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Liquefaction Hazard Mapping of Chennai, India using SPT Data

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Abstract: Liquefaction hazard is one of the major concerns for earthquake geotechnical engineering. In this paper an attempt has been made to assess liquefaction potential of Chennai city using SPT N values. Chennai is located between 12.75° to 13.25° N and 80.0° to 80.5° E on the southeast coast of India and in the northeast corner of Tamil Nadu. To understand the liquefaction possibility of Chennai city, about 650 Borelogs have been collected from different geotechnical agencies and used for the analysis. These boreholes were drilled for different projects in Chennai, most of them were drilled up to hard stratum and a minimum depth of 10m. SPT borehole data contains information about depth of water table, the classification of soil and the field observed 'N' values, index properties, rock depth. These borehole information are used to prepare N corrected table by applying the universally followed correction factors for liquefaction study. These corrected N values are further used to estimate the factor of safety against liquefaction of soil layer. Based on the factor of safety, the regional liquefaction hazard maps have been developed for depths of 1.5m, 3.0m, 6.0m and 10.0m. To represent the worst scenario, least factor of safety has been identified for each borehole location and mapped. Further the estimated factor of safety against liquefaction is used to estimate liquefaction potential index by considering depth of layer. These results are analyzed and compared in this paper.

Keywords: *Earthquakes, liquefaction, Liquefaction potential and SPT*

Introduction:

Liquefaction potential of an area is one of the important factors to be considered in an earthquake prone area during site selection and planning stages of engineering structures and human settlements. Liquefaction is most likely to occur in case of moderate to high magnitude 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 (Marcuson 1978). Usually sites close to the epicenter or location of fault rupture of an earthquake with ground water close to ground surface are most susceptible to liquefaction. For a particular site, cohesion less soil with uniform gradation and round shape, in a very loose state, which has been recently deposited with no cementations and no prior preloading or seismic shaking, is most susceptible to liquefaction. First step towards mitigation of liquefaction hazard is evaluating and mapping of the liquefaction potential of soil zones in the area. Past earthquake damages have left the lesson that study of seismic microzonation i.e mapping of earthquake hazard values and its effects for earthquake prone can help to reduce the earthquake damages. Microzonation is a process that involves incorporation of Geologic, Seismologic and Geotechnical concerns into Economically, Sociologically and politically justifiable and defensible land-use planning for earthquake effects so that architects and engineers can place and design structures that will be less susceptible to damage during earthquakes. Liquefaction hazard mapping is the one of the most important component in the process of seismic microzonation mapping. Liquefaction hazard mapping has been done by many researchers worldwide, in particular Todorovska and Trifunac (1999); Aaron et al (2001); Kelson et al (2001); Dellow et al (2003); Utah Geological Survey (2003); Palmer et al (2003); Sonmez (2003); Pearce et al (2004); Brankman et al (2004), Ozdemir and Ince (2005); Yilmaz and Yavuzer (2005); Pearce and Baldwin (2005); Yilmaz and Bagci (2006); Holzer et al (2006); Baise et al (2006) and USGS (2006). In this study, an attempt has been made to map the liquefaction hazard of Chennai city using about 650 SPT boreholes with N values. Factor of safety against liquefaction (FS) has been estimated considering simplified procedure (Seed and Idriss, 1971) and subsequent revisions of the simplified procedures (Seed et al., 1983, 1985; Youd et al., 2001; Cetin et al., 2004). Estimated FS has been used to prepare liquefaction factor of safety map for a depths of 1.5m, 3.0m, 6.0m and 10.0m. To represent the worst possibility, least factor of safety from each borehole has been identified mapped. Further liquefaction potential index has been estimated considering the factor of safety and depth of layer.

Study Area and Seismicity:

Chennai is located between 12.75° – 13.25° N and 80.0° – 80.5° E on the southeast coast of India and in the northeast corner of Tamil Nadu. It is India's fourth largest metropolitan city covering an area of 1,177 km². The city stretches nearly 25.60 km along the bay coast from the southern part to the northern part of the city. The seacoast is flat and sandy for about one km from the shore. Topographically the area has a very gentle easterly slope of approximately 0.001 with a few isolated hillocks and depressions. The shallow bed rock has been reported in east and south zone of city and deep bed rock at central, west and north zone of the city (Ballukraya and Ravi 1994, Anbazhagan, 2004). Four cycles of erosion have been identified and the land forms constitute assemblage of fluvial estuarine and marine deposits. Two ephemeral rivers, Cooum to the North and Adyar to the South, meander through the study area. There is also a waterway now blocked, running parallel as close to the sea coast. Almost the entire area is covered by the Pleistocene / Recent Alluvium, deposited by two rivers, Cooum and Adyar. . The thickness of this formation ranges from a few meters in the southern parts to as much as 50 m in the central and northern parts, with an average of 20 to 25 m. This is made up of mainly clays, sands, sandy clays and occasional boulder/ gravel zones (Boominathan et al, 2008). India has long seismic history in Himalayan region attributed by plate boundary earthquakes and moderate seismic history in peninsular region. Even though only a few major earthquakes have been reported in peninsular India, but they are catastrophic. These earthquakes have alarmed researchers to understand and map the effects of earthquake in urban areas. Seismicity of India and Peninsular India has been addressed by many researchers and those details are presented in Anbazhagan (2007). The author has highlighted that seismic activity in the peninsular India has increased when compared to the past based on many researchers' comments. The seismic hazard map of India was updated in 2000 by the Bureau of Indian Standards (BIS). According to the new map more areas of Tamil Nadu are susceptible to damage from earthquakes than previously thought (ASC, 2009). The city of Chennai, formerly in Zone II now lies in Zone III. Boominathan et al, (2008), presented the site response study of Chennai using deterministic seismic hazard analysis and generated amplification site period and Spectral acceleration ratio maps. Vipin et al (2009) generated surface peak ground acceleration map of south India assuming the different site class of A, B, C and D using probabilistic hazard analysis. The author has shown that expected surface PGA for site class D is 0.25g for 10% probability of exceedance in 50 years. As there is no detailed PGA map available for Chennai city, PGA value given by Vipin et al (2009) is considered in the paper for liquefaction study.

Spt Borehole Data with N Corrections:

Geotechnical borehole data with SPT N values and soil properties were collected from different geotechnical investigation companies by Anbazhagan (2004) and used for preliminary microzonation of Chennai city. Preliminary investigation liquefaction results are presented in Anbazhagan and Premalatha (2004). From this data base About 650 borelogs have been selected for this study, most of these bore logs having SPT- N values with index and engineering properties up to rock depth and a few of them up to 10 - 20m depth. The SPT data collected are 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 borelog contains 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}). The details of N correction and typical calculation have been presented in Anbazhagan (2007 and 2009).

Liquefaction Studies in India:

Historically ground failure due to liquefaction has not been 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 (Rajendran and Rajendran, 2001). Paleo-liquefaction studies in Assam also confirm liquefaction failures during Assam earthquake (Sukhija et al., 1999). Recent 2001 Bhuj liquefaction failures are classical examples of failure due to liquefaction in India. In India limited work has been done towards liquefaction hazard mapping, Ramakrishnan et al (2003) have derived a band ratio to map liquefaction and test 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 (2004); Anbazhagan and Premalatha (2004) and Rajesh and Balasenthilnathan (2005) presented preliminary liquefaction hazard mapping of Chennai city. Rao and Neelima Satyam (2007) assessed in detail the liquefaction potential of soils in Delhi using about 1200 SPT-boreholes and published a liquefaction hazard map of Delhi. Sahoo et al (2007) presented the evidence for the liquefaction in India near Baramulla (Jammu and Kashmir) due to the 2005 Kashmir earthquake. Anbazhagan and Sitharam (2008) presented the liquefaction susceptibility map, least factory of safety against liquefaction map with cyclic Triaxial result for Bangalore region. Anbazhagan (2009) published safe and vulnerable zones in Bangalore for the liquefaction based on liquefaction potential index and liquefaction severity index.

Estimation of 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 of the simplified procedures (Seed et al., 1983, 1985; Youd et al., 2001; Cetin et al., 2004). 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.

1. The seismic demand of a soil layer is represented by a Cyclic Stress Ratio (CSR).
2. 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:

$$FS = \left(\frac{CRR_{7.5}}{CSR} \right) MSF \quad ....(1)$$

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. A detailed procedure to calculate the factor of safety against liquefaction has been given in Anbazhagan (2009). After applying necessary corrections to SPT 'N' values (as discussed in above) corrected "N" [$(N_1)_{60cs}$] values were obtained. A simple excel spread sheet has been developed to automate these calculations for all the 640 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.

Table 1: *Typical Liquefaction Analysis Calculation*

Epichlorohydrin M/s TPL TPL North site, Manali
Magnitude, Mw = 6, Peak Acceleration (g) = 0.25

Depth	Corrected	σ_{vo}	σ_{vo}'	rd	CSR	FC	Liquid Limit	CRR	MSF	FS
(m)	N value	KN/m^2	KN/m^2			%	%			
2.5	9	42.5	17.98	0.98	0.38	0	0	0.11	1.56	0.46
3.5	5	57.5	23.17	0.97	0.39	0	1	0.08	1.56	0.33
4.5	6	72.5	28.36	0.97	0.4	0	2	0.09	1.56	0.35
5.5	5	87.5	33.55	0.96	0.41	0	3	0.09	1.56	0.34
7	11	111.5	42.83	0.95	0.4	22	4	0.13	1.56	0.5
8.5	10	134	50.62	0.93	0.4	25	5	0.12	1.56	0.47
10	6	158	59.9	0.91	0.39	0	6	0.09	1.56	0.38
12	12	194	76.28	0.85	0.35	0	7	0.14	1.56	0.6
14	26	228	90.66	0.8	0.33	33	8	0.32	1.56	1.53
16	14	260	103.04	0.75	0.31	0	9	0.15	1.56	0.78
18	24	296	119.42	0.69	0.28	19	10	0.27	1.56	1.49
20	8	326	129.8	0.64	0.26	19	11	0.11	1.56	0.63
22	34	364	148.18	0.59	0.23	19	12	0.88	1.56	5.89
24	19	398	162.56	0.53	0.21	19	13	0.19	1.56	1.4

Mapping of Factor of Safety against Liquefaction:

Factor of safety against liquefaction corresponding to depth of 1.5m, 3.0m, 6.0m and 10.0m are complied and mapped separately. Figure 1a and 1b shows FS map at depth of 1.5m and 3.0m from the original ground level. Figure 1a shows that major part of the study area has the factor of safety of more than 1.2, which is basically safe from liquefaction and many smaller patches of area close to the coast and rivers which show FS less than 1.2. Similarly Figure 1b shows the major area having FS more than 1.2 but this area is comparatively less when compared to the corresponding area in 1.5m depth. Area having FS of less than 1.2 is larger at 3.0m depth when compared to the 1.5m depth. Figure 2a and b shows FS map for a depth of 6.0m and 10.0m depth. Figure 2a and 2b show similar patterns i.e area having FS more than 1.2 is covering major part of city particularly western and southern part of study area and area having FS less than 1.2 is covering lesser part of city particularly on eastern and north east part of the study area. Further the minimum factor of safety from each bore logs has been mapped by considered the lowest factor of safety values at that location. Figure 3 shows the map of minimum factor of safety against liquefaction (FS) for Chennai city. For the worst case liquefaction possibility is represented by the minimum factor safety map, which shows that major part of north, east and Southern side of city has FS less than 1.2. Even though these maps are giving the FS at different depth and least FS for location, these maps have not taken the layer thickness into account, which is one of the important factors in liquefaction phenomena. Liquefaction potential of Chennai city has been further investigated using FS and layer thickness using liquefaction potential index (LPI) and liquefaction susceptibility index (LSI) in the next section.

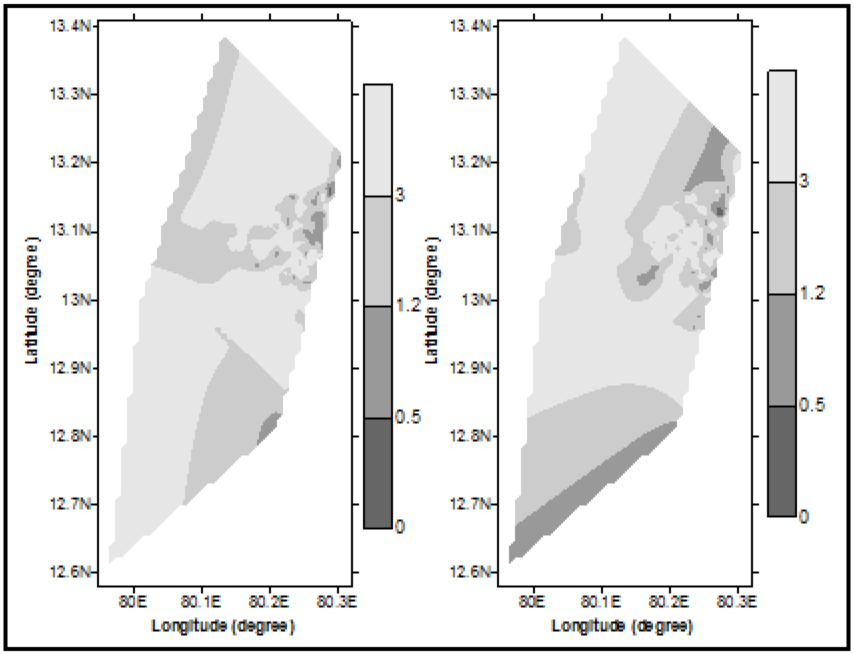

Figure 1 (a) and (b): *Factor of Safety at a Depth of 1.5m and 3.0m*

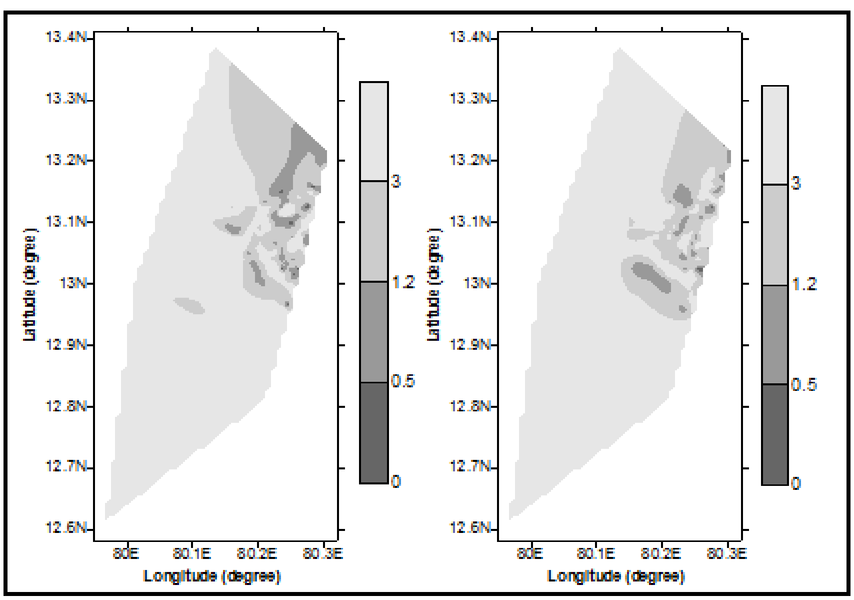

Figure 2 (a) and (b): *Factor of Safety at a Depth of 6.0m and 10.0m*

Mapping Of 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 cannot be used to quantify the severity of liquefaction of a particular location (Sonmez and Gokceoglu, 2005). To address this issue, Iwasaki et al (1982) proposed liquefaction potential index (L_I) and its severity categories. The details about the liquefaction potential index are presented in Anbazhagan (2009). The estimated L_I is grouped according to Sonmez (2003) liquefaction potential category.

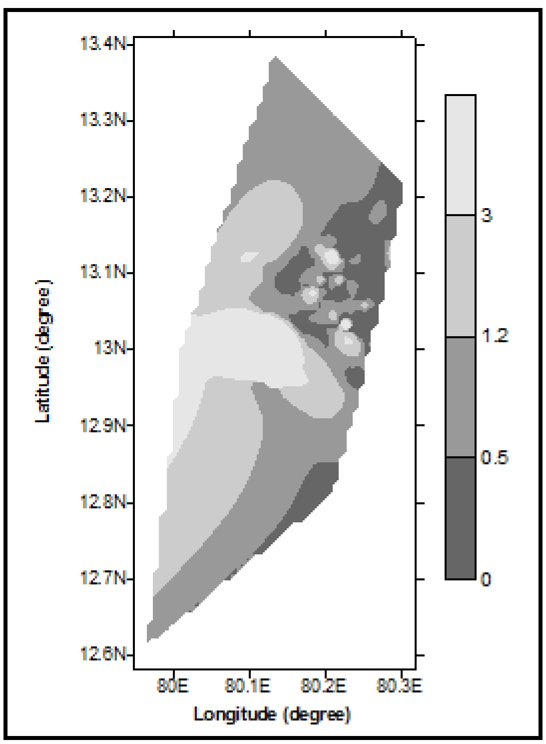

Figure 3: *Map of Minimum Factor of Safety*

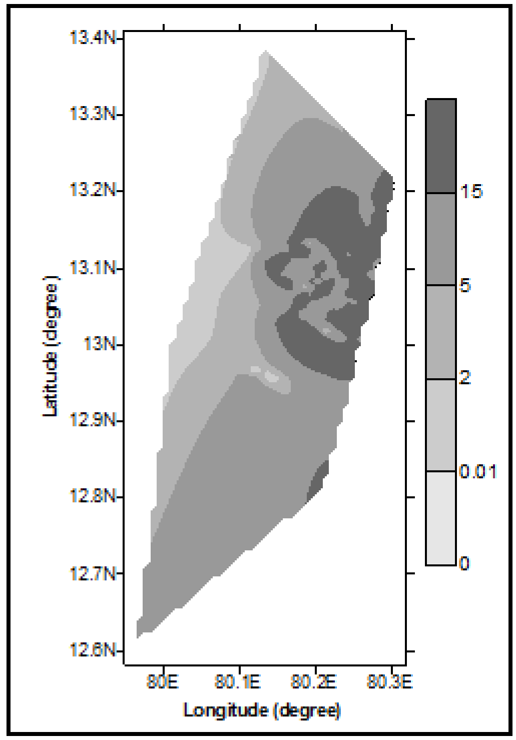

Figure 4: *Map of Liquefaction Potential Index for Chennai City*

Figure 4 shows the map of liquefaction potential index for the study area considering liquefiable layer thickness. The study shows that small part in the western side of study area is non liquefiable (L_I is 0) and major portion of study area is liquefiable (L_I > 0). Eastern part of study area may have moderate to very high liquefaction potential and central part of study area may have low to moderate liquefaction potential. These results match well with the map of minimum factor of safety against liquefaction (Figure 3).

Mapping of Liquefaction Severity Index:

Determination of factor of safety against liquefaction using deterministic method is not the best method to judge whether liquefaction occurred in a post-earthquake investigation or not, due to an unknown degree of conservatism (Yuan et al. 2003). The probabilities of soil liquefaction depending on factor of safety values are performed by Chen and Juang (2000) and Juang et al. (2003). Equation for the probability of liquefaction is proposed by Juang et al. (2003) 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, (2005). Lee et al. (2003) proposed liquefaction risk index (I_R) by combining Juang et al. (2003) and Iwasaki et al (1982). Sonmez and Gokceoglu, (2005) presented the limitations and alternate name for liquefaction risk index. Sonmez and Gokceoglu, (2005) proposed the revised probabilities of soil liquefaction depending on factor of safety values called liquefaction severity index (L_S) and its classification. The details about liquefaction severity index are presented in Anbazhagan (2009). For the study area liquefaction severity index (L_S) is shown in Figure 5.This study shows that major of the part of the western side of the study area has probability of 0 to 15%. Eastern parts of study area have liquefaction probability of 15% to 65% post earthquakes. This study reveals that mapping of FS with depth can help to identify liquefiable layer and mapping of minimum FS can help to understand worst possibility of liquefaction. But both of them are unable to provide the quantified information about the severity of liquefaction at particular site, which is essential for seismic microzonation. Mapping of liquefaction potential index is directly linked to damage to engineering structures, because damage tends to be severe if the liquefiable layer is thick. But liquefaction potential index map will not give probability of liquefaction for future earthquakes. The mapping of liquefaction severity index of the study area can provide the information about probability of liquefaction post occurrence of an earthquake.

Conclusions:

In this study, liquefaction potential of the study area has been mapped by three approaches, 1) mapping factor of safety for a depth of 1.5m, 3.0m 6.0, and 10m and minimum irrespective of depth, which can be used to find liquefiable area for worst case. 2) Mapping liquefaction potential index, which can be used to calculate 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 estimate the probability of liquefaction for post earthquake. These three maps have their own advantages depending on the application. This study shows that many locations have lesser values of factor of safety against liquefaction, only if the least factor of safety is mapped. Liquefaction potential index mapping shows that the liquefiable area is more on eastern side of the study area. Major part of the study area is liquefiable with a probability of 35 to 65% post earthquakes considered for study.

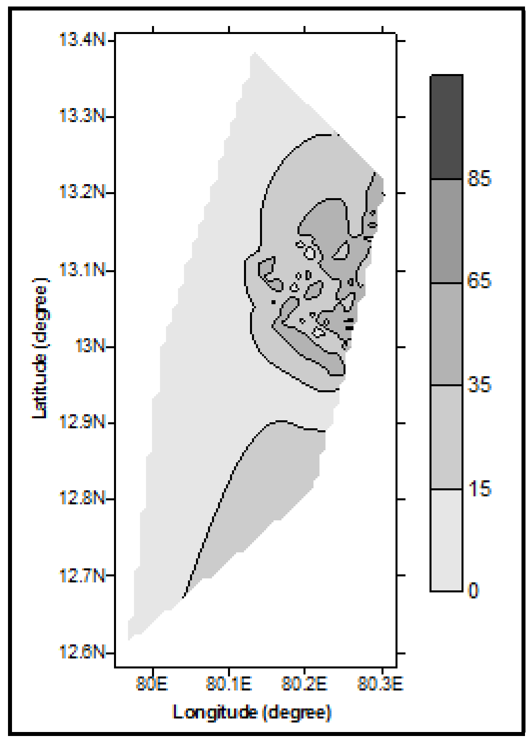

Figure 5: *Mapping of Liquefaction Severity Index*

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