Liquefaction Hazard Mapping of Bangalore, South India

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Abstract

This paper presents identification and mapping of vulnerable and safe zones for liquefaction hazard. About 850 bore logs data collected from geotechnical investigation reports have been used to estimate the liquefaction factor of safety for Bangalore Mahanagara palike (BMP) area of about 220 km^2. Liquefaction factor of safety is arrived based on surface level peak ground acceleration presented by Anbazhagan and Sitharam[5] and liquefaction resistance, using corrected standard penetration test (SPT) N values. The estimated factor of safety against liquefaction is used to estimate liquefaction potential index and liquefaction severity index. These values are mapped using Geographical information system (GIS) to identify the vulnerable and safe zones in Bangalore. This study shows that more than 95% of the BMP area is safe against liquefaction potential. However the western part of the BMP is not safe against liquefaction, as it may be subjected to liquefaction with probability of 35 to 65%. Three approaches used in this study show that 1) mapping least factor of safety irrespective of depth may be used to find liquefiable area for worst case. 2) mapping liquefaction potential index can be used to assess the liquefaction severity of the area by considering layer thickness and factor of safety and 3) mapping of liquefaction severity index can be used to access the probability of liquefaction of area.

Keywords: Earthquakes, liquefaction, Liquefaction potential and SPT.

Introduction

During site selection and planning of stages for the engineering structures and human settlements, liquefaction potential of an area is one of the important factors to be considered in earthquake geotechnical engineering. Liquefaction can occur in moderate to major earthquakes, which can cause severe damage to structures. Transformation of a granular material from solid state to liquid state due to increased pore pressure and reduced effective stress is defined as liquefaction.[21] The first step towards mitigation of liquefaction hazard, is evaluating accurately the liquefaction potential of soil zones in the area. Liquefaction hazard mapping has been done by many researchers world wide, Todorovska and Trifunac[44]; Aaron et al[1]; Kelson et al[20]; Dellow et al[14]; Utah Geological Survey[46]; Palmer et al[24]; Sonmez[41]; Pearce et al[25]; Brankman et al[11], Ozdemir and Ince[23]; Yilmaz and Yavuzer[48]; Pearce and Baldwin[26]; Yilmaz and Bagci[47]; Holzer et al[15]; Baise et al[9] and USGS[45] in particular.

Historically ground failure due to liquefaction was not well reported in India. However, a few case studies on paleo-liquefaction show evidence of liquefaction in India in historic times. Sand blow was evident during 1819 Bhuj earthquake and sand dykes at Beltaghat site during 1897[27]. Paleo-liquefaction studies in Assam also confirm liquefaction failures during Assam earthquake[43]. Recent 2001 Bhuj liquefaction failures are classical examples of failure due to liquefaction in India. Bhuj earthquake has demonstrated many ground failures due to earthquake such as ground cracking, lateral spreads, sand boiling, sand blows, crates formations and lateral and vertical deformations in the embankments. Even in the Pakistan earthquake of 2005, evidence of liquefaction and ground failure near Baramulla, Jammu and Kashmir was reported by Sahoo et al[31].

In India limited work has been done for liquefaction hazard mapping. Ramakrishnan et al[29] have derived a band ratio to map liquefaction and tested it for sensitivity with respect to field-based observations. The proposed band ratio (Liquefaction Sensitivity Index - LSeI) was observed to be sensitive and efficient in mapping the liquefaction in parts of Kachchh region. Anbazhagan[4]; Anbazhagan and Premalatha[6] and Rajesh and Balasenthilnathan[28] presented preliminary liquefaction hazard mapping of Chennai city. Rao and Neelima Satyam[30] assessed in detail the liquefaction potential of soils in Delhi using about 1200 SPT-boreholes and published a liquefaction hazard map of Delhi. In this study, an attempt is made to map the vulnerable and safe zones for liquefaction potential by considering least factor of safety against liquefaction, liquefaction potential index and liquefaction severity index.

Study area and seismic status

Bangalore is in South Karnataka Plateau (Mysore Plateau) and is situated in south India. Its topography has a large difference in elevation only in the western part of the city with the highest point being Doddabettahalli (about 962m above Mean Sea Level, MSL) and the lowest elevation is being 830 m above MSL. The study area selected is Bangalore metropolis covers about 220 km^2 (see fig. 1). Currently Bangalore is in seismic zone – II, according to the seismic zonation map prepared by Bureau of India Standards. But recent studies by Sitharam et al[38], Sitharam and Anbazhagan[37] and Anbazhagan et al[3] have highlighted that the seismicity of Bangalore region is on a rise when compared to the past which is also evident with reports of recent local tremors felt in this region. These authors have suggested that this region may be upgraded from seismic zone II to zone III.

Further Anbazhagan and Sitharam[5] have presented the surface level peak ground acceleration map by carrying out one-dimensional (1-D) ground response analysis (using the program SHAKE 2000) by considering standard penetration test (SPT) data and shear wave velocity data from multichannel analysis of surface wave (MASW) survey. The population in the city is growing at a faster rate and is currently about 7000 people /km^2. Due to the rapid rise in population and industrialization, many lakes and water bodies are converted to residential and industrial areas. With occurrence of an earthquake, these filled up areas may be vulnerable to liquefaction. Hence it is necessary to access the liquefaction potential of the area.

Borelogs with N corrections

Geotechnical borelog data was collected from archives of Torsteel Research Foundation in India (TRFI) and Indian Institute of Science (IISc), from geotechnical investigations carried out for several major projects in Bangalore. About 850 borelogs are used to generate three-dimensional subsurface model of Bangalore[39]. Majority of the bore logs are having SPT- N values with index and engineering properties more than depth of 20 m. The SPT data collected is field 'N' values, which are measured N values without applying any corrections. Usually for liquefaction analysis, the field SPT "N" values have to be corrected with various corrections and a seismic borelog has to be obtained. The seismic borelogs contain information about depth, observed SPT 'N' values, density of soil, total stress, effective stress, fines content, correction factors for observed "N" values, and corrected "N" values. The 'N' values measured in the field using standard penetration test procedure have been corrected for various corrections, such as:(a) Overburden Pressure (C_N), (b) Hammer energy (C_E), (c) Borehole diameter (C_B), (d) presence or absence of liner (C_S), (e) Rod length (C_R) and (f) fines content (C_{fines}).[12, 26, 34, 35, 40, 50] Corrected 'N' value i.e., $(N_1)_{60}$ are obtained using the following equation:

$$(N_1)_{60} = N \times (C_N \times C_E \times C_B \times C_S \times C_R) \tag{1}$$

The corrected "N" Value *$(N_1)_{60}$* is further corrected for fines content based on the revised boundary curves presented by Idriss and Boulanger[16] for cohesionless soil as described below:

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \tag{2}$$

$$\Delta(N_1)_{60} = \exp\left[1.63 + \frac{9.7}{FC+0.001} - \left(\frac{15.7}{FC+0.001}\right)^2\right] \tag{3}$$

where FC = percent fines content (percent dry weight finer than 0.074mm). Typical N correction calculations and values are presented in Anbazhagan and Sitharam[5].

Factor of safety against liquefaction

Factor of safety against liquefaction of soil layer has been evaluated based on the simplified procedure[32] and subsequent revisions of the simplified procedures[12, 34, 35, 50]. In this study, the earthquake induced loading is expressed in terms of cyclic shear stress and this is compared with the liquefaction resistance of the soil. Liquefaction calculation or estimation requires two variables for evaluation of liquefaction resistance of soils. Two variables are defined based on cyclic stress approaches which are as follows:

The seismic demand of a soil layer is represented by a Cyclic Stress Ratio (CSR). The capacity of soil to resist liquefaction is represented by Cyclic Resistance Ratio (CRR).

If the cyclic stress ratio caused by the earthquake is greater than the cyclic resistance ratio of in situ soil, then liquefaction could occur during the earthquake. The factor of safety against liquefaction is defined as follows:

$$FS = \left(\frac{CRR_{7.5}}{CSR}\right) MSF \tag{4}$$

here subscript 7.5 for CRR denotes that CRR values are calculated for the earthquake moment magnitude of 7.5. MSF is the magnitude scaling factor. The higher factor of safety means that soil is more resistant to liquefaction. Here liquefaction resistance is estimated using an in-situ test based on corrected SPT 'N' values.

Cyclic Stress Ratio (CSR)

The excess pore pressure generation to initiate liquefaction depends on the amplitude and the duration of the earthquake induced cyclic loading. In the cyclic stress approach the pore pressure generation is related to the cyclic shear stresses, hence the earthquake loading is represented in terms of cyclic shear stresses. The earthquake loading can be evaluated by using Seed and Idriss[36] simplified approach. The earthquake loading is evaluated in terms of uniform cyclic shear stress amplitude and it is as given below:

$$\text{Cyclic stress ratio (CSR)} = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma_{vo}'}\right) r_d \tag{5}$$

In this equation $0.65\,\frac{a_{\max}}{g}$ represents 65 % of the peak cyclic shear stress, $a_{\max}$ is peak ground surface acceleration, g is the acceleration due gravity, σ_{vo} and σ_{vo}' are the total and effective vertical stresses and r_d = stress reduction coefficient. For the calculation of stress reduction coefficient, many correlations are available which are discussed in detail in a 1996 NCEER workshop report[50]. Youd et al[50] have recommended that for routine practice and non-critical projects, the equations given by Liao and Whitman[21] may be used to estimate average values of r_d .In this study the same has been used and it is given as below:

$$r_d = 1.0 - 0.00765z \quad \text{for } z \le 9.15 \text{ m} \tag{6}$$

$$r_d = 1.174 - 0.0267z \quad \text{for } 9.15 \text{ m} < z \le 23 \text{ m} \tag{7}$$

Cyclic Resistance Ratio (CRR)

Liquefaction resistance of soil depends on how close the initial state of soil is to the state corresponding to "failure". The liquefaction resistance can be calculated based on laboratory tests and in situ tests. Here, liquefaction resistance using in situ test based on SPT 'N' values is attempted. Cyclic resistance ratio (CRR) is arrived based on corrected "N" value as per Seed et al[34], Youd et al[49]; Cetin et al[12]. Seed et al[34] present a plot of CRR versus corrected 'N' value from a large amount of laboratory and field data. However, here the corrected 'N' values are used to calculate the CRR for the magnitude of 7.5 earthquakes using the equation proposed by Idriss and Boulanger[17] as given below:

$$CRR = \exp\left\{\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right\} \tag{8}$$

However this estimation is proposed for a magnitude of 7.5 on the Richter scale. For the present study, for the earthquake moment magnitude of 5.1 has been considered for evaluating Magnitude Scaling Factor (MSF).

Magnitude Scaling Factor (MSF)

The CRR curves developed either using the SPT N values or CPT q_c values or shear wave velocity (Vs) corresponding to an earthquake of magnitude 7.5. Seed and Idriss[36] have suggested the use of magnitude scaling factors (MSF) for earthquakes of magnitude other than 7.5. The widely available MSF are Seed and Idriss[36] scaling factors, Revised Idriss scaling factors, Ambraseys[2] scaling factors, Arango[8] scaling factors, Andrus and Stokoe[7] scaling factors and Youd and Noble[49] scaling factors. Detailed discussion and comparison of these scaling factors are available in Youd et al[50] and Bhandari et al[10]. An NCEER- 1996 and 1998 NCEER/NSF workshop[50] have recommended the revised Idriss scaling factors[17] and it was used by Yilmaz and Bagci[47] for soil liquefaction susceptibility and hazard mapping in the residential area of Kutahya (Turkey). The magnitude-scaling factor used in the present study is the revised Idriss scaling factor for the magnitude less than 7.5 and it is given as below:

$$\text{MSF} = \left[\frac{10^{2.24}}{\text{M}_\text{W}^{2.56}}\right] \tag{9}$$

From the available 850 geotechnical borelog data base, about 620 borelogs have been selected for present calculations. After applying necessary corrections to SPT 'N' values (as discussed above) corrected "N" [$(N_1)_{60cs}$] values were obtained. A simple excel spread sheet has been developed to automate these calculations for all the 620 borelogs with depth. The factor of safety for each layer of soil is arrived by considering corresponding "$(N_1)_{60cs}$" values. Typical liquefaction analysis calculation table is shown in table 1. The minimum factor of safety from each bore logs has been considered to map the factor of safety against liquefaction at that location. Figure 2 shows the map of minimum factor of safety against liquefaction (FS) for Bangalore city. Typical borelogs having a lower factor of safety are shown in figure 3. Figure 3 clearly shows that there is filled up soil up to a depth of about 2 m having low field 'N' values. This location also has a shallow water table at about 1.4 m from the ground level. These factors may be attributed to the low factor of safety in these locations.

Liquefaction Potential Index

Factor of safety against liquefaction of soil layer is represented by the ratio of cyclic resistance to the cyclic stress ratio, but this will not tell us whether the site is liquefiable or not. Factor of safety against liquefaction is neither a sufficient tool for the estimation of liquefaction severity of the site nor a practical parameter to prepare liquefaction severity maps for microzonation purpose. Factor of safety against liquefaction can be used to assess that a layer can either liquefy or not, but it can not be used to quantify the severity of liquefaction of particular location[42]. To address this issue, Iwasaki et al[18] proposed liquefaction potential index (L_I) and its severity categories. These authors have also suggested that damage to engineering structures tends to be severe if the liquefiable layer is thick, shallow and FS is less than 1. Later, Sonmez[41] has highlighted the limitations of L_I and severity categories suggested by Iwasaki et al[18]. Sonmez[41] modified equations of L_I by considering the threshold factor of safety value of 1.2 and reclassified the severity categories. In this study liquefaction potential index (L_I) has been estimated for Bangalore and severity map is also generated using relation proposed by Sonmez[41] and Sonmez and Gokceoglu[42].

$$L_I = \int_0^{20} F(z)W(z)dz \tag{10}$$

$$F(z) = 0 \;\; for\; FS \ge 1.2 \tag{11}$$

$$F(z) = 2x10^6 e^{-18.427FS} \;\; for\; 1.2 \succ FS \succ 0.95 \tag{12}$$

$$F(z) = 1 - FS \;\; for\; FS < 0.95 \tag{13}$$

$$W(z) = 10 - 0.5z \;\; for\; z \prec 20m \tag{14}$$

$$W(z) = 0 \;\; for\; z \succ 20m \tag{15}$$

Liquefaction potential index (L_I) has been estimated using factor of safety calculated in previous section by developing the MATLAB code. Estimated L_I is used to assess the liquefaction potential of the site based on Sonmez[41] classification categories. Sonmez[41] introduced additional two new classification categories into the classification proposed by Iwasaki et al[18] as "non-liquefiable" and "moderate" and preserved the boundary values of L_I for the categories of "high" and "very high". Sonmez[41] proposed "non-liquefiable" sites when FL>1.2 throughout the soil column from surface to a depth of 20 m, L_I of the soil column becomes zero. Sonmez[41] has pointed out that the threshold value of FS between non-liquefiable and marginally liquefied conditions (FS=1.2) is open to discussion and the threshold value for the non-liquefiable category suggested in his study can be changed depending on the data in future studies. In this study, parameters proposed by Sonmez[41] have been considered to identify the liquefaction potential area in Bangalore. The estimated L_I is grouped according to Sonmez[41] liquefaction potential category, which is given in table 2. Figure 4 shows the liquefaction potential of the study area. The study shows that most of study area is non liquefiable (L_I is 0) and some portion of northern part has low liquefaction potential. Western part of study area may have low to very high liquefaction potential. These results match well with the map of factor of safety against liquefaction (Figure 2).

Liquefaction severity index

Determination of factor of safety against liquefaction using deterministic method is not the best judgment of whether liquefaction occurred in a post-earthquake investigation due to an unknown degree of conservatism[51]. The probabilities of soil liquefaction depending on factor of safety values are preformed by Chen and Juang[13] and Juang et al[19]. Equation for the probability of liquefaction is proposed by Juang et al[19] and probability of liquefaction (P_L) ranges from zero to one as a function of factor of safety. Original equations and the likelihood of liquefaction of a soil layer classification are discussed in Sonmez and Gokceoglu[42]. Sonmez and Gokceoglu[42] presented the limitations and alternate name for liquefaction risk index. Sonmez and Gokceoglu proposed the revised probabilities of soil liquefaction depending on factor of safety values called liquefaction severity index (L_S) and its classification. In this study liquefaction severity index (L_S) has been calculated to identify the probability of liquefaction potential using the method proposed by Sonmez and Gokceoglu[42]. The proposed equations by Sonmez and Gokceoglu[42] for the determination of L_S are given below:

$$L_S = \int_0^{20} P_L(z)W(z)dz \qquad (16)$$

$$P_L(z) = \frac{1}{1+\left(FS/0.96\right)^{4.5}} \; for\ FS \le 1.411 \qquad (17)$$

$$P_L(z) = 0\ for\ FS \succ 1.411 \qquad (18)$$

or the soil layer with FL 1:411 can be considered as non-liquefiable layer considering Clay Content and Liquid Limit, where the term of *W(z)* is the same as in equations 14 and 15. The liquefaction severity index (L_S) is calculated and classified according to new liquefaction severity classification suggested by Sonmez and Gokceoglu[42]. Table 3 shows the Liquefaction severity classification suggested by Sonmez and Gokceoglu. For the study area liquefaction severity index (L_S) is shown in figure 5. This study shows that major part of study area comes under non liquefiable category having L_S as 0. Few locations in the northern part of study area have very low liquefaction probability and portion of study area in western part has low to moderate liquefaction probability for post earthquakes. This result is clearly shown in figure 2 and figure 4.

Conclusion

In this study, vulnerable and safe zone for liquefaction potential of the study area has been identified using three approaches, 1) mapping least factor of safety irrespective of depth, which may be used to find liquefiable area for worst case. 2) Mapping liquefaction potential index, which can be used to assess the liquefaction severity of the area by considering layer thickness and factor of safety and 3) mapping of liquefaction severity index, which can be used to access the probability of liquefaction. These three maps have their own advantages depending on the requirements. This study shows that many locations have lesser values of factor of safety against liquefaction, only if the least factor of safety is mapped. But when compared to the total area, area having lesser factor of safety is very small. Liquefaction potential index mapping shows that the liquefiable area is very less. The probability of liquefaction using factor of safety shows that the major part of study area has zero probability and smaller area is liquefiable for probability of 35 to 65%. This study shows that study area is safe against liquefaction but areas having filled up soil and tank bed need more detailed study. First method can be used to liquefaction hazard mapping worst case. The second and third method can be used for the purpose of seismic microzonation and hazard mapping of the area.

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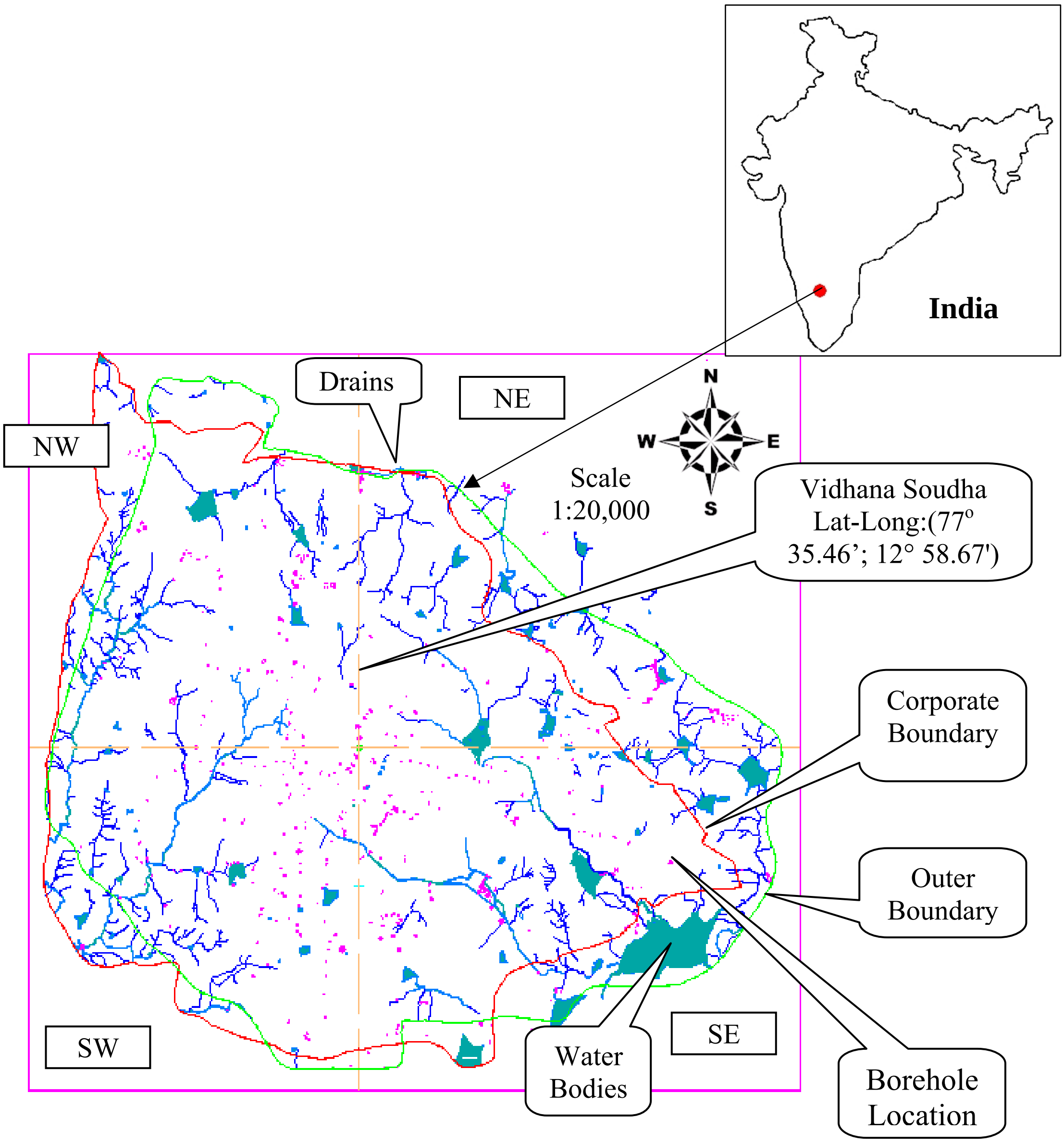

Fig.1: GIS model of borehole locations along with water body features

Table 1
Typical liquefaction analysis for a borehole

Magnitude, M_w = 5.1 **Peak Acceleration = 0.35g**

Depth (m)	Corrected N value $(N_1)_{60cs}$	σ_{vo} kN/m^2	σ_{vo}' kN/m^2	r_d	CSR	FC %	CRR	MSF	FS
1.50	4	30.00	30.00	0.99	0.22	46.2	0.08	2.68	0.94
3.20	3	64.00	47.32	0.98	0.30	40.9	0.08	2.68	0.69
4.20	21	84.00	74.19	0.97	0.25	53.3	0.22	2.68	2.36
5.20	20	104.00	94.19	0.96	0.24	53.1	0.21	2.68	2.35
7.00	44	140.00	122.34	0.95	0.25	57.1	19.54	2.68	NA
8.50	102	170.00	155.29	0.93	0.23	59.2	NA	2.68	NA

NA- Not applicable

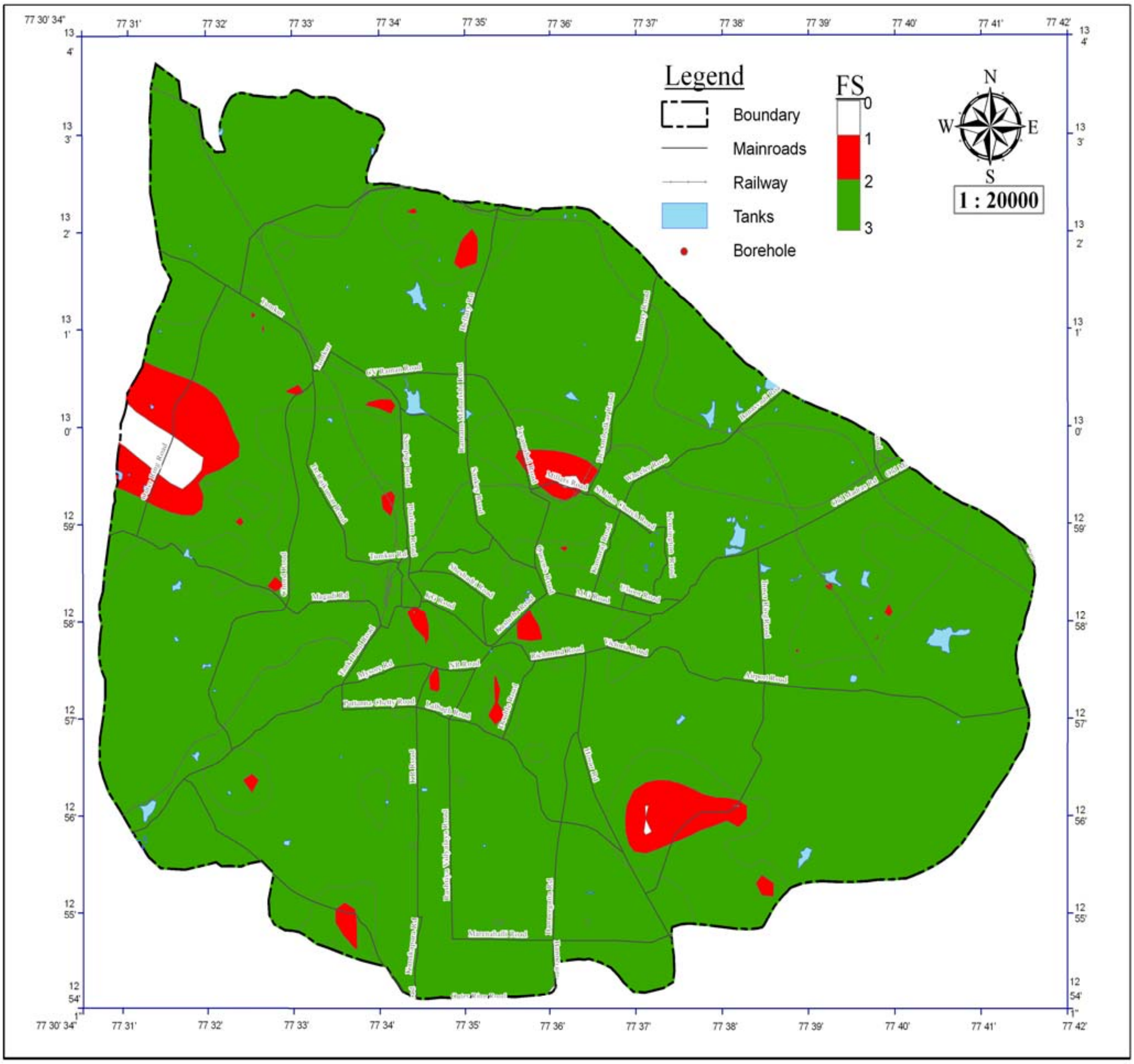

Fig. 2: Map of factor of safety against liquefaction

Table 2
Liquefaction potential classification proposed by Sonmez[41]

Liquefaction Potential Index (L_I)	Liquefaction potential category
0	Non- liquefiable (based on FS ≥1.2)
$0< L_I \leq 2$	Low
$2< L_I \leq 5$	Moderate
$5< L_I \leq 15$	High
$15 > L_I$	Very high

Table 3
Liquefaction severity classification proposed by Sonmez and Gokceoglu[42]

Liquefaction severity Index (Ls)	Description
$85\leq L_S< 100$	Very High
$65\leq L_S< 85$	High
$35\leq L_S< 65$	Moderate
$15\leq L_S< 35$	Low
$0< L_S< 35$	Very Low
$L_S=0$	Non liquefied

BORE LOG

Location Institute of Arospace Medicine — Date of commencement 21.11.2005
BH No 5 — Date of completion 22.11.2005
Ground Water Table 1.4m

Depth Below GL(m)	Soil Description	Thickness of Strata (m)	Legend	Details of Sampling: Type	Details of Sampling: Depth (m)	SPT N Value
0.0				SPT	1.5	3/4//04
	Filled Up Soil					N=8
2.0		2				
				UDS	3.0	
3.0	Reddish			SPT	3.5	10/13//16
	Clayey sand					N=29
4.5		2.5		UDS	4.5	
	Yellowish			SPT	5.0	10/10/13
6.0	Sandy Silt	1.5				N=23
				UDS	6.0	
				SPT	6.5	13/20/32
7.0	Greyish/ Yellowish					N=52
	Silty sand with mica					
				SPT	7.5	16/23/29
12.0						N=52
				SPT	9	34/47/62
						N=109
14.0				SPT	10.5	75R for
						5cm Penetration
16.5		10.5				
	Weathered Rock			SPT	12*	75R for
	16.5m to 17m				and	no Penetration
17.0	CR=15%,RQD=Nil	0.5			Below	

Bore hole Terminated at 17 m; Sample not retrived; SPT - Standard Penetration Test; CR-Core Recovery; UDS - Undisturbed Sample; RQD-Rock Quality Designation; R -Rebound.

Fig. 3: Typical borelog having low N values

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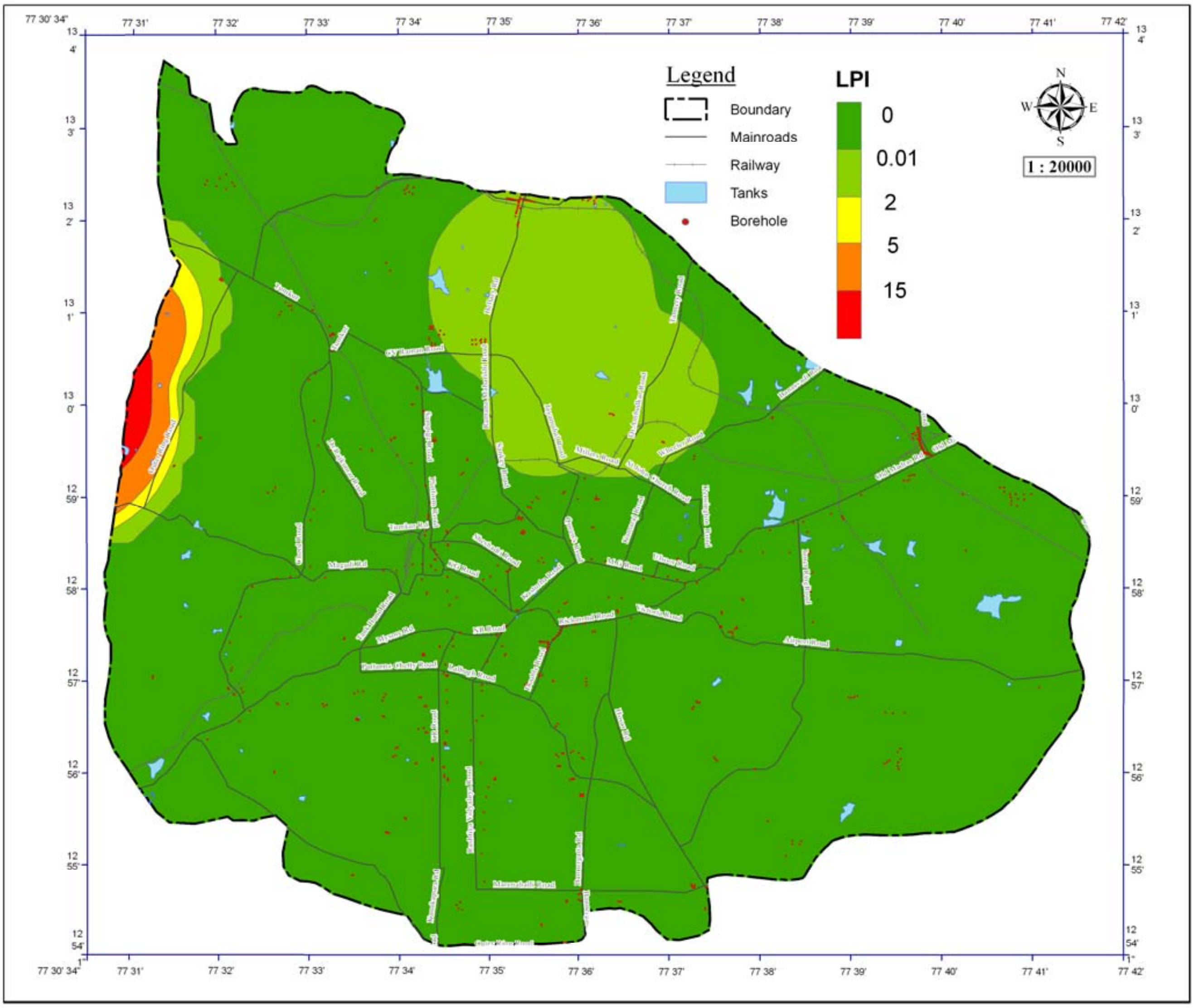

Fig. 4: Liquefaction potential hazard map

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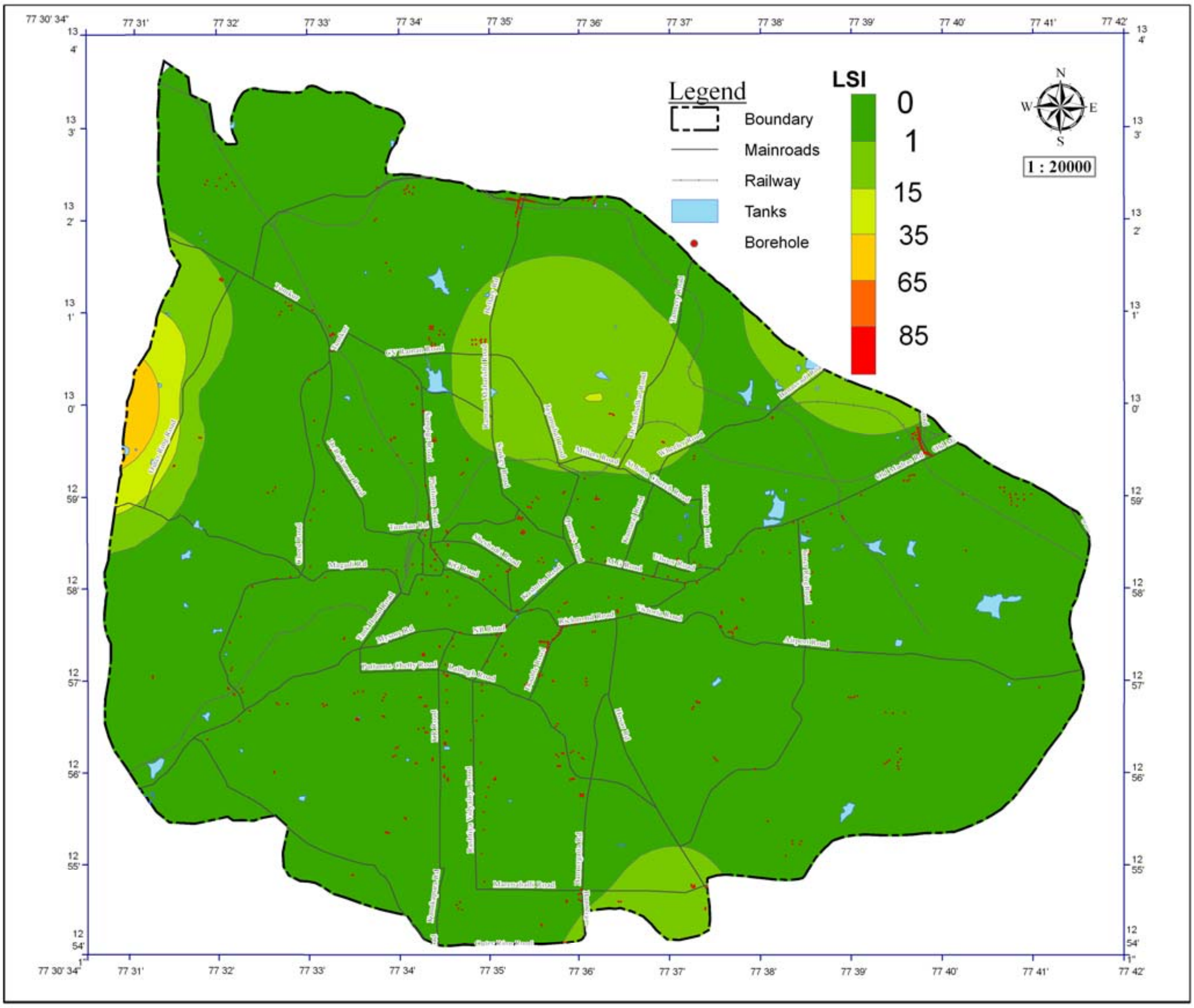

Fig. 5: Liquefaction severity map of Bangalore

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