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Assessment and mapping of Liquefaction Potential of Chitwan by Deterministic and Reliability Approach

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Abstract

During Seismic activity, liquefaction is one of the effects which results in failure of structures, damage to property and loss of life. Nepal lies in one of the most seismically active regions in the world. Large number of earthquakes have occurred from past to till date in Nepal. The historical seismicity data and recent seismic activities in Nepal and adjoining areas indicate that Nepal is at high seismic risk. In chitwan district during 2015 Gorkha earthquake, sign of liquefaction was reported. So, liquefaction potential evaluation of selective areas of Chitwan district is done in this research. This study uses both deterministic and reliability technique for predicting the liquefaction potential of soils due to seismic activity of selective areas of Chitwan. In deterministic approach, liquefaction potential assessment is done by calculating factor of safety. Models and parameters involved in deterministic approach has certain uncertainties due to which different models give dissimilar safety factor. So, in order to deal with the different uncertainties involved in the deterministic approach, reliability analysis is required. Using reliability analysis, the liquefaction potential can be accessed in terms of the probability of occurrence of liquefaction. Liquefaction Potential Index is calculated using both deterministic and reliability method and comparison is done. Also factor of safety against liquefaction and liquefaction potential index are calculated at different earthquake scenarios and it is seen that with increase in magnitude and peak ground acceleration, the liquefaction potential of soil increases considerably. In this study liquefaction potential maps of some areas of Chitwan are generated and it is seen that at Gorkha earthquake 2015 magnitude 7.8 and PGA 0.192g, only some southern parts near to Rapti river tends to have very high liquefaction potential and from map generated using reliability method, it is seen that more areas are susceptible to very high liquefaction possibility.

Keywords

Liquefaction, Earthquake, Chitwan , Deterministic, Reliability, First order second moment(FOSM)

1. Introduction

Liquefaction is a effect due to earthquake loading which mostly occurs in loose saturated cohesionless soils. During earthquake shaking, the saturated soil loses its strength and the soil behave like a fluid. Soil behaving like fluid have no strength so the structures build over the soil get collapsed and may get sucked into the ground. Sometimes the underground structures such as pipelines may come to the surface as a result of liquefaction. During undrained loading condition, the pore pressure in the soil increases as a result liquefaction is initiated [1]. Under undrained loadings, the saturated loose sand tends to densify which results in rise of pore pressure, due to which the effective confining pressure decreases. As a result, there is decrease in the shear strength of the soil, which ultimately initiates liquefaction in the soil. [2].

Though, many liquefaction phenomena have been observed in past, but liquefaction process was given emphasized by engineers and seismologists of the world only after destructive earthquakes of Niigata (1964, Mw=7.6) and Alaska (1964, Mw=9.2). From then on numbers of field investigations as well as laboratory investigations on liquefaction process of soil have been performed which revealed that liquefaction of soil is a process in which under rapid loading saturated loose granular soil loses its strength as a result of increase in pore water pressure and decrease in effective stress. The liquefied soil has a certain fluidity enough to make movement from few meters to several kilometers. Several ground failures such as surface settlement, sand boil, lateral spreading, landslides, settling and tilting of buildings, severe damage to lifeline systems, failure of waterfront structures, lateral movement of bridge supports etc. can be caused by soil liquefaction. For occurrance of liquefaction, a high magnitude earthquake may not need to be necessary, a low magnitude earthquake of Mw=5 can initiates liquefaction process but at higher magnitude earthquake of Mw=5.5-6.0, the liquefaction cases gets increased [3]. Therefore, in tectonically active region it is necessary to evaluate liquefaction susceptibility of the area to assess the seismic hazard of the region.

2. Study Area

The study area is a part of Chitwan district in the central-southern part of Nepal located in Bagmati province as shown in Figure 1. It is situated between 27°33’48”N to 27°42’15”N (latitude) and 84°10’34”E to 84°40’09”E (longitude). The total area of the study area is about 526 km^2. The study area covers Bharatpur Metropolitan city, Ratnanagar Municipality, Khairahini Municipality and Rapti Municipality. Bharatpur, largest city of Nepal after Kathmandu, is its administrative centre. The total area of Bharatpur Metropolitan City is about 432.95 Km2 and Bharatpur is among the cities in Nepal which are rapidly developing. Bharatpur is a commercial as well as academic center of chitwan and surrounding districts. Narayani river, one of the major river of Nepal and largest of the chitwan district flows through district and on the eastern bank of this river, Bharatpur city lies. This river separates two districts Chitwan to the east and Nawalparasi to the west. Rapti river which run through the center of district from east to the west is the second largest river in the district.

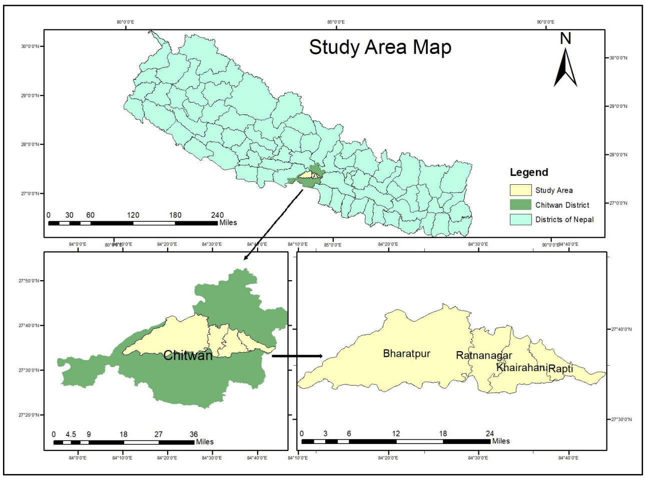

Figure 1: Study Area of the research

2.1 Geology of the area

Chitwan is a dun valley also called as Intermontane valley (an alluvial basin) trending in NNW–SSE situated within the Siwalik Hills of the Nepal Himalaya. It is also called inner Terai (Bhitri Madhesh) which is a plain land. Chitwan is a river valley in which Narayani River and Rapti River transports the sediments to the west and to the east respectively.

The valley consists of Terai, Siwalik, and the Mahabharata Range based on physiography and the Siwalik region is the largely populated area. Soft sandstone, mudstone and conglomerate encircle the valley, whereas the central part of the valley which is a low-lying plain land, consists of silt, sand, and gravel [4, 5]. There is a broad alluvial fans deposition in the eastern valley floor due to small rivers originating from the lower himalayan region. Narayani River deposited alluvial sediments are on the floor of basin in the west [6].

Deposits in Chitwan’s valley comprise of channel deposits, alluvial fan deposits and overbank deposits which are being accumulated from Pleistocene and Holocene age. This deposits are still being continously deposited to the present day. The study area consists of alluvial deposits by Narayani river which comprises of swamp, levee and riverbed sediments. The soil deposits in Chitwan dun are grouped as Bharatpur Sand, Narayanghat Sand and Devghat Gravel. Unsorted sediments pebble,boulder forms Bharatpur sand while Narayanghat Sand consists of fine to coarse sand. Similarly gravel, pebbles/cobbles/boulder forms Devghat Gravel [7]. The geology of the study area comprises of recent as well as old alluvium, which constitute river deposited alluvial sediments of mostly coarse and fine sand, boulder, gravel, silt and clay. New sediments which are brought down every year by active streams overlap the recent alluvial deposits, which engage themselves in fluvial process [8].

2.2 Seismicity of the area

Six great/large damaging earthquakes having magnitudes greater than or equal to 7.6 (in years 1255, 1408, 1505, 1833, 1934, and 2015) and several strong earthquakes since 1255 were experienced in Nepal in the past [9]. These earthquakes have caused significant damages with large human casualties and huge physical loss. Past events of earthquake and recent research on seismological studies have clearly showed that the whole region of Nepal lies in the active seismic zone and is prone to large earthquakes. From the research, it was found out that frontal part of the Higher Himalaya, lesser Himalaya and Siwalik are the most vulnerable zones.

As a result of thrusting in the Main Frontal Thrust (MFT), Frontal Churia (Siwalik) Range is formed on the south of Chitwan Dun. Also, the north of the Chitwan Dun valley is bounded by Siwalik ranges (Inner Churia Ranges) which is developed by thrusting action in the Central Churia Thrust (CCT). To the north of the Inner Churia Ranges, Lesser Himalayan Mahabharat Range lies. In the last few centuries, there is absence of great earthquakes (Mw >8) in the region around the Chitwan Dun. In the north of the Chitwan Dun, Gorkha earthquake 2015 was originated which also doesnot create any rupture on the surface along the Himalayan Front. [10] pointed the chances of future seismic hazards in the dun valleys of Central Nepal due to movement of Indian plate towards and under Eurasian plates along the Central Himalaya and also due to the inability of propagation of rupture to southwards due to the Gorkha earthquake, there is accumulation of stresses in the Sub- Himalaya in Central Nepal. In Chitwan Dun, various active out-of-sequence thrust segments have also been recognised which are displacing Quaternary landforms to the north of Main Frontal Thrust. Thus, during any future large magnitude earthquakes, the potential of formation of surface rupture rises due to all these identified active thrusts in the Chitwan valley [10].

According to a new seismic zoning map of Nepal in NBC 105: 2020 published by the Department of Urban Development and Building Construction (DUDBC), the PGA during an earthquake could be as high as 0.3g to 0.4g based on a probabilistic seismic hazard assessment with 10% probability of exceedance during the 50 years of study period

3. Materials and Methods

3.1 Data collection

SPT data and laboratory tests data of 86 boreholes in Chitwan are collected from different geotechnical laboratories and consultancies and used in this research. Ground Water table(GWT) is found to be shallow during Monsoon season, so for this study GWT is assumed at surface for considering worst case.

3.2 Methods

3.2.1 Deterministic Approach

The stress-based approach suggested by Youd and Idriss [11] was used for the analysis of liquefaction potential of soil and calculation of factor of safety (FS) against liquefaction on each soil layer. For the evaluation of liquefaction resistance of soils, two variables are calculated which are cyclic stress ratio (CSR) and cyclic resistance ratio (CRR). CSR is the seismic demand due to earthquake on a soil layer and CRR is the strength of the soil to resist liquefaction.

The CSR is computed from the equation given below:

$$CSR = 0.65\left(\frac{\sigma_{vo} a_{max}}{\sigma'_{vo} g}\right)\frac{r_d}{MSF} \tag{1}$$

where, CSR is evaluated at 1 atm effective stress,
σ_{vo} = total overburden pressure,
σ'_{vo} = effective overburden pressure,
a_{max} = peak horizontal acceleration at the ground surface,
r_d = stress reduction factor,
MSF= magnitude scaling factor and
g= acceleration due to gravity.
For estimating the average values of r_d, equations given below are used [12]:

$$r_d = 1 - 0.00765z \qquad for(z \leq 9.15) \tag{2a}$$

$$r_d = 1.174 - 0.0267z \quad for(9.15 < z \leq 23) \tag{2b}$$

where z is the depth in meters.

The MSF expression as recommended by Youd and Idriss [11] is given below:

$$MSF = \frac{10^{2.24}}{M_w^{2.56}} \tag{3}$$

The field N values recorded are corrected using various corrections factors such as overburden correction, energy correction,etc. Following equation is used for estimating the corrected N values:

$$(N_1)_{60} = NC_N C_E C_B C_R C_S \tag{4}$$

Where $(N_1)_{60}$ is the N value normalized to a 100kPa of overburden pressure and 60% of hammer efficiency.

N is the no. of blows observed in field and C_N, C_E, C_B, C_R, C_S are the correction factor for overburden pressure, hammer efficiency ratio, borehole diameter, rod length, sampler with or without liner respectively. As granular soil comprising greater fine content, FC, results in rise in penetration resistance of soil. Thus the corrected SPT count, i.e., $(N_1)_{60}$ are again corrected for fine content. For fine content(FC) correction for $(N_1)_{60}$ to an equivalent clean sand value $(N_1)_{60cs}$, following expression is used:

$$(N_1)_{60cs} = a + b(N_1)_{60} \tag{5}$$

where a and b are coefficients calculated using following relationships:

$$a = 0, b = 1 \qquad for(FC \leq 5\%) \tag{6a}$$

$$a = \exp\left[1.76 - \left(\frac{190}{FC^2}\right)\right] \tag{6b}$$

$$b = \left[0.99 - \left(\frac{FC^{1.5}}{1000}\right)\right] \qquad for(5 < FC < 35) \tag{6c}$$

$$a = 5, b = 1.2 \qquad for(FC > 35) \tag{6d}$$

The CRR of cohesionless soil is estimated by the following expression for any fine content:

$$CRR_{M=7.5} = \frac{1}{34 - (N_1)_{60cs}} + \frac{(N_1)_{60cs}}{135} + \frac{50}{[10(N_1)_{60cs} + 45]^2} - \frac{1}{200} \tag{7}$$

The above equation is only applicable for $(N_1)_{60cs} < 30$. For $(N_1)_{60cs} \geq 30$, the soil offers more resistance to liquefaction as soils are too densely packed and are categorized as non-liquefiable.
Finally for the evaluation of liquefaction, factor of safety (FS) is estimated, which is the ratio of CRR upon the CSR, using following expression:

$$FS = \left(\frac{CRR_{M=7.5}}{CSR}\right) \tag{8}$$

Liquefaction Potential Index (LPI)
Since factor of safety only gives liquefaction potential of only the particular layer of soil, LPI gives the liquefaction potential at a place considering the whole depth of soil in a borehole. LPI is the summation of liquefaction potential of each layer considering entire soil depth. So LPI is mostly used for generation of liquefaction susceptibility maps as it evaluate the liquefaction potential of the soil column instead of a single soil layer at particular depth. Liquefaction potential index (LPI)was first introduced by Iwasaki et al. [13] and following expression was given to calculate the vulnerability of a site to liquefaction.

$$LPI = \int_0^z F(z)W(z)\,dz \tag{9}$$

where z = depth of layer; F(z) = function of factor of safety against liquefaction
F(z) = (1- FS) for FS less than or equal to 1 and
F(z) = 0 for FS greater than 1, and
W(z) = (10-0.5z) which is a depth-weighting factor.
Soil upto depth of 20m is considered in this approach to obtain Liquefaction Potential Index. Liquefaction potential risk of a given site can be categorized into four classes according to the value of LPI at that site [13] as shown in Table 1:

Table 1: Liquefaction Potential Classification [13]

LPI	Liquefaction Susceptibility
0	Very Low
$0 < LPI \leq 5$	Low
$5 < LPI \leq 15$	High
LPI > 15	Very High

3.2.2 Reliability Approach

Initially performance function is determined in reliability method. If S is used to denote CSR and R is used to denote CRR, the performance function is Z = R - S which tells about the occurrance of soil liquefaction. Thus, we can suppose that liquefaction will occur if Z = R - S $<$ 0 and liquefaction won't occur if Z = R - S $>$ 0. If Z = R - S = 0, it may liquefy or not liquefy [14].

If R and S representing CRR and CSR are assumed to be random variables, then we can also say Z as random variable which represent performance function of occurrance of liquefaction. So these three states of performance function could be calculated using the occurrence probability of liquefaction. The probability at which Z = R - S $\leq$ 0 or if performance function is less than or equal to one then it is known as probability of liquefaction occurrence [14]. The reliability analysis can be performed using different methods such as a Hasofer–Lind reliability method, a Point Estimate Method, First Order Second Moment (FOSM) method, a Monte Carlo Simulation method, and a combined method [15]. Here we use FOSM method of reliability analysis.

First order second moment (FOSM)

As First order second moment(FOSM) method only dependent on random variable's standard deviations and means, this method is most simple and generally used for the computation of liquefaction performance function. For the computation of statistics of random variable, Z = R - S i.e. performance function variable, this FOSM method make use of statistics of the random independent variables, like S and R which simplifies the complicated integration process in a easier way. In this method independent random variables S and R are assumed to follow normal distribution which also indicates the performance function random variable Z also follow normal distribution. Considering μ_S, μ_R as means of CSR and CRR and σ_S, σ_R as standard deviations of CSR and CRR respectively, then, μ_z, σ_z, δ_z representing the mean value, the standard deviation and the coefficient of variation (COV) respectively of performance function, Z could be represented as [14]

$$\mu_z = \mu_R - \mu_S \tag{10}$$

$$\sigma_z = \sqrt{\sigma_R^2 + \sigma_S^2} \tag{11}$$

$$\delta_z = \frac{\sigma_z}{\mu_z} \tag{12}$$

The inverse of coefficient of variation(COV) (δ_z) also known as the Reliability Index β is expressed as:

$$\beta = \frac{\mu_z}{\sigma_z} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{13}$$

Log-normal distribution model can describe the engineering field's basic random variables in a much better way than the normal distribution model. So considering logarithmic variables, the Reliability Index could be expressed as:

$$\beta = \frac{\ln\left[\frac{\mu_{CRR}}{\mu_{CSR}}\frac{\sqrt{\delta_{CSR}^2+1}}{\sqrt{\delta_{CRR}^2+1}}\right]}{\sqrt{\ln\left[(\delta_{CRR}^2+1)(\delta_{CSR}^2+1)\right]}} \tag{14}$$

From the Reliability Index β, the probability of occurrence of liquefaction P_L could be estimated by:

$$P_L = 1 - \phi(\beta) \tag{15}$$

where $\phi(\beta)$ is cumulative probability function of normally distributed random variables. The Facor of Safety could be calculated using the following equation:

$$FS = \frac{\mu_R}{\mu_S} \tag{16}$$

The equation for β represented below could be obtained by re-arranging Eqs. (14) and (16),

$$\beta = \frac{\ln\left[FS\frac{\sqrt{\delta_{CSR}^2+1}}{\sqrt{\delta_{CRR}^2+1}}\right]}{\sqrt{\ln\left[(\delta_{CRR}^2+1)(\delta_{CSR}^2+1)\right]}} \tag{17}$$

From above relation, using factor of safety, Reliability Index,β is calculated and finally the liquefaction probability is evaluated from β.

Uncertainties in CSR

In the estimation of CSR, the key role is of peak ground acceleration(PGA). Because of the uncertainties in the PGA, the CSR values are different for same input. Expansion of the function by Taylor series is used by FOSM method to estimate the function. After the first-order terms, the expansion is reduced because of which if second derivative and higher order derivatives of the function are significant, the accuracy of the method deteriorates. The mean μ and coefficient of variation δ of CSR using FOSM method is expressed as:

$$\mu_{CSR} = 0.65\frac{\mu_{a_{max}}}{g}\frac{\mu_{\sigma_{vo}}}{\mu_{\sigma'_{vo}}}\frac{\mu_{r_d}}{\mu_{MSF}}\frac{1}{\mu_{K_\sigma}} \tag{18}$$

$$\delta_{CSR}^2 = \delta_{a_{max}}^2 + \delta_{\sigma'_{vo}}^2 + \delta_{\sigma_{vo}}^2 + \delta_{r_d}^2 + \delta_{MSF}^2 + \delta_{K_\sigma}^2 - 2\delta_{\sigma'_{vo}\sigma_{vo}}\delta_{\sigma_{vo}}\delta_{\sigma'_{vo}} \tag{19}$$

where μ and δ indicates the respective mean and coefficient of variation,COV of respective variables and $\delta_{\sigma'_{vo}\sigma_{vo}}$ indicates the coefficient of correlation between effective and total stress. The correlation coefficient $\delta_{\sigma'_{vo}\sigma_{vo}}$ between σ_{vo} and σ'_{vo} could be estimated using Pearson's method [15].

Uncertainties in CRR

Using the insitu SPT-N values, the capacity CRR of the soil against liquefaction of soil is estimated. The corrected SPT N values are very significant in the calculation of CRR. Some correction factors are involved in the process of evaluating corrected N value. Due to these factors the uncertainties in SPT values increases. There is also some errors in the field while measuring the SPT values and if all the the uncertainties from measurement errors and corrections factors are taken into account then the net uncertainties would be much higher while evaluating SPT N values. Using the mean value of $(N_1)_{60cs}$ and Eq. (7), the mean of CRR,μ_{CRR} could be estimated. The coefficient of variation(COV) of CRR, δ_{CRR} could be calculated by using expression given by Jha and Suzuki [15].

$$\delta_{CRR} = \frac{\Delta CRR}{2\mu_{CRR}} \quad (20)$$

where,

$$\Delta CRR = CRR_{\left(\mu_{(N_1)_{60cs}} + \sigma_{(N_1)_{60cs}}\right)} - CRR_{\left(\mu_{(N_1)_{60cs}} - \sigma_{(N_1)_{60cs}}\right)} \quad (21)$$

where $\mu_{(N_1)_{60cs}}$ represents the mean of corrected SPT-N values and $\sigma_{(N_1)_{60cs}}$ represents the standard deviation of corrected SPT-N values. Li et al. [16] consider a probability of 35 as the threshold between occurrence of liquefaction and non-liquefaction. In a probabilistic framework, using liquefaction probability, the Liquefaction Potential Index(LPI) can be computed using expression given below [16]:

$$LPI = \int_0^z F(z)W(z)\,dz \quad (22)$$

where z = depth of layer; F(z) = function of probability of liquefaction
F(z) = 0 for $P_L < 0.35$
F(z) = P_L-0.35 for $P_L \geq 0.35$ and
W(z) = (10-0.5z) which is a depth-weighting factor.
The site could be categorized into four classes of liquefaction potential risk based on the value of LPI [16] as shown in Table 2:

Table 2: Liquefaction Potential Classification [16]

LPI	Liquefaction Susceptibility
0	Very Low
$0 < LPI \leq 5$	Low
$5 < LPI \leq 13$	High
LPI > 13	Very High

4. Results and Discussion

Results from Deterministic and Reliability methods are compared and discussed as follows:

From Figure 2, we can see that even if the factor of safety against liquefaction is more than 1, there is certain possibility of liquefaction. Also we can see that probability of liquefaction decreases as there is increase in factor of safety.

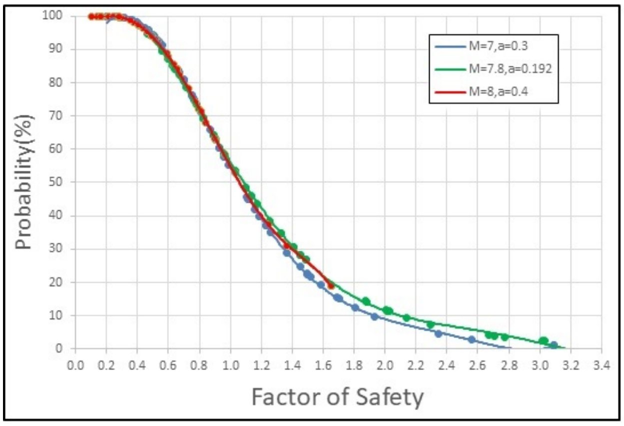

Figure 2: Graph between probability of liquefaction and Factor of Safety for M=7, a=0.3, M=7.8, a=0.192 and M=8, a=0.4.

Table 3: Factor of Safety against liquefaction and liquefaction probability for a borehole

Depth	FS	$P_L(\%)$
1	0.594	88
2	0.673	82
3	1.560	22
4	1.438	27
5	0.818	70
6	1.223	39
7.5	1.143	44
9	0.560	90
10.5	1.083	49
12	0.396	98
13.5	0.647	84
15	0.928	61

From above Table 3, at 6m depth of borehole, the factor of safety obtained was 1.223 from deterministic analysis, which is greater than one and hence it should not liquefy. But the probability of liquefaction (P_L) obtained from reliability analysis is 39% which suggests there is chances for liquefaction. Thus, we can say that factor of safety from deterministic method alone shouldn't be used for the evaluation of occurrence of liquefaction.

LPI is also evaluated from Probability of liquefaction using Li et al. [16] and the LPI from reliability method is compared with LPI from deterministic method as shown in Figure 3.

From LPI calculated, sites are categorized into four classes as Very High, High, Low and Very Low susceptibility of liquefaction. From figure 3 and Table 4, it is found that deterministic method underestimates

Table 4: No. of sites with different liquefaction potential

Earthquake scenario	No. of Liquefaction susceptible cases							
	Deterministic Method				Reliability Method			
	Very Low	Low	High	Very High	Very Low	Low	High	Very High
M=7, a=0.3	19	34	18	15	12	19	25	30
M=7.8, a=0.192	30	33	17	6	16	34	17	19
M=8, a=0.4	6	5	22	53	0	0	6	80

the liquefaction susceptibility of site than reliability method.

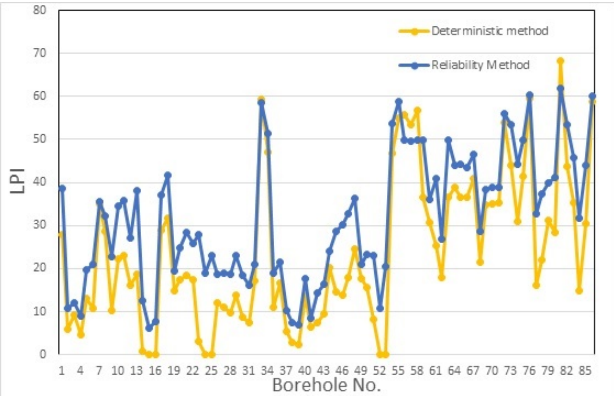

Figure 3: Graph plotted for LPI from deterministic and reliability method for M=8, a=0.4.

The maps developed using GIS considering deterministic approach for two earthquake scenarios are shown in Figure 4 and Figure 5.

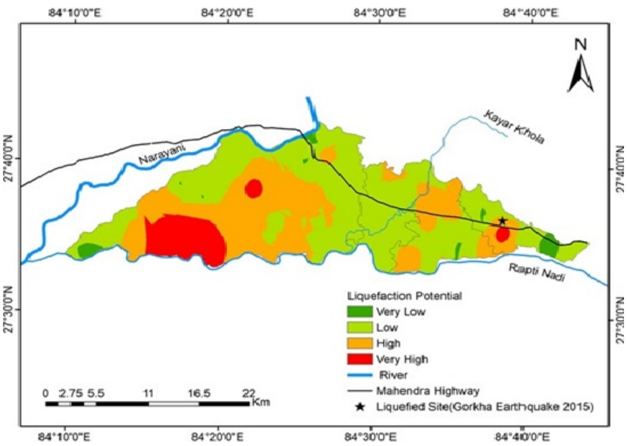

Figure 4: Liquefaction Potential Map for M=7.8 and a=0.192 (Deterministic Method)

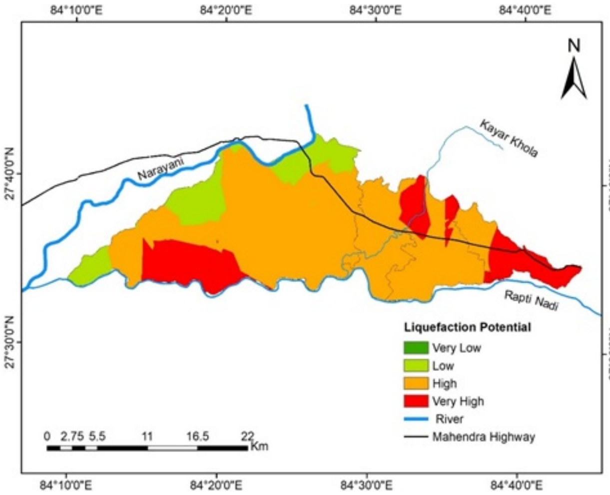

Figure 5: Liquefaction Potential Map for M=7 and a=0.3 (Deterministic Method)

The map developed using GIS considering reliability approach for two earthquake scenarios are shown in Figure 6 and Figure 7.

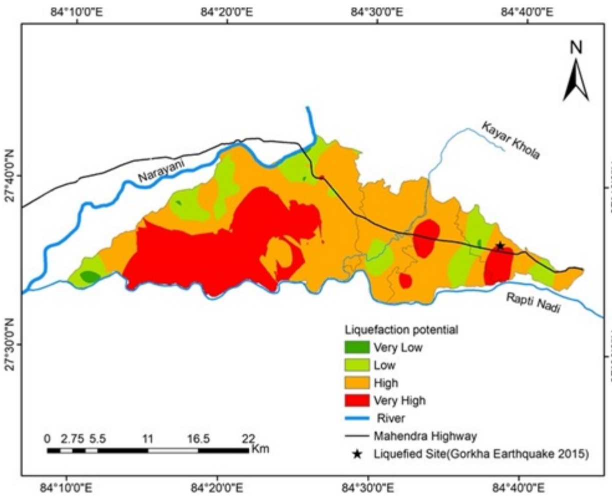

Figure 6: Liquefaction potential map based on LPI for M=7.8, a=0.192 (Reliability approach)

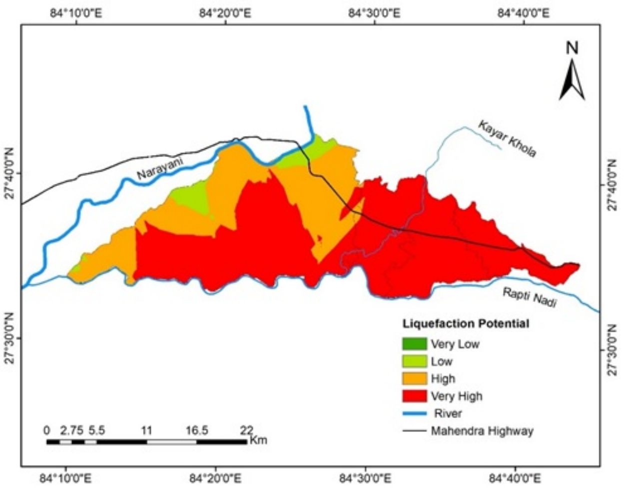

Figure 7: Liquefaction potential map based on LPI for M=7, a=0.3(Reliability approach)

From above maps, it is found that south-west part of chitwan is more susceptible to liquefaction. Also some places of Rapti Municipality are susceptible to liquefaction which is in very good agreement with observed surface manifestation of soil liquefaction during 2015 Gorkha earthquake.

5. Conclusions

The general aim of this research is to estimate the liquefaction potential of soil of Chitwan based on standard penetration test (SPT) data. In this study, different approaches have been discussed to analyze the liquefaction potential. In first part, calculation of liquefaction potential is carried out with the deterministic approach obtained from the literatures and in second part, reliability approach is used for liquefaction analysis. Comparison between deterministic and reliability method shows, there is possibility of liquefaction even if the factor of safety from deterministic method is greater than 1. Liquefaction susceptible maps are developed for Gorkha earthquake scenario and it shows that the liquefied site during Gorkha earthquake lies in high to very high liquefaction susceptible area. Also, these generated maps can be helpful for future planning of infrastructure in Chitwan.

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