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3-D Subsurface Modelling and Preliminary Liquefaction Hazard Mapping of Bangalore City Using SPT Data and GIS

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Introduction

The response of soil due to seismic hazards producing a significant amount of cumulative deformation or liquefaction has been one of the major concerns for geotechnical engineers working in the seismically active regions. 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 sate due to increased pore pressure and reduced effective stress is defined as liquefaction (Marcuson 1978). When this happens, the sand grains loose its effective shear strength and will behave more like a fluid. The grain size distribution of soil, duration of earthquake, amplitude and frequency of shaking, distance from epicenter, location of water table, cohesion of the soil and permeability of the layer affects liquefaction potential of soil (Seed and Idriss 1971). The liquefaction hazards are associated with saturated sandy and silty soils of low plasticity and density. The liquefaction potential of soil is generally estimated from laboratory tests or field tests. Among the field in-situ tests, the SPT test has been widely used for this purpose. Corrected 'N' values from large number of SPT test data in Bangalore have been used for direct assessment of ground's liquefaction resistance in this study. This study has been carried out as part of the seismic microzonation of Bangalore city.

The study area is about 220 sq.km in Bangalore city (12° 58" N and 77° 37" E) and situated at about 910 m above Mean Sea Level (MSL), which is the principal administrative, industrial, commercial, educational and cultural capital of Karnataka state, in the South - Western part of India. The population of greater Bangalore region is over 6 million. Bangalore city is the fastest growing city and the fifth largest city in India. Recent earthquakes in different parts of the country, particularly the one at Bhuj during the last year has influenced the importance of earthquake resistant construction. In addition, Bangalore city that once had more than 150 lakes has reclaimed much of these water bodies, leaving only 64, today. Most of these lake beds, which are silted up, have been

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used for construction of layouts and industrial parks. These silted up lake beds, which are encroached for the development, in low lying areas are prone to submergence in rainy season. Because of density of population, mushrooming of buildings of all kinds from mud buildings to RCC framed structures and steel construction and, improper and low quality construction practice, Bangalore is vulnerable even against average earthquakes.

In this study the 3-D subsurface model of geotechnical data has been created using Geographical information system (GIS). An attempt has been made to prepare the preliminary liquefaction hazard mapping using SPT bore log using simplified procedures. The simple spread sheet has been generated for "N" corrections and calculation of factor of safety against liquefaction. Based on the factor of safety, the regional hazard maps are generated for the assumed earthquake local magnitude of 6 and 7. The cyclic triaxial tests have been carried out on undisturbed soil sample collected from few locations where factor of safety is more than 1.5. The test shows that pore pressure ratio reaches 0.94 with in 20 cycles, and beyond this it remains the same up to 120 cycles of loading, the soil samples did not liquefy even up to 120 cycles.

Seismicity of the Region

In recent years much of the seismic activity in the state of Karnataka has been in the south, in the Mysore-Bangalore region. Historically tremors have occurred in many other parts of the state such as Bellary, which is in the northern part of Karnataka. The seismic data of region have been collected from different sources and some of them are presented in Table 1. The past earthquake events are more than 125 moderate earthquakes from moment magnitude of 3.5 to 6.2. Table 1 show the earthquake that has occurred close to Bangalore was in the range of 2 to 5.5 in Richter magnitude. Figure 1a shows around 10 earthquake events per decade with an increase in number of events. Figure 1b shows that for the last four decades earthquake of magnitude 3.5 to 5.7 have been occurring frequently in the region.

The morphology of southern Karnataka shows that the series of water falls, cascades and rabid along the Cauvery river, particularly between Sivasamudram in Karnataka and Mettur in Tamil Nadu, could be due to reactivation of Precambrian faults across part of the old course and lateral displacement of the uplifted blocks, giving rise to change in the course of the river which is shown in Figure 2 (Valdiya 1998). Figure 2 shows the active faults speculated at present by Valdiya (1998) in south of Bangalore on either side within 100 kms. Similarly, in the north the Arkavathi River that follows a remarkably straight fault valley in the Manchenabele-Aganahalli-Ramagiri tract as shown in Figure 3. Valdiya (1998) highlighted that the recent uplift is in the order of 7 to 10 m on the eastern side formed gully erosion on the Manchenabele reservoir area corroborating to the recent movement of the faults. Valdiya (1998) also indicate that in Southeast of Kanakapura (see Figure 3),the Hosdurga stream flows about 10 kms in a straight valley before entering on entrenched swing and they have pointed the evidence to the western block rising up a few meters and blocking the flow of the Hosdurga stream. As described by Radhakrishna and Vaidyanadhan (1997), the south eastern part of Karnataka (Bangalore) is surrounded by remobilized terrain and it is marked by a 5 km wide steep-dipping mylonite belt, which can be traced for nearly 400 km. Despite its steep dip many workers consider it as a thrust on the basis of seismic evidence. From the above discussion, it is clear that there are several active faults in and around Bangalore. Figure 3 shows faults present close to Bangalore at a distance of about 20 to 50 kms, have a length varying from about 35 to 89 kms. From the past earthquakes, the hypocentral distance is estimated to be around 15 to 40 kms below the Ground level (Mandya Earthquake, Jan 2001, ML 4.3, www.asc-india.org).

TABLE 1: List of Past Earthquake Events Close to Bangalore

Date & Year	Magnitude	Latitude (^{0}N)	Longitude (^{0}E)	Nearest Place
12 Mar. 1829	**5.7**	**13.000**	**75.500**	**Bangalore Area**
13 Mar. 1829	**5.8**	**13.000**	**77.600**	**Bangalore Area**
01 April 1843	6.0	15.200	76.900	Bellary-Kolagallu Area
23 Aug. 1858	**5.8**	**13.000**	**77.600**	**Bangalore Area**
07 Jan. 1961	**5.0**	**13.000**	**77.300**	**Bangalore Area**
12 Feb. 1970	5.0	13.000	76.100	Hassan Area
16 May 1972	4.7	12.400	77.000	Doddegowdanakoopal
17 May 1972	4.5	12.400	77.000	Malavalli Area
15 Nov. 1973	4.0	17.000	76.300	Almel Sindgi Area
12-May-1975	4.7	13.800	75.300	North of Shimoga
1976	**3.8**	--	--	**Siddapur-(Hoskote)**
30April 1983	**2.3**	**12.70**	**77.12**	**West of Ramanagara**
20 Mar. 1984	4.6	12.550	7.770	Denkanikota Area
27 Nov. 1984	4.5	12.870	78.000	Masti Berikal Area
17 Oct. 1985	2.3	12.62	77.45	North of Kanakapura
17 Oct. 1987	2.3	12.62	77.45	North of Kanakapura
3 May 1990	4.6	13.000	75.500	Dharmasthala Area
30 Nov. 1991	2.3	12.85	77.63	South-East of Bangalore
24 Jul. 1993	**2.9**	**12.94**	**77.59**	**Bangalore**
30 Sep. 1993	6.2	18.066	76.451	Khilari
14 Nov. 1993	4.5	12.200	77.050	Tallakad-Kollegal Area
1 Oct. 1995	**2.4**	**13.02**	**77.54**	**Bangalore**
29 Jan. 2001	4.3	12.444	77.360	Mandya Area

The revised seismic map of India shows that the greater part of the Bangalore district falls under seismic zone II (IS 1893 Part I - 2002). Design Horizontal Seismic Coefficient from the revised code for Bangalore city considering rock to soft soil varies from 0.0125g to 0.020g. However, geologist and engineers expect these values to be much higher owing to their recent studies (Sitharam et al. 2006; Sitharam and Anbazhagan 2007; Ganesha Raj and Nijagunappa 2004). GaneshaRaj and Nijagunappa (2004) have highlighted the need for upgrading Bangalore region to zone III based on their remote sensing and seismotectonic studies in the area. In the present study an earthquake of local magnitude of 6 and 7 have been considered for liquefaction hazard analysis.

Bangalore Map with Borehole Locations

The Bangalore map forms the base layer for development of GIS model and preparation of microzonation maps. The map consists of 220 sq. km area of Bangalore city with several layers of information. Some of the important layers considered are the boundaries (Outer and Administrative), Contours, Highways, Major roads, Minor roads, Streets, Rail roads, Water bodies, Drains, Landmarks and Borehole locations. The map entities were developed in view of two aspects, first, for locating the bore logs to the utmost accuracy on a scale of

1:20000 and secondly, for identification of bore logs by end user. Digitized map was synthesised mainly using hard copy of Bangalore map, published by Survey of India and several other maps from standard publishers were used for cross reference and verification. Digitization of the map layers was done in AutoCAD and then imported to Arc view GIS 8.1.The physical locations of some important buildings and distance from a known location were verified for the developed map. The latitudes and longitudes were confirmed using GPS stations at selected locations. Few combinations of layers in the map are shown in Figures 4 - 6. Figure 4 depicts the location of boreholes with 1 km × 1 km grid pattern within the corporate boundary of Bangalore along with outer boundary circumscribing the ring road. It gives a clear view of the spatial distribution of boreholes in Bangalore region. An average of about four bore holes are available within the grid of 1 km × 1 km. Figure 5 shows the location of boreholes with the elevation contours at 10m intervals, which clearly indicates that Bangalore is situated in undulated terrain. Figure 6 depicts the borehole locations with respect to water features like lakes, tanks and natural drains. Figure 7 shows the rock level map of Bangalore; this view gives a visual idea of the depth soil overburden available in each borehole locations. Several other important layers are also available in the map, which would be of interest to many engineering groups.

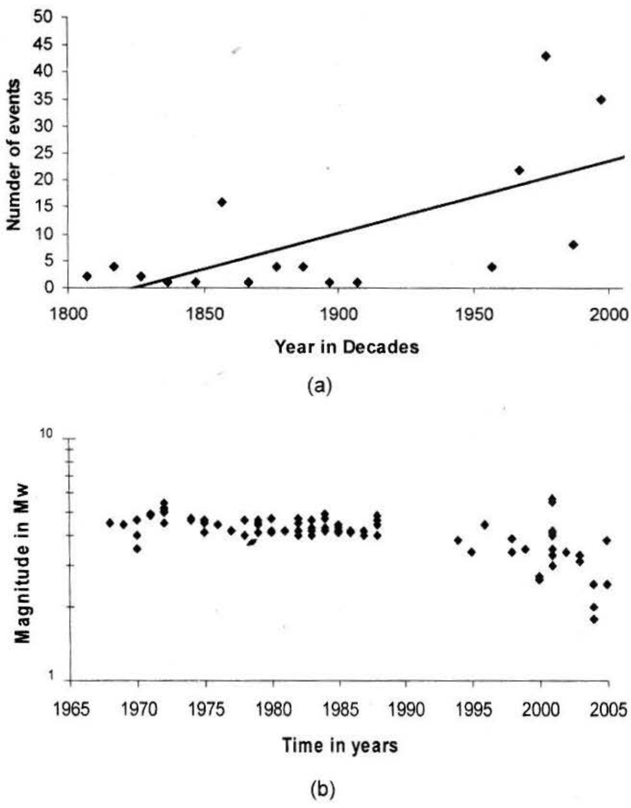

Fig. 1 (a) Number of Earthquake Events per Decade
(b) Magnitude Distribution for Last Four Decades

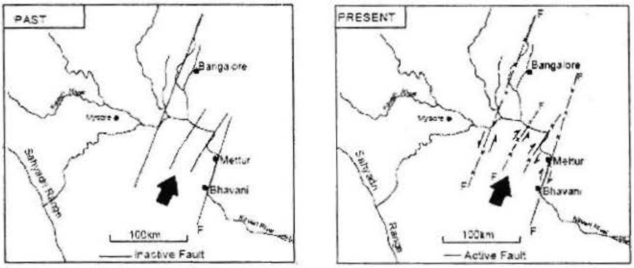

Fig. 2 Active Faults present close to Bangalore (after Valdiya 1998)

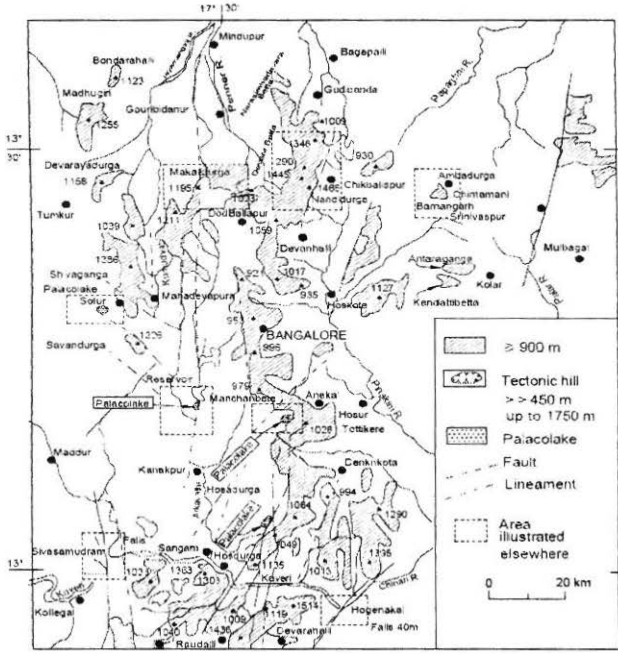

Fig. 3 Active Faults near by Bangalore (after Valdiya 1998)

Geotechnical Data

Geotechnical data was basically collected from archives of Torsteel Research Foundation in India (TRFI) and Indian Institute of Science, (IISc) for geotechnical investigations carried out for several major projects in Bangalore. The data are collected from important projects in Bangalore during the years 1990-2003. So far 852 bore-log information has been keyed into the database. Most of the data so far selected for the database is on a average depth of 20 m below the ground level. Majority of the bores with depths greater than 15 m (See Figure 8) were carried out for several grade separator projects of flyovers, bridges, etc. Most investigations for residential and commercial complexes were below 15 m and wherever bed rock or refusal strata ("N">100) has been encountered, investigation has been terminated at that depth for these projects. The properties keyed into the database at a particular depth are location details, physical properties, grain size distribution, Atterberg limits, and strength properties for soil and rock along with SPT 'N' values. Distribution of boreholes in four quadrants of Bangalore city considering Vidhana Soudha as the centre point (shown in Figure 4) in the North-south and East-West directions is shown in Figure 8. Attempts are being made for geostatistical analysis of the collated data to study the subsurface features and their variations. The GIS model developed currently consists of about 850 borehole locations marked on the digitized Bangalore map of 1:20000 scale. The boreholes are represented as 3 dimensional objects projecting below the map layer in 0.5 m intervals. Also image files of bore logs and properties table have been attached to location in plan. These 3-D boreholes are generated with several layers with a bore location in each layer overlapping one below the other and each layer representing 0.5 m interval of the subsurface. Each borehole in this model is attached with geotechnical data along the depth. The data consists of visual soil classification, standard penetration test results, ground water level, time during which test has been carried out, and other physical and engineering properties of soil. Typical soil profiles for the purpose of general identification of soil layers in the Bangalore area is shown in Table 2.

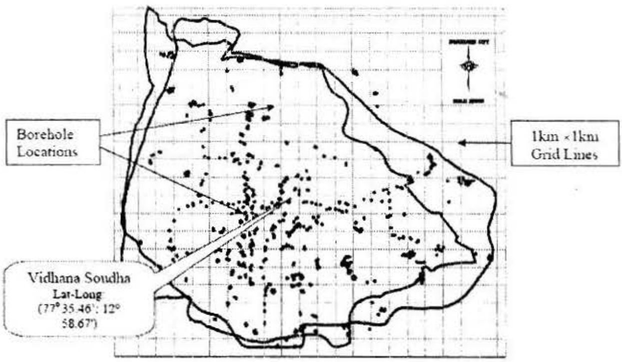

Fig. 4 GIS Model of Borehole Locations in Bangalore

Fig. 5 GIS Model of Borehole Locations with respect to Contours

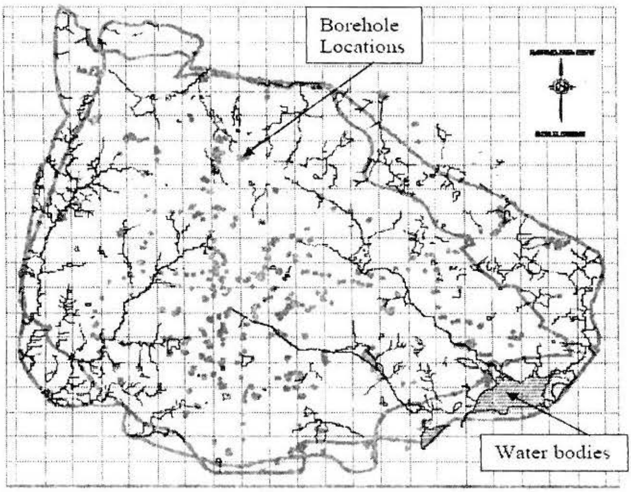

Fig. 6 GIS Model of Borehole Locations with respect to Water Features

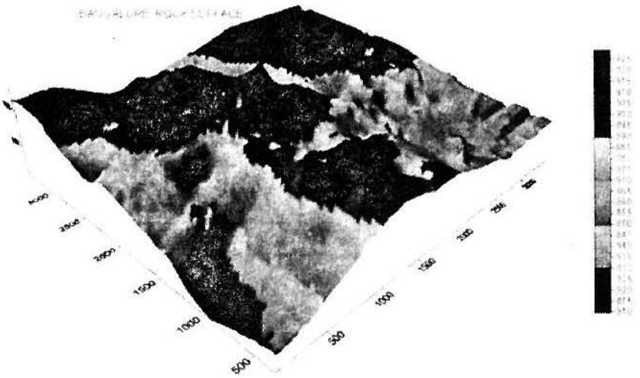

Fig. 7 Rock Level Map of Bangalore City

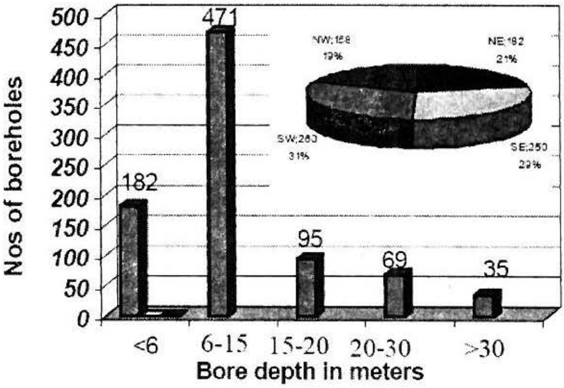

Fig. 8 Distribution of Bores Holes in Quadrant and Depth Wise

TABLE 2: General Soil Distribution in Bangalore

Layer	Soil Description with Depth and Direction			
	Northwest	Southwest	Northeast	Southeast
First Layer	Silty sand with clay 0-3m	Silty sand with gravel 0-1.7m	Clayey sand 0-1.5m	Filled up soil 0-1.5m
Second layer	Medium to dense silty sand 3m-16m	Clayey sand 1.7m-3.5m	Clayey sand with gravel 1.5m-4m	Silty clay 1.5m-4.5m
Third Layer	Weathered Rock 16m-27m	Weathered Rock 3.5m-8.5m	Silty sand with Gravel 4m-5.5m	Sandy clay 4.5m-7.5m
Fourth layer	Hard Rock Below the 27m	Hard Rock Below 8.5m	Weathered rock 5.5m-17.5m	Weathered Rock 7.5m-18.5m
Fifth Layer	Hard Rock	Hard Rock	Hard Rock Below 17.5m	Hard Rock Below 18.5m

Corrections Applied for SPT "N" Values

850 geotechnical bore logs are used to obtain seismic bore logs with the application of appropriate corrections to field SPT "N" values. The seismic bore log 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" value. 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) Bore hole diameter (C_B), (d) presence or absence of liner (C_S), (e) Rod length (C_R) and (f) fines content (C_{fines}) (Seed et al. 1983, 1985; Youd et al. 2001; Cetin et al. 2004, Skempton 1986 and Pearce and Baldwin 2005). Corrected N value i.e. N_{60} is obtained using the following equation:

$$N_{60} = N \times (C_N \times C_E \times C_B \times C_S \times C_R \times C_{fines}) \quad (1)$$

(a) Correction for overburden pressure (C_N) (Seed and Idriss 1982)

$$C_N = 2.2/(1.2 + \sigma'_{vo}/P_a \quad (2)$$

where σ'_{vo} = effective overburden pressure, P_a = 100 kPa, and C_N should not exceed a value of 1.7.

(b) Correction for hammer energy ratio

The energy delivered to the sampler tube depends on the type of hammer, anvil, lifting mechanism and the method of hammer release. The correction factors adopted to modify measured "N" values to a 60% energy ratio for various types of hammer and anvils (Robertson and Wride 1998) are listed in Table 3.

(c)The other correction factors adopted such as correction for borehole diameter, rod length and sampling methods modified from Skempton (1986) and listed by Robertson and Wride (1998) are presented in Table 4.

(d) Correction for Fines Content (Finn et al 1995)

The corrected "N" value ($C_{N\,60}$) is further corrected for fines content as described below:

$$N_{1\,(60)} = N_{60} \times C_{fines} \qquad (3)$$

where C_{fines} = 1 + 0.004FC + 0.055(FC/N60), and

FC = percent fines content (percent dry weight finer than 0.074 mm).

A typical seismic bore log generated for a borehole data is shown in Table 5. From the seismic bore log data, factor of safety against liquefaction is evaluated as explained in the following sections.

TABLE 3: Hammer Correction Factor (Robertson and Wride 1998)

Type of Hammers	Notation	Range of correction
Donut Hammer	C_{ER}	0.5-1.0
Safety Hammer	C_{ER}	0.7-1.2
Automatic-trip Donut Hammer	C_{ER}	0.8-1.3

TABLE 4: Correction Factors for Borehole Diameter (CB), Rod Length (CR) and Sampling Method (CS)

Factor	Equipment Variable	Notation	Correction
Borehole Dia.	65-115mm	C_B	1.00
Borehole Dia.	150mm	C_B	1.05
Borehole Dia.	200mm	C_B	1.15
Rod Length	<3m	C_R	0.75
Rod Length	3-4m	C_R	0.80
Rod Length	4-6m	C_R	0.85
Rod Length	6-10m	C_R	0.95
Rod Length	10-30m	C_R	1.00
Sampling method	Standard samplers	C_S	1.00
Sampling method	Sampler without liners	C_S	1.1-1.3

Factor of Safety against Liquefaction

Factor of Safety against liquefaction of soil layer has been evaluated based on the Simplified Procedure (Seed and Idriss, 1971) and subsequent revisions (Seed et al. 1983, 1985; Youd et al. 2001; Cetin et al. 2004). In this method, the earthquake induced loading is expressed in terms of cyclic shear stress and this is compared with the liquefaction resistance of the soil. The liquefaction potential and resistance calculation procedure adopted are given below:

The Cyclic Stress Ratio is calculated based on simplified approach recommended by Seed and Idriss (1971) and Kramer (1996):

$$\text{Cyclic stress ratio (CSR)} = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma_{vo}'}\right)r_d \qquad (4)$$

The parameter a_{max} is the peak horizontal acceleration at the ground surface generated by an earthquake; a_{max} is estimated using Boore et al. (1993)

relation. g = acceleration due to gravity; σ_{vo} and σ_{vo}' are total and effective vertical over burden stresses, respectively; and r_d = stress reduction coefficient.

Cyclic resistance ratio (CRR) is arrived based on corrected "N" value as per Seed et al. (1985), Youd et al. (2001); Cetin et al. (2004). Seed et al. (1985) presents a plot of CRR versus corrected "N" value from a large amount of laboratory and field data. However this estimation is proposed for a magnitude of 7.5 on the Richter scale. For the present study, for the earthquake local magnitude of 6 and 7 has been considered, and hence the necessary Magnitude Scaling Factor (MSF) has been evaluated. The magnitude - scaling factor for the magnitude less than 7.5 is calculated as below (Seed and Idriss 1982):

$$\text{MSF} = \left[\frac{10^{2.24}}{M_W^{\;2.56}} \right] \tag{5}$$

Finally, factors of safety for liquefaction are calculated using:

$$FS = \left[\frac{CRR_{7.5}}{CSR} \right] MSF \tag{6}$$

The factor of safety for each layer of soil was arrived by considering corresponding "N" values. Typical liquefaction analysis is shown in Table 6. It is to be noted here that, apart from Seed and Idriss (1983) recommendation, the Modified Chinese criterion was also used to arrive at the factor of safety for the clayey sand and silty clayey soils. The Modified Chinese Criteria has been applied by considering the Atterberg limits of soil. As per the modified Chinese criteria, if Liquid limit of the soil is greater than 35, the deposits are classified as non liquefiable.

Liquefaction Hazard Maps and Discussion

To prepare the hazard zoning map, Bangalore map along with different layers as discussed earlier have been used. Liquefaction 'susceptibility' is a measure of a soil's inherent resistance to liquefaction, and can range from not susceptible, regardless of seismic loading, to highly susceptible, which means that very little seismic energy is required to induce liquefaction. Susceptibility has been evolved by comparing the properties of top soil deposits of Bangalore to the other soil deposits where liquefaction has been observed in the past (based on Seed et al. 1985). Liquefaction susceptibility was evaluated based on the primary relevant soil properties such as grain size, fine content, and density, degree of saturation, SPT "N" values and age of the deposit of each bore logs. These susceptible areas have been identified by considering the approach of Pearce and John (2005) i.e. soil is susceptible for liquefaction if (1) presence of sand layers at depths less than 20 m, (2) encountered water table depth less than 10 m, and (3) SPT field "N" blow counts less than 20. Liquefaction susceptibility map for Bangalore city has been shown in Figure 9. From the Figure susceptible areas are only considered for the evaluation of factor of safety against liquefaction.

TABLE 5: Seismic Bore Log for Borehole

BHL 157-2										Water Table = 1.2m/05-12-1996			
							Correction Factors For						
Depth, m	Field "N" Value	Density (kN/ m³)	T.S kN/ m²	E.S kN/ m²	C_N	Hammer Effect	Bore hole Dia	Rod Length	Sample Method	$C.N_1$	F.C %	C.F.C	Corrected "N" Value
1.50	1	20.00	30.00	30.00	1.47	1	1.05	0.75	1	1.16	70	4.310	5
4.00	1	20.00	80.00	55.48	1.25	1	1.05	0.8	1	1.05	75.3	4.876	5
5.50	21	20.00	110.00	70.76	1.15	1	1.05	0.85	1	21.62	53.3	1.336	29
6.60	17	20.00	132.00	81.97	1.09	1	1.05	0.85	1	16.53	49.8	1.350	22
8.00	33	20.00	160.00	96.24	1.02	1	1.05	0.95	1	33.49	66.1	1.363	46
9.20	61	20.00	184.00	108.46	0.96	1	1.05	0.95	1	58.59	55.1	1.267	74

T.S = Total Stress, E.S = Effective Stress, C_N = Correction for overburden correction;
F.C = Fines content; N_{60} = Corrected 'N' Value; C_{fines} = Correction for Fines content;
$N_{1(60)}$ = Corrected 'N' Value after correction for fines content

TABLE 6: Typical Liquefaction Analysis for a Borehole

BHL 157 – 2: Peak Acceleration (g) = 0.066; Magnitude, M_w = 6.0

Depth (m)	Corrected 'N' value	σ_{vo} kN/m²	σ_{vo}' kN/m²	r_d	CSR	FC %	Liquid Limit %	CRR	MSF	FS
1.50	5	30.00	30.00	0.98	0.04	70	32	0.05	1.77	2.11
4.00	5	80.00	55.48	0.94	0.06	75.3	30	0.05	1.77	1.52
5.50	29	110.00	70.76	0.92	0.06	53.3	25	0.55	1.77	15.91
6.60	22	132.00	81.97	0.90	0.06	49.8	29	0.40	1.77	11.37
8.00	46	160.00	96.24	0.88	0.06	66.1	34	0.55	1.77	15.51
9.20	74	184.00	108.46	0.86	0.06	55.1	31	0.55	1.77	15.52

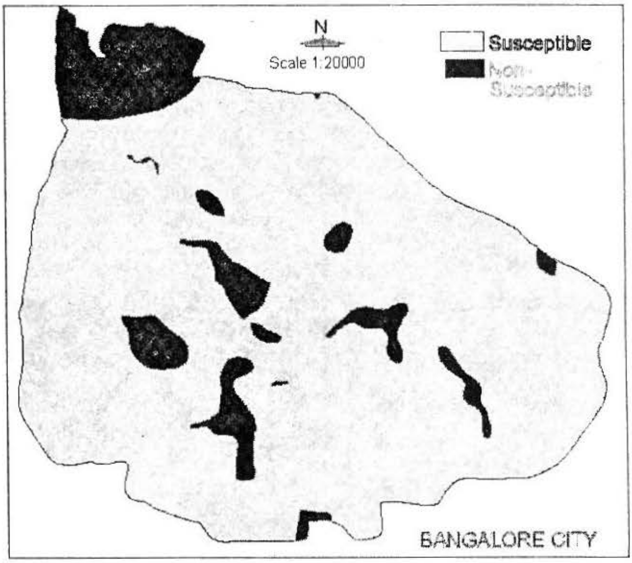

Fig. 9 Liquefaction Susceptibility Map for Bangalore City

Liquefaction hazard mapping has been done by many researchers using the SPT data in particular Palmer et al (2003), Brankman et al. (2004), Pearce and John (2005) and Yilmaz and Bagci (2005). Similar kind of approach is followed in this paper. The preliminary liquefaction hazard maps are prepared for the assumed local magnitude of 6 and 7. The minimum factor of safety from each bore log has been considered to represent the factor of safety against liquefaction at location, which are used for the mapping. These factors of safety against liquefaction have been grouped in to 7 groups as shown in Table 7.

Figure 10 shows the map of factor of safety against liquefaction (FS) for Bangalore city to the local magnitude of 6. Figure 10 shows that factor of safety against liquefaction locations are more than unity for a local magnitude of 6. Southern part and close to the central part of the city has a FS value of 1 to 2. From the bore logs it is clear that the top surface up to 1.5 m has filled up soil followed by the Fine to medium silty sand up to depth of 8.0 m. Also a ground water table varies from 0.5 to 1.2 m below the ground level. Middle of the southeastern part show a FS of 2 to 3; this is attributed to presence of thick silty sand layer up to depth of 6.5 m. Here also the ground water table varies from 0.5 to 0.9 m. Further FS 3 to 4 is identified in a small area in the central western side of city. The ground water table is found at a depth of 0.5 to 0.8 m from the ground level. Also, subsurface is characterized by sandy silt and silty clay layers found up to a depth of 5.5 m, having field "N" of 4 to 12. Area in the middle of the southeastern part of city shows FS of 4 to 5 due to presence of silty sand with clay up to depth of 5m having the field "N" value of 7 to 14. The ground water table in the area varies from 1.2 to 5 m. Major part of city shows that the factor of safety against liquefaction are more than 5 for the magnitude of 6, which is due to the presence of clayey sand and dense silty sand having the field "N" values of 15 and above. These areas also witness the ground water table at deeper depth.

Figure 11 shows the distribution of factor of safety against liquefaction for the local earthquake magnitude of 7. In this map, area covering the lower factor of safety (<5) is more when compared to the local earthquake magnitude of 6. It is obvious that increase in the magnitude increases the CSR values and thus increasing the possibility of liquefaction susceptibility. Bangalore city is safe against liquefaction except few locations where shallow water table with sand silty and filled up soils has been found.

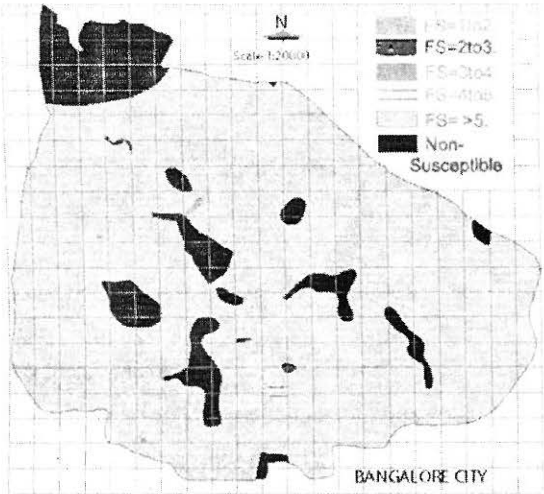

Fig. 10 Factor of Safety against Liquefaction for the Local Magnitude of 6

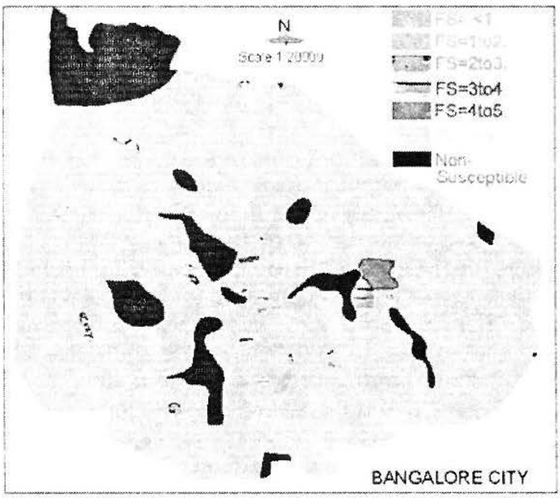

Fig. 11 Factor of Safety against Liquefaction for the Local Magnitude of 7

Cyclic Triaxial Experiments: Undisturbed Soil Samples

Undisturbed samples were collected from few locations in (south west region) Bangalore city to verify the liquefaction potential of the soil. This is done by conducting cyclic triaxial test in the laboratory on the undisturbed soil samples collected from Boreholes locations of 482, 810 and 91. The test has been carried out as per ASTM: D 3999 (1991) in strain controlled mode. Cyclic triaxial tests are carried out with double amplitude axial strains of 0.5%, 1% and 2% with a frequency of 1Hz. A typical cyclic triaxial test results are presented in Figures 12 and 13. Figure 12 shows the variation of deviatoric stress versus strain plot for more than 120 cycles of loading (axial strain = 0.25%; applied confining pressure 100 KPa, for the undisturbed sample corresponding to depth 3m below GL, in-situ density of the soil sample 2.0 gm/cc with in-situ moisture content 15%, at 3.0 m depth). Figure 13 shows the pore pressure ratio versus number of cycles. From these plots it is clear that even after 120 cycles, the average pore pressure ratio is about 0.94 and deviatoric stresses vs. strain plots have not become flat, indicating no liquefaction. The resistance to liquefaction is very high. The calculated factor of safety against liquefaction results, for this borehole is also very high indicating no liquefaction. These results matches well with the lab test results.

TABLE 7: Factor of Safety and Severity Index of Liquefaction

Group	Factor of safety range	Severity Index
1	<1	Very High
2	1 to 2	High
3	2 to 3	Moderate
4	3 to4	Low
5	4 to 5	.Very Low
6	>5	Nil
7	Not Susceptible	NL

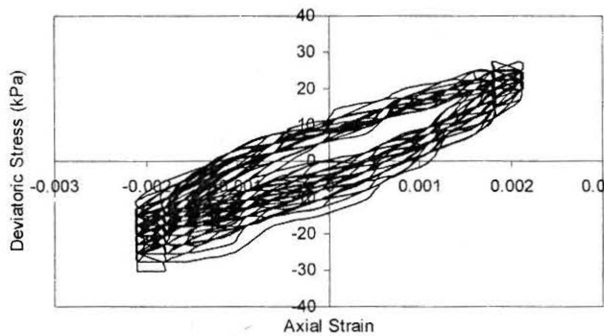

Fig. 12 Typical Hysteresis Loops from a Cyclic Triaxial Test

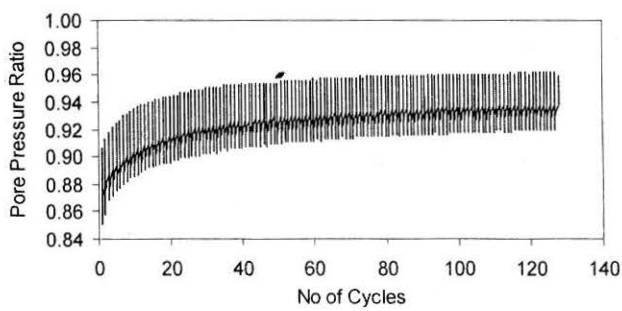

Fig. 13 Typical Pore Pressure Ratio Plot with Number of Cycles

Concluding Remarks

In this study, a 3-D subsurface geotechnical model has been generated based on large amount of geotechnical borehole data and Geographical Information System on a scale of 1:20000 for the Bangalore city. This model has been prepared by superposing Bangalore city map with important layers such as buildings, streets, roads, railway network, water bodies, contours and bore logs with geotechnical test data. The preliminary liquefaction hazard study has been carried out by assuming the local earthquake magnitude of 6 and 7. Liquefaction susceptibility map has been prepared based on the soil layer properties, water table depth and field "N" values. The factor of safety against liquefaction for the susceptible areas in Bangalore city have been calculated by developing simple spread sheets using simplified procedure for each block area of 1km x 1km and presented in the form of 2-dimensional maps. Study shows that Bangalore is safe against liquefaction except at few locations where the overburden is sandy silt with shallow water table. Stain controlled Cyclic triaxial tests on undisturbed soil samples collected from south west region of Bangalore city indicates that the soil is not susceptible for liquefaction.

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