx \quad (4)$$

where, LPI stands for liquefaction potential index, F is a function of probability of liquefaction P_L and $w(z)$ is function of depth of soil strata z.

$$F = P_L - 0.35 \quad (5)$$

$$w(z) = 10 - 0.5*z \quad (6)$$

Then, probability of ground failure P_G was calculated based on liquefaction potential index [10] and liquefaction susceptibility map was prepared using ArcGis.

$$P_G = \frac{1}{1+\exp^{4.71-0.71*LPI}} \quad (7)$$

2. Results and Discussions

Sixty borehole logs were considered for analysis. Locations of the boreholes are shown Figure 2. All computations were performed in MS Excel spreadsheets. The results obtained were plotted using ArcGIS. The susceptibility map, shown in Figure 3 , was prepared with 2015 Gorkha earthquake as scenario earthquake, with magnitude of 7.8MW and PGA value of 0.16g.

The study was done for borehole up to 15m in depth as recommended by Kramer [7]. Data were first screened during preliminary investigation and remaining data were analyzed quantitatively. The procedure outlined in methodology was followed for quantitative evaluation.

The regions shown in red are at very high risk and those in grey are areas having no risk of liquefaction at all. It was found that 32.57 percentage of total area of Kathmandu valley is at very high risk of liquefaction hazard under aforementioned conditions. However, the numbers differ for different magnitude of earthquake and PGA values. For example, for PGA value of 0.2g and 0.3 g, 48.59 and 52.36 percentage of area was found to be at very high risk of liquefaction respectively. The value is much higher than that suggested by UNDP/UNCHS, which was also based on PGA value of 0.3g, however only 25 percentage of total area of Kathmandu valley was found to be having high susceptibility.

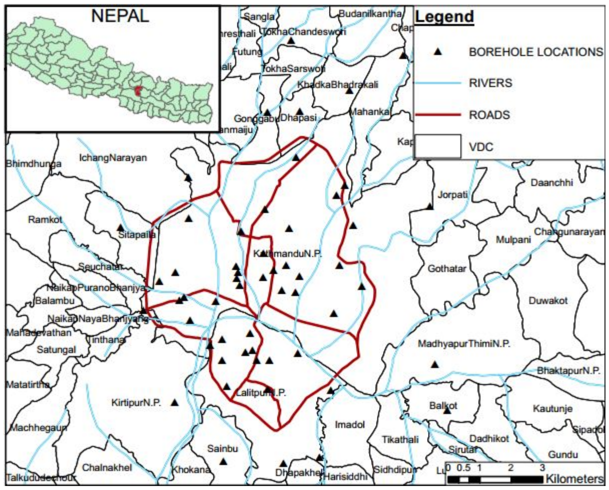

Figure 2: Location of Boreholes used in this study

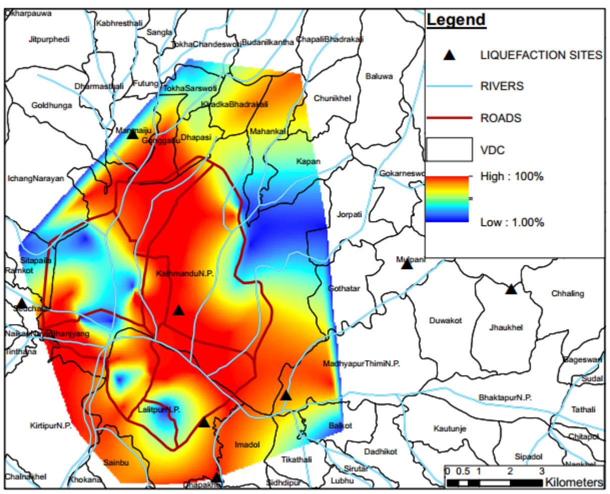

Figure 3: Liquefaction Susceptibility Map of Kathmandu valley, along with places where liquefaction was observed during the 2015 Gorkha earthquake

Table 1: Area(%) under different risk zone for MW = 7.8 and PGA = 0.16 g

PGA	RISK				
	NO	LOW	MEDIUM	HIGH	V. HIGH
0.16g	3.17	10.25	31.53	22.49	32.57

The relationship between probability of liquefaction and SPT value and probability of ground failure and depth of groundwater table are shown in Figures 4 – 11. It was found that, probability of liquefaction has strong relationship with SPT value and varied inversely. For

Table 2: Area (%) under Different Risk Zone for various values of PGA ($\#Mw = 7.8$) and Earthquake magnitude($*PGA = 0.16g$)

	RISK				
	NO	LOW	MEDIUM	HIGH	V.HIGH
0.16g#	3.17	10.25	31.53	22.49	32.57
0.2g#	0.88	7.43	22.96	20.14	48.59
0.3g#	0.73	6.65	21.07	19.2	52.36
6 Mw*	92.92	4.6	2.36	0.107	
7 Mw*	22.3	18.11	34.56	14.76	10.26
8 Mw*	2.3	8.46	26.67	24.54	38.01

Table 3: Number of locations (out of 60) under different levels of risk with different depths of ground water table

GWT	RISK				
	NO	LOW	MEDIUM	HIGH	V.HIGH
0 m	7	1	0	2	50
5 m	12	2	0	2	44
10 m	23	1	5	10	21
15 m	60	0	0	0	0

borehole number 2 from Newroad, probability of liquefaction for layers with SPT values 20, 21 20 and 22 were found to be 99.9%, 97%, 44% and 36% respectively. Such inconsistency can be attributed to variation in fines content of corresponding strata. Similar observations were made by Neupane and Suzuki as well. Similarly, another important factor that influences the effects of liquefaction is groundwater table. The probability of surface manifestation of liquefaction was found to decrease with increase in depth of ground water table. Below 6m depth, chances of surface manifestation of liquefaction, under 2015 like earthquake event, were found to be very slim in all three cases shown below. However, the value was found to be significant for Anamnagar, Bhanimandal, Baneswor, Sankhamul, etc. for water table as deep as 10m. This may be a reason for small number of liquefaction related issues in the recent 2015 Gorkha Earthquake. On the basis of findings of this study and previous literature, it is evident that some parts of Kathmandu valley pose high risk liquefaction. Eyewitness account of 1935 Nepal-Bihar earthquake suggests occurrence of ground oscillation and fountains as high as 3-4m (Rana

1935). With magnitude of earthquake 8.0, JICA's study on the disaster assessment estimated, 1.3% of population would die and another 3.8% would be seriously injured (JICA 2002) and much of the damage in lifeline services in valley would create impact on urban population. To prevent and mitigate the probable disaster in future, it is of prime importance that detail studies are carried about the effects of liquefaction in the valley, along with geotechnical evaluation of the deposits of the valley and empirical method of studying liquefaction behavior of sand deposit in the valley is an appropriate tool for the identification of safe and unsafe zone against liquefaction for particular area. The region receives heavy rainfall for three months in a year in the form of monsoon. Thus, there is heavy fluctuation of ground water table throughout the year, however mean ground water table in Kathmandu valley is found to lie between 5 - 9 m. It is found that, more than half of the locations studied lie in very high risk in terms of liquefaction with ground water table between 5 – 10 m. The data changes with ground water table as shown below:

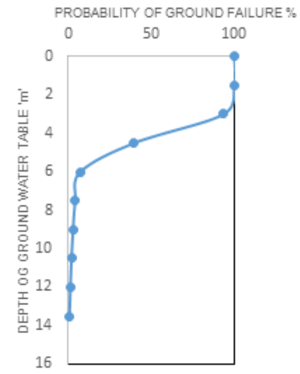

Figure 5: Probability of Ground failure vs Depth of Ground water table (Putalisadak)

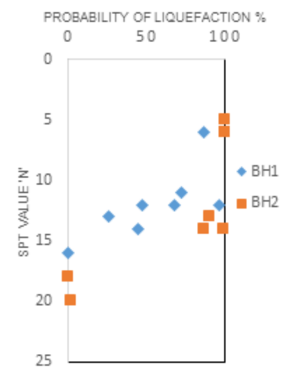

Figure 6: Probability of ground failure vs SPT (Gongabu)

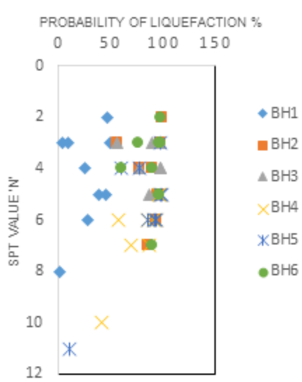

Figure 4: Probability of Liquefaction vs SPT Value (Putalisadak)

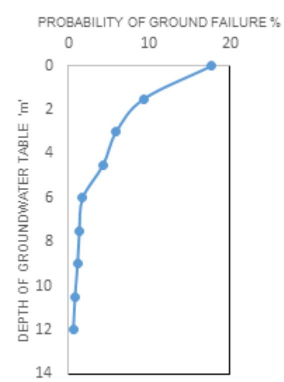

Figure 7: Probability of ground failure vs Depth of ground water table (Gongabu)

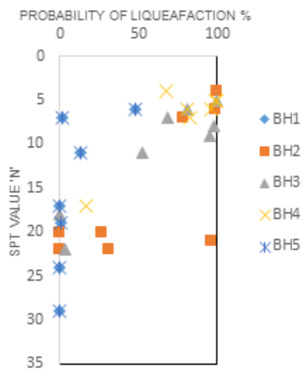

Figure 8: Probability of liquefaction vs SPT value (Newroad)

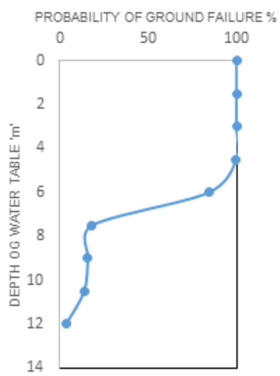

Figure 9: Probability of ground failure vs depth of water table (Newroad)

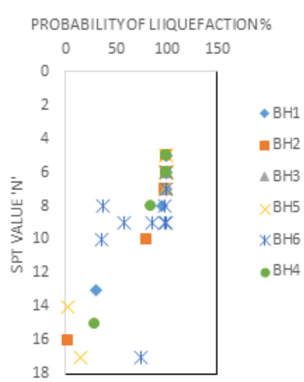

Figure 10: Probability of liquefaction vs SPT value 'N' (Anamnagar)

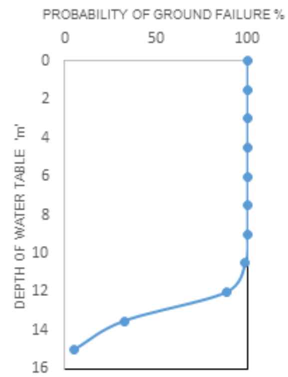

Figure 11: Probability of ground failure vs depth of ground water table (Anamnagar)

3. Conclusions

Evaluation of liquefaction potential of a densely populated city like Kathmandu is a complex and multi-disciplinary undertaking. In this paper, soil liquefaction potential has been evaluated using model suggested by Cetin et al., and Li et al. Although data constraint has prevented more refinement, the authors believe that this zonation has identified hazardous region within the valley pretty well.

1. The probabilistic liquefaction potential evaluation using borehole logs from different regions of Kathmandu valley showed that 33 percentage of total area of Kathmandu valley lies in very high risk zone and 22.5 percentage of area in high risk zone. 3 percentage of total area was found to be risk free under the 2015 earthquake scenario.

2. Probability of liquefaction was found to be strongly influenced by SPT value. It was found to generally decrease with increase in SPT value. However, inconsistency in this general rule arose in several cases due to large variation in fines content. Increase in fines content leads to reduction in liquefaction potential of soil.

3. The extents of effects of liquefaction are found to be governed largely by depth of water table. The ground level manifestation of liquefaction was found to decrease exponentially with increase in depth of water table as shown in above figures.

However, not all locations are found to respond in similar fashion to fluctuation in water table. Out of 60 locations, 29 were observed to be in very high risk with water table as deep as 10m. Similarly, for water table at depth of 5m, 35 locations were found to be at high risk of liquefaction. Thus, we see that potentially quantifiable soil are present up to significant depth in Kathmandu valley.

4. The results of the study showed some agreement with previous studies. The study done by MOHPP /UNDP 1994, had shown that Singadurbar, Maharajgunj and Jamal were in high potential zone, agreeing with findings of the study.

5. It was found imperative that liquefaction hazard be studied in light of intensity of earthquake. It was found to vary acutely with change in magnitude of earthquake and PGA values. So, detailed seismic hazard analysis of the region is necessary.

6. Five of the liquefaction sites during 2015 Gorkha earthquake were found to lie within study area and all these sites were found to lie in zones identified as very high and high potential zone by this study.

7. The deposit of Kathmandu valley is highly heterogeneous. A detailed geological investigation of the deposit must be done in order to determine optimum distance required between two borehole logs, so that more reliable liquefaction hazard map can be prepared.

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