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Liquefaction Potential Assessment of selective sites inside Kathmandu Valley considering different Earthquake Scenarios and comparison with existing Liquefaction Susceptibility Maps

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Abstract

Kathmandu is the Capital city and lies in highly earthquake prone region of Nepal. There have been cases of liquefaction in Valley after the 1934 Bihar-Nepal earthquake, 1988 Nepal earthquake and 2015 Gorkha Earthquake. Various studies have been done in the field of liquefaction by various researchers and liquefaction Susceptibility maps have been generated. Most researches have relied on finding out Factor of Safety but, liquefaction occurring due to 2015 Gorkha earthquake show that previously generated maps are not representative and need to be reviewed. Here, Liquefaction potential of Kathmandu has been studied analyzing Standard Penetration Test (SPT) data of 25 sites and 124bore holes and Liquefaction Potential Index (LPI) and Factor of Safety have been found out for various conditions and have been compared with previously generated maps.

Keywords

Earthquake, Liquefaction, Liquefaction Potential Index, Liquefaction Susceptibility

1. Introduction

Liquefaction is loss in shear strength of granular saturated deposits due to increase in pore water pressure by earthquake. The soil liquefaction depends on the magnitude of earthquake, intensity and duration of ground motion, the distance from the source of the earthquake, site specific conditions, ground acceleration, type of soil and thickness of the soil deposit, relative density, grain size distribution, fines content, plasticity of fines, degree of saturation, confining pressure, permeability characteristics of soil layer, position and fluctuations of the groundwater table, reduction of effective stress, and shear modulus degradation (Kramer, 1996; Youd et al., 2001).

The deposition in the Kathmandu Valley is lacustral and fluvial in origin with a maximum thickness of 500 m (Subedi et al. 2013). The deposited sediments are usually a mix of clay, silt, sand, and gravel. After the devastating Mw 8.2 Bihar-Nepal earthquake in 1934, the occurrence of liquefaction case studies at many places in the Kathmandu Valley was reported by Rana (1935). Liquefaction susceptibility analysis conducted by UNDP/MOHPP (1994) and Piya (2004) for an M7.8 scenario earthquake and a peak ground acceleration of approximately 0.3 g showed the liquefaction potential in the Kathmandu Valley. Liquefaction susceptibility was classified as "high" and "medium" in areas along the major rivers. Subedi et al. (2013) also evaluated the liquefaction potential of soils in the Kathmandu Valley using empirical relations based on the Standard Penetration Tests (SPT).

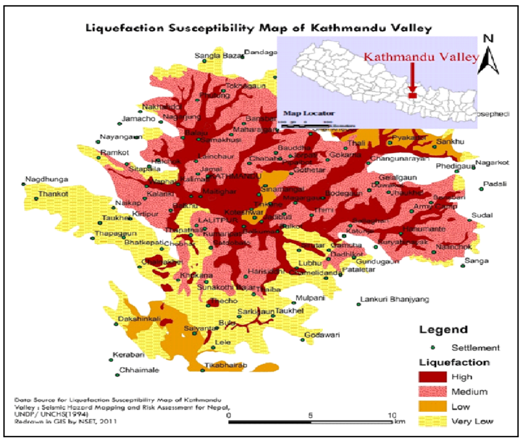

Figure 1: Liquefaction Susceptibility Map of Kathmandu Valley.UNDP/UNCHS(1994)

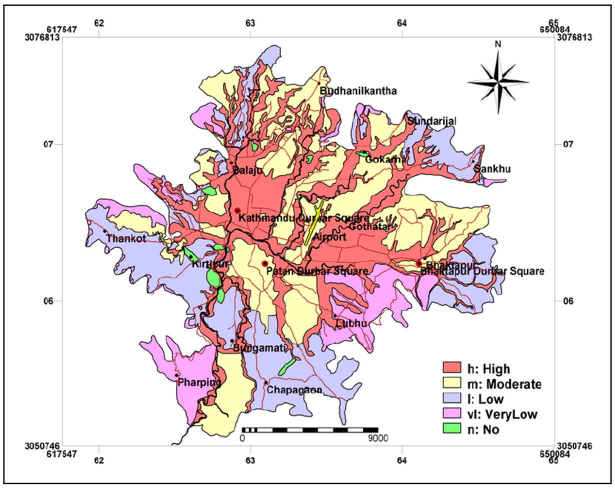

Figure 2: Liquefaction Susceptibility Map of Kathmandu Valley after Piya (2004)

The liquefaction potential assessment in the Kathmandu Valley has relied almost exclusively on SPT blow counts and borehole data (Piya 2004; Subedi et al. 2013). Recently Sharma et al. (2017) and Gautam et al. (2017) concluded that the existing susceptibility maps are unrepresentative and highlighted the urgent need of new map using updated methodologies. Existing maps are based on very limited SPT data, used old methodologies, calculated FS, not LPI. e.g. UNDP (1994): 123 bore holes for map generation which can't be representative.

2. Methodology

The stress-based approach suggested by Idriss and Boulanger (2008) was adopted to perform an analysis of the factor of safety (FS) with respect to liquefaction on each layer and Iwasaki et.al. (1982) method was used to estimate the liquefaction potential index (LPI) of the sites. In this method, the stress (loading) that results in liquefaction is defined as the cyclic stress ratio (CSR), and the property of the soils to resist liquefaction is termed as the cyclic resistance ratio (CRR).

The FS with respect to liquefaction can be calculated using Equation 1:

$$FS = \frac{CRR}{CSR} \quad (1)$$

Here, CRR=$CRR_{7.5}$*M.S.F*Kσ

Where, $CRR_{7.5}$ is the cyclic resistance ratio calibrated for the earthquake of magnitude 7.5; MSF is the magnitude scaling factor that accounts for the effects of shaking duration and Kσ is a factor for the presence of sustained static shear stresses, such as may exist beneath foundations or within slopes.

MSF and Kσ were calculated using Equation 2 (Idriss and Boulanger 2008):

$$MSF = 6.9e^{-\frac{M_w}{4}} - 0.058 \ (\leq 1.8)$$

$$K_\sigma = 1 - C_\sigma \ln\left(\frac{\sigma_v'}{P_a}\right) \leq 1.1$$

$$C_\sigma = \frac{1}{18.9 - 2.55\sqrt{(N_1)_{60cs}}} \leq 0.3 \quad (2)$$

The available SPT N value was used for the estimation of CRR. The available SPT N value was corrected using Equation 3:

$$(N_1)_{60} = NC_N C_E C_B C_R C_S \quad (3)$$

where, $(N_1)_{60}$ is the SPT blow count normalized to an overburden pressure of 101 kPa and a hammer efficiency of 60 percent, N is the measured SPT blow count, and $C_N C_E C_B C_R C_S$ are the correction factors for the overburden stress, hammer energy ratio, borehole diameter, rod length and samplers with or without liners, respectively.

The $CRR_{7.5}$ is calculated by Equation 4 (Idriss and Boulanger 2008).

$$CRR_{7.5} = \exp\left(\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right) \quad (4)$$

where, $(N_1)_{60cs}$ is an equivalent clean-sand SPT blow count. Equation 4 provides a significantly improved basis for engineering assessment of the likelihood of liquefaction initiation for earthquake of magnitude 7.5 (Idriss and Boulanger 2008). Equations 5 and 6 are used to calculate $(N_1)_{60cs}$:

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \quad (5)$$

$$\Delta(N_1)_{60} = \exp\left(1.63 + \frac{9.7}{FC+0.01} - \left(\frac{15.7}{FC+0.01}\right)^2\right) \quad (6)$$

where FC is the fines content in the soils.
The CSR is calculated by Equation 7:

$$CSR = 0.65\frac{\tau_{max}}{\sigma'_{vc}} = 0.65\frac{\sigma_{vc}}{\sigma'_{vc}}\frac{a_{max}}{g}r_d \quad (7)$$

where: a_{max} is the peak horizontal acceleration at the ground surface, g is the gravitational acceleration, σ_{vc} and σ'_{vc} are the total overburden stress and effective overburden stress respectively, and r_d is the stress reduction coefficient given by Equation 8:

$$r_d = exp\left[-1.012 - 1.126sin\left(\frac{z}{11.73} + 5.133\right) + M_w\left(0.106 + 0.118sin\left(\frac{z}{11.28} + 5.142\right)\right)\right] \quad (8)$$

where: z is the depth of soil layer in meter.

For predicting the severity of liquefaction at a site through considering the soil profile in the top 20 m, the LPI is calculated using Equation 9 (Iwasaki et al. 1982):

$$LPI = \int_0^z F(z)W(z)dz \quad (9)$$

where z = depth of layer; F(z) = function of FS against liquefaction defined as F(z) = 1 for FS less than or equal to1 and F(z) = 0 for FS greater than 1, and W(z) = depth-weighting factor which equals 10-0.5z.

This approach integrates the FS of the upper 20 m soil column to obtain the liquefaction potential of a site. Based on the LPI value, liquefaction susceptibility of the site can be classified into four categories as: Very Low(LPI=0), Low(LPI less than 5), High(LPI between 5 and 15), and Very High(LPI greater than 15) (Iwasaki et al.1982).

3. Results and Discussions

3.1 Liquefaction Potential Assessment

Liquefaction potential of liquified (e.g. Imadol, Mulpani, and Duwakot) and non-liquified sites due to 2015 Gorkha earthquake was done. For the analysis 25 sites and 124 bore holes in different parts of Kathmandu Valley were used. Idriss and Boulanger(2008) method was used to estimate factor of safety and Iwasaki et al. (1982)method was used to find Liquefaction Potential Index.

SPT blow counts before the main shock were obtained and used for the analysis. The available SPT data were analyzed for four different scenarios:

1. Peak Ground Acceleration (PGA) of 0.18g, Moment Magnitude (Mw)=7.8 and Ground Water table on surface
2. Peak Ground Acceleration (PGA) of 0.18g, Moment Magnitude (Mw)=7.8 and Ground Water table according to field observations
3. Peak Ground Acceleration (PGA) of 0.3g, Moment Magnitude (Mw)=8 and Ground Water table on surface
4. Peak Ground Acceleration (PGA) of 0.3g, Moment Magnitude (Mw)=7.8 and Ground Water table according to field observations

The highest value of liquefaction potential index from each site was used to obtain liquefaction susceptibility of the site. The results were obtained as shown in table 1 (table shown on next page) :

The liquefaction susceptible sites were divided in four categories as Very Low, Low, High and Very High. The number of sites falling in each category are as shown in Table 2(table shown on next page) .

Sample plot of Factor of Safety against Depth in two liquified sites during 2015 Gorkha Earthquake is as shown:

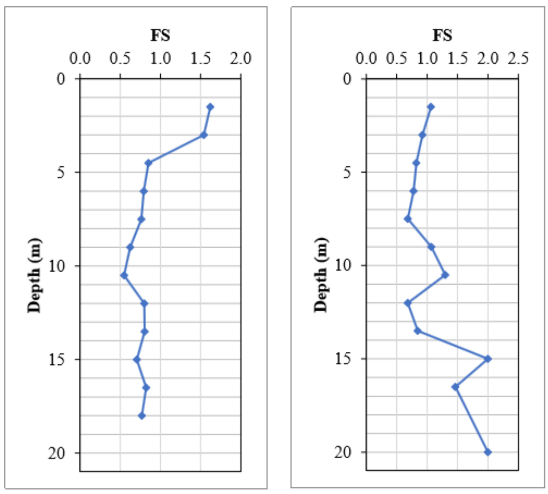

Figure 3: Plot of Factor of Safety with respect to depth in Imadole and Duwakot for PGA 0.18g, Mw=7.8 Considering Ground Water Table

The obtained Liquefaction Susceptibility results for four different scenarios were mapped as shown in Figures 4, 5, 6 and 7.

Table 1 : Liquefaction Potential Index and Liquefaction Susceptibility of Various Sites inside Kathmandu Valley for different earthquake, peak ground accelarations and ground water table scenarios

	0.18g Mw=7.8 GWT=0		0.18g Mw=7.8 GWT		0.3g Mw=8 GWT=0		0.18g Mw=8 GWT	
Sites	lpi	Potential	lpi	Potential	lpi	Potential	lpi	Potential
Anamnagar	3.7	Low	0.8	Low	17.9	Very High	9.0	High
Balkumari	0.3	Low	0.0	Very Low	8.7	High	7.5	High
Baneshwor	8.6	High	7.3	High	19.1	Very High	18.4	Very High
Bhaisepati	0.9	Low	0.0	Very Low	47.9	Very High	39.7	Very High
Bouddha	0.5	Low	0.0	Very Low	11.2	High	1.9	Low
Chhampee	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Duwakot	23.7	Very High	11.0	High	49.0	Very High	41.5	Very High
Gongabu	2.6	Low	0.5	Low	11.2	High	5.9	High
Gwarko	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Pulchowk	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Hattiban	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Imadol	25.7	Very High	16.5	Very High	54.7	Very High	40.8	Very High
Jhamsikhel	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Kalanki	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Kuleshwor	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Kumaripati	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Kupondol	6.6	High	0.0	Very Low	14.8	High	7.3	High
mulpani	11.6	High	3.5	Low	48.7	Very High	37.0	Very High
Nakkhu	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Rabibhawan	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Sukedhara	1.0	Low	0.8	Low	4.9	Low	2.1	Low
Civil mall	4.3	Low	2.5	Low	17.5	Very High	8.3	High
Teku	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Tokha	0.0	Very Low	0.0	Very Low	0.0	Very Low	0.0	Very Low
Wotu	12.9	High	1.5	Low	22.8	Very High	14.6	High

Table 2 Different Categories of Liquefaction Susceptibility for different Scenarios.

Condition	Very Low	Low	High	Very High
PGA=0.18g, Mw=7.8, GWT =0m	12	7	4	2
PGA=0.18g, Mw=7.8, with GWT	16	6	2	1
PGA=0.3g, Mw=8, GWT=0m	12	1	4	8
PGA=0.3g, Mw=8, with GWT	12	2	6	5

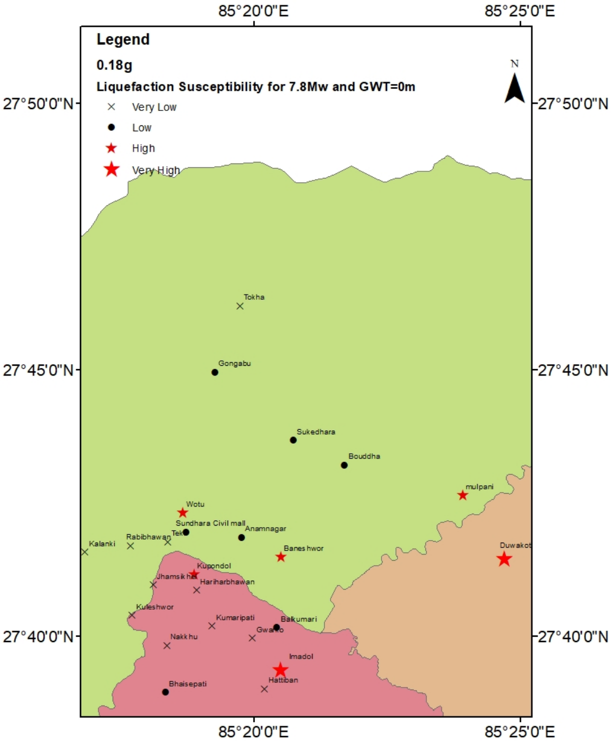

Figure 4: Liquefaction Susceptibility map for scenario 1

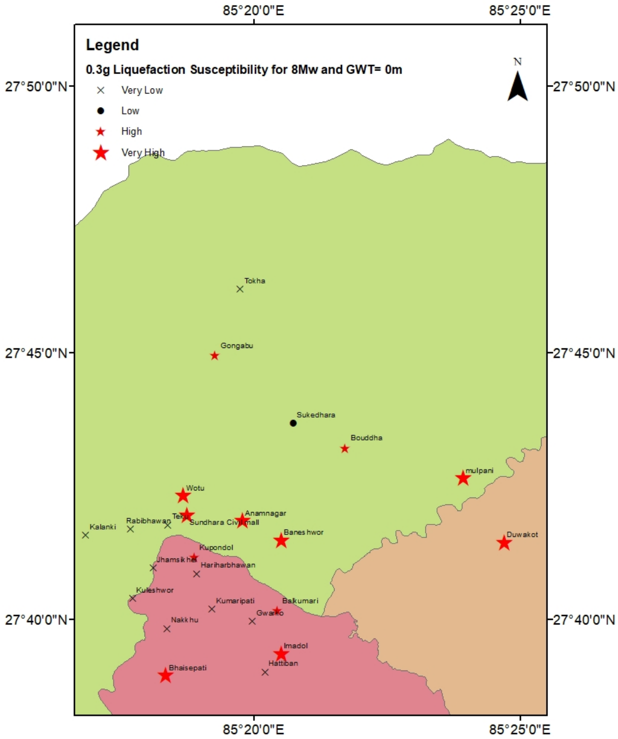

Figure 6: Liquefaction Susceptibility map for scenario 3

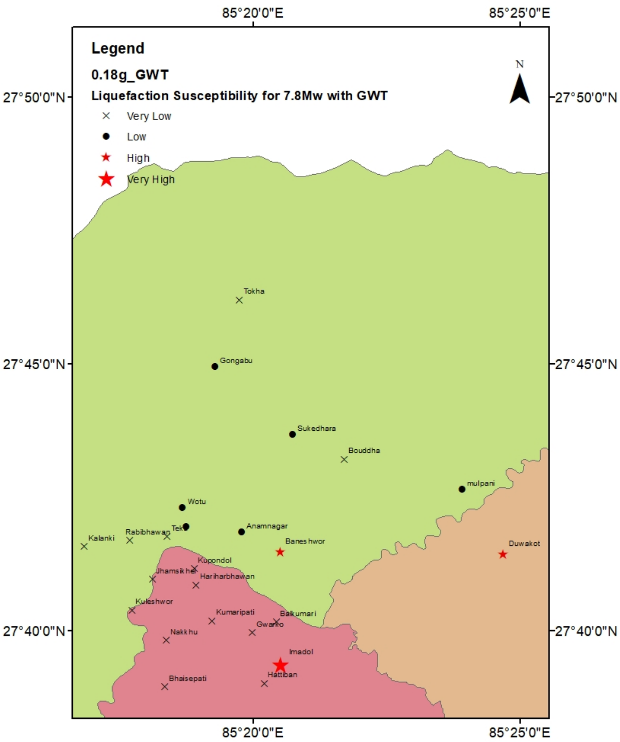

Figure 5: Liquefaction Susceptibility map for scenario 2

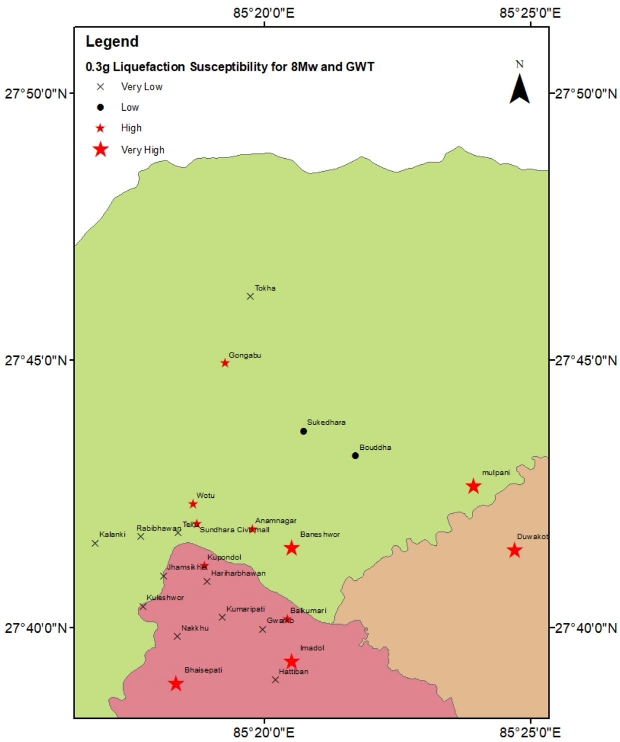

Figure 7: Liquefaction Susceptibility map for scenario 4

4. Conclusions

Factor of Safety and Liquefaction Potential Index were calculated using SPT data for various earthquake, ground acceleration and ground water table scenarios. Results were compared with available Liquefaction Susceptibility Maps. Analysis done on liquefied sites due to 2015 Gorkha Earthquake (PGA 0.18 g, Mw = 7.8) show factor of safety less than 1 in various layers and high to very high Liquefaction Susceptibility but some of these sites in previously generated maps were shown to be low to moderately liquefiable. It was found that the existing liquefaction potential maps are unrepresentative and underestimate the liquefaction susceptibility in Kathmandu Valley and those maps need to be modified using newly developed methodologies and updated using available geotechnical data.

Also, the results show that, low GWT and lower PGA during 2015 Gorkha Earthquake resulted in lower number of Liquefactions. But, higher GWT, higher PGA and higher magnitude of earthquake seems to increase liquefaction susceptibility in the Kathmandu Valley. The research is incomplete without the generation of Liquefaction Susceptibility Map. Hence, it is high time to generate the Liquefaction Susceptibility Map of the Kathmandu Valley using updated methodologies.

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