9.6 Soil Liquefaction Hazard Scenario considering PGA for 10% Probability of Exceedance in 50 years with 475 years Return Period at the Surface Consistent Level

Kolkata may get inflicted from a wide range of ground motions generated from the seismotectonic framework of the City. Therefore, the reliable liquefaction hazard assessment requires the consideration of all the ground motions and the earthquakes contributing to the same. In order to consider the ground motion generated from all the future possible earthquakes of various magnitudes at each possible distance, PGA values with 10% probability of exceedance in 50 years with 475 years of return period at surface level assessed by performing Probabilistic Seismic Hazard Analysis (described in Chapters 4 and 8) has been used to generate a deterministic soil liquefaction scenario and to provide a perspective of the liquefaction risk of the region. Earthquake magnitude is used as a proxy for duration in liquefaction analyses and also in the MSF calibration. Various researchers have proposed the use of modal magnitude *i.e.* the magnitude corresponding to the strongest contribution to PGA for the MSF evaluation; however, the use of mean magnitude produces results closer to those computed with the entire distribution of possible magnitudes than that of modal magnitude (Kramer, 2008). Therefore, for the present analysis mean magnitude of all the earthquakes considered for the PSHA analysis *i.e.* M_w 6.8 has been used for the calibration of Magnitude Scaling Factor at each borehole location. The PGA values with 10% probability of exceedance in 50 years at surface level of a few representative sites are presented in Table 9.11.

Table 9.11 **Peak Ground Acceleration (PGA) for 10% probability of exceedence in 50 years with 475 years of return period at surface level for the representative sites of Kolkata**

Location	PGA (g) at surface level
Barabazar	0.234
Saltlake	0.288
Paikpara	0.263
Howrah	0.222
Shibpur	0.250
Sarsuna	0.250
Alipur	0.196
Sonarpur	0.209
Dum Dum	0.245
Rajarhat	0.265

In order to estimate the overall variation of FOS of the region corresponding to PGA values with 10% probability of exceedance in 50 years with depth, box plot of the FOS values against liquefaction of the study region for the four depth ranges *i.e.* 0-5 m, 5-10 m, 10-15 m and 15 m & below has been generated and depicted in Figure 9.16 in addition to the fundamental statistical elements, *i.e.* minimum value, maximum value, mean value, first quartile (25th percentile) and third quartile (75th percentile) of FOS values. It has been observed in these box plots that FOS values are at the lowest at most of the sites, with closest interquartile range of 0.4-0.9 for the depth range of 5-10 m followed by the FOS values corresponding to the sediments lying at the depth range of 10-15 m with the interquartile range of 0.6-1.0, which suggests the vulnerability of sediments to liquefaction in the depth range of 5-15 m.

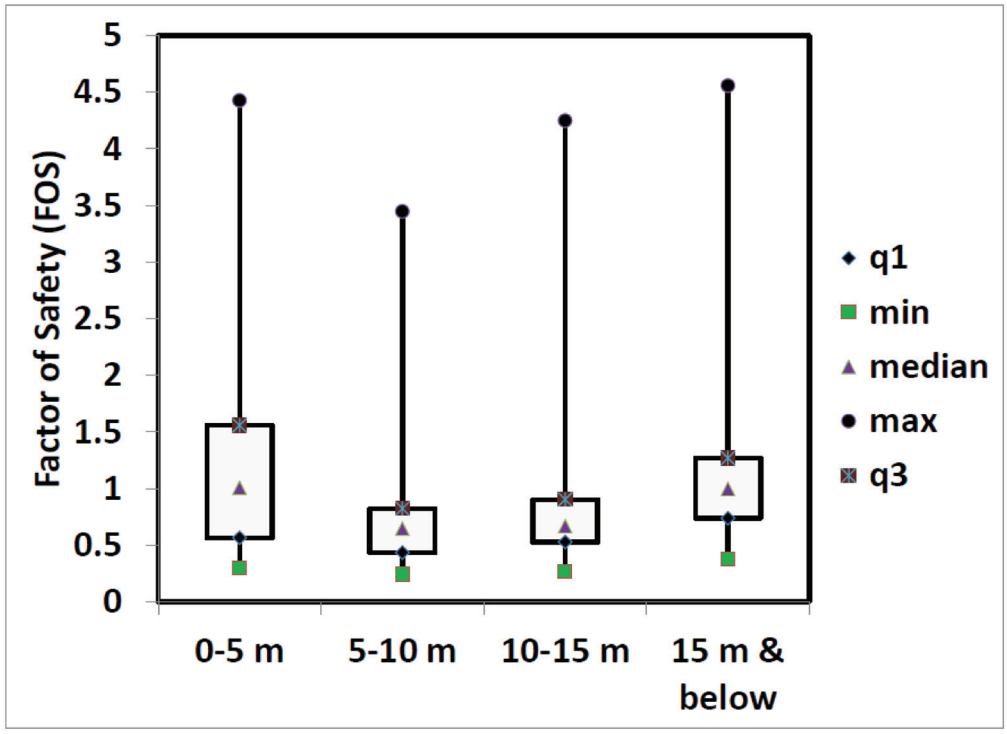


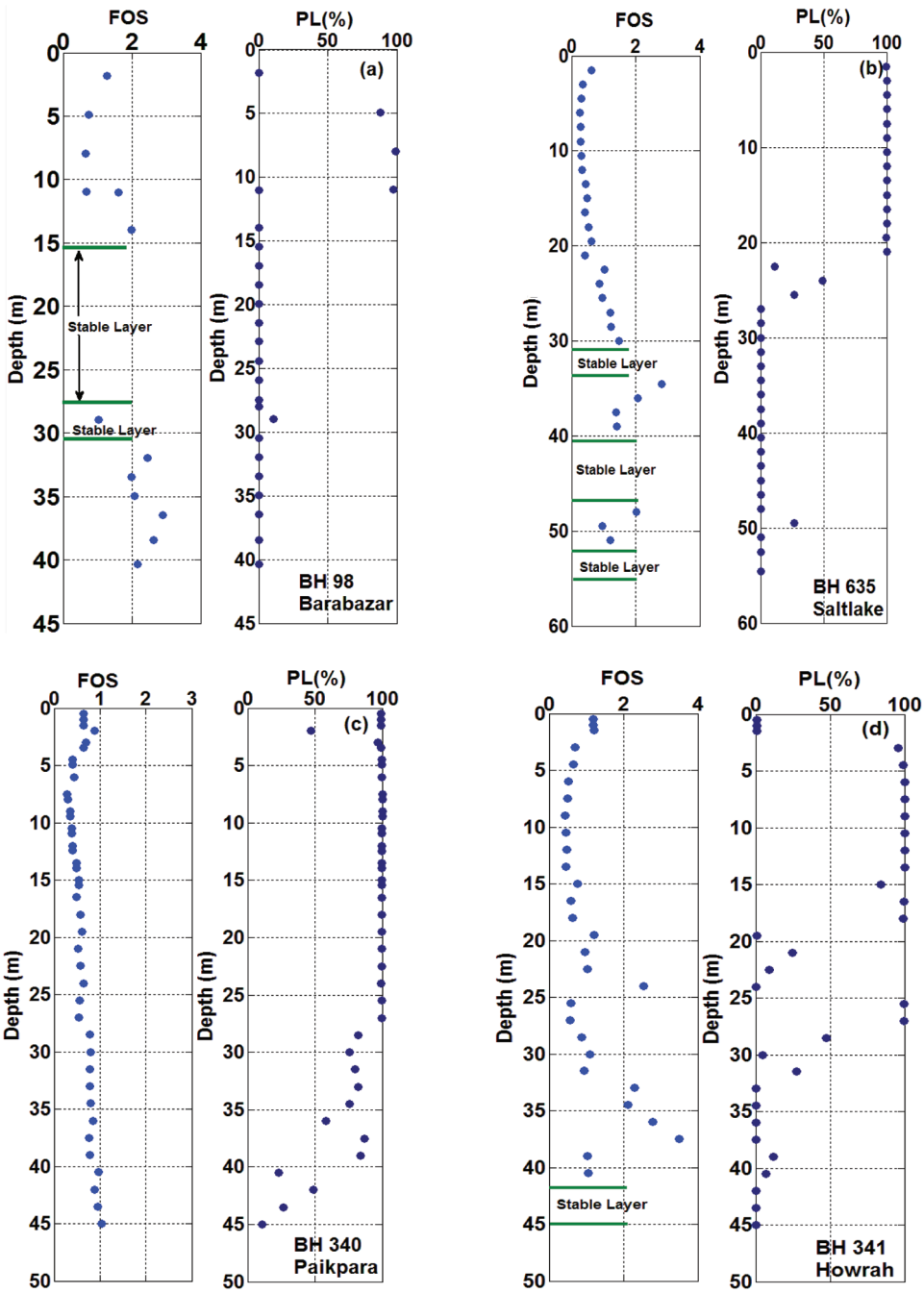
Figure 9.16 **Box Plot of Factor of Safety for PGA values for 10% probability of exceedance in 50 years with 475 years of return period at surface level at a depth range of 0-5 m, 5-10 m, 10-15 m and 15 m & below. 'q1' and 'q3' represents first quartile (25th percentile) and third quartile (75th percentile) respectively whereas, 'min', 'median' and 'max' indicate minimum, median and maximum value of computed FOS values.**

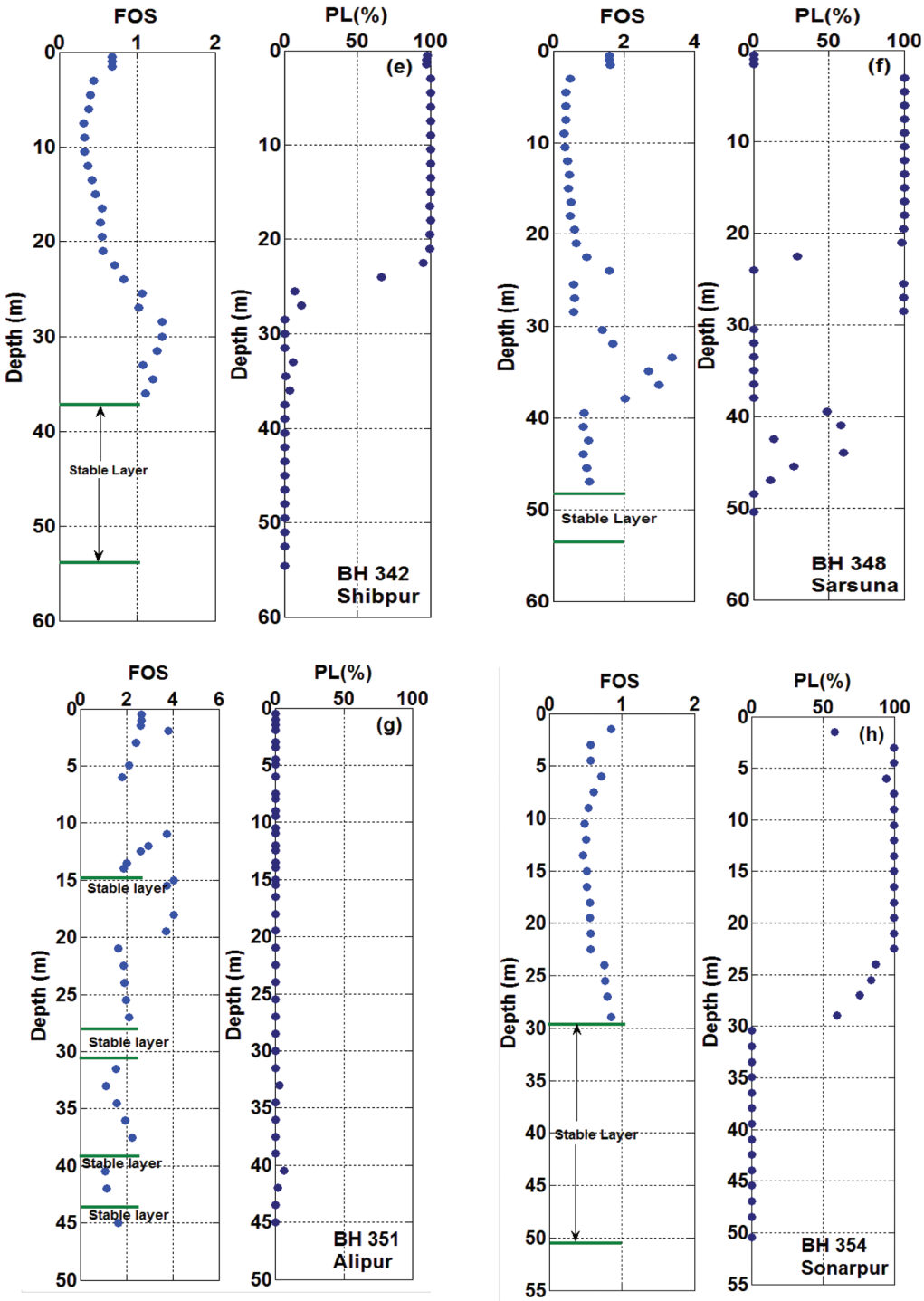
A representative computation for a borehole located at Rajarhat with PGA of 0.265g for the considered scenario is presented in Table 9.12.

Table 9.12 **A representative computation of attributes *viz.* FOS, P_L and LPI to quantify soil liquefaction for Rajarhat by considering PGA values with 10% probability of exceedance in 50 years with 475 years of return period at surface level**

BH No.	630	GWL	6.4 m					PGA	0.265g
Depth	SPT-N	FC (%)	$(N_1)_{60}$	$(N_1)_{60cs}$	CRR	r_d	CSR	FOS	P_L
1.95	4	80	6.3236	12.0712	0.1330	0.9852	0.1993	0.6672	98.27
3.45	4	71	5.0072	10.8399	0.1240	0.9645	0.1951	0.6354	99.36
4.95	3	58	3.2067	9.2114	0.1126	0.9410	0.1904	0.5917	99.88
6.45	3	80	3.0202	8.7678	0.1097	0.9153	0.2128	0.5153	100.00
7.95	3	80	2.8638	8.6114	0.1086	0.8877	0.2291	0.4741	100.00
9.45	1	80	0.9200	6.6676	0.0961	0.8590	0.2409	0.3990	100.00
10.95	6	42	5.2445	11.6170	0.1296	0.8295	0.2482	0.5223	100.00
12.45	7	42	5.8341	12.2066	0.1340	0.7998	0.2516	0.5325	99.99
13.95	9	42	7.1708	13.5434	0.1443	0.7703	0.2530	0.5703	99.95
15.45	11	42	8.3899	14.7624	0.1541	0.7414	0.2524	0.6106	99.74
16.95	15	42	10.9560	17.3286	0.1770	0.7135	0.2513	0.7046	95.48
18.45	18	42	12.6115	18.9841	0.1941	0.6869	0.2490	0.7794	82.04
19.45	19	42	12.9616	19.3342	0.1980	0.6700	0.2468	0.8023	75.61
21.45	18	31	11.6804	18.5457	0.1894	0.6385	0.2406	0.7870	80.03
22.95	24	31	15.0177	21.8829	0.2313	0.6172	0.2395	0.9658	23.19
24.45	28	31	16.8966	23.7619	0.2634	0.5979	0.2375	1.1091	3.62
25.5	25	31	14.7205	21.5858	0.2269	0.5856	0.2327	0.9750	21.02
27	26	31	14.8029	21.6682	0.2281	0.5701	0.2295	0.9936	17.09
28.5	30	31	16.5211	23.3864	0.2563	0.5568	0.2288	1.1202	3.05
30	32	31	17.0472	23.9125	0.2664	0.5459	0.2274	1.1717	1.32
31.5	28	31	14.4511	21.3164	0.2230	0.5373	0.2226	1.0018	15.53
33	34	31	17.0238	23.8891	0.2659	0.5312	0.2255	1.1793	1.16
34.5	50	31	24.3182	31.1834	0.5699	0.5275	0.2403	2.3719	0.00
36	54	31	25.5413	32.4066	0.6873	0.5262	0.2458	2.7961	0.00
37.5	59	31	27.1679	34.0332	Stable	0.5275	0.2547	Stable	0.00
39	62	31	27.8218	34.6870	Stable	0.5313	0.2621	Stable	0.00
40.5	76	31	33.2658	40.1311	Stable	0.5377	0.3018	Stable	0.00
42	100	31	42.7319	49.5972	Stable	0.5467	0.3644	Stable	0.00
43.5	59	31	24.6333	31.4986	0.5968	0.5584	0.2711	2.2015	0.00
45	98	31	40.0079	46.8732	Stable	0.5728	0.3985	Stable	0.00
								LPI	18.87

The Factor of Safety values have been further used to estimate the extent of liquefaction in terms of Probability of Liquefaction for each layer of all the 654 borehole sites along with the Liquefaction Potential Index of the soil column of top 20 m along with the Liquefaction Risk Index for the same. The variation of FOS and the Probability of Liquefaction values with depth for the previously mentioned representative sites have been presented in Figure 9.17.




FOS
PL(%)
Depth (m)
Stable Layer
(e)
BH 342
Shibpur
(f)
BH 348
Sarsuna
(g)
Stable layer
BH 351
Alipur
(h)
BH 354
Sonarpur

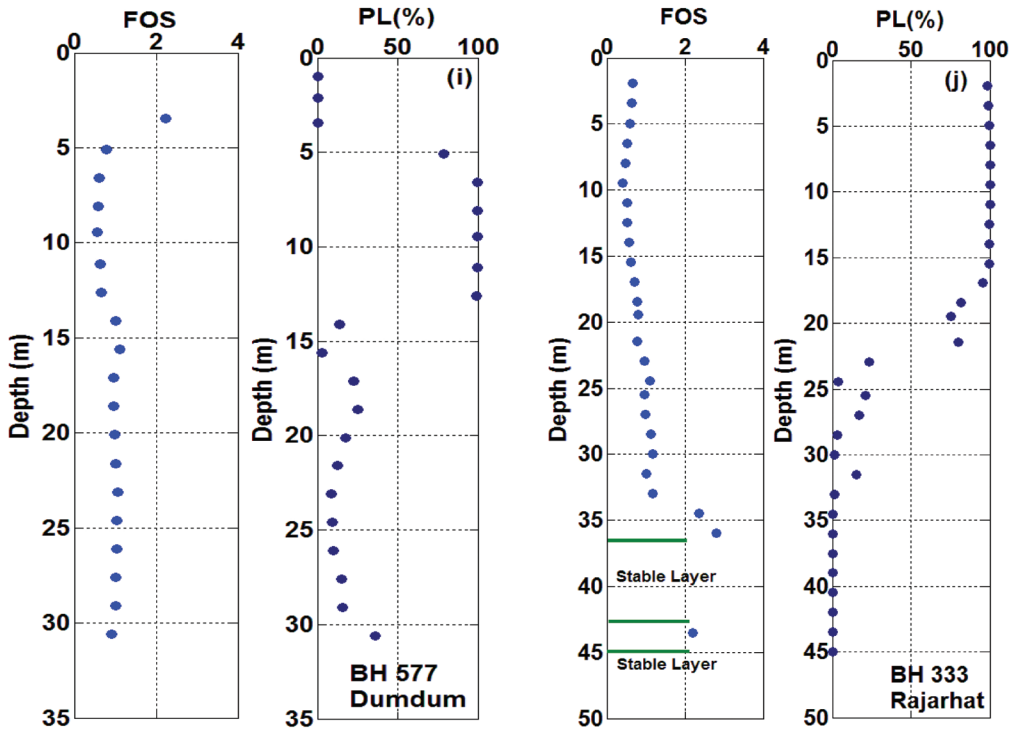


Figure 9.17 **Factor of Safety plot with corresponding Probability of Liquefaction curve of representative sites of Kolkata due to PGA values with 10% probability of exceedance in 50 years with 475 years of return period at surface level, green label represent the stable layer with SPT-N value greater than 35 (Youd *et al.*, 2001) associated with the sites at (a) Barabazar, (b) Saltlake, (c) Paikpara, (d) Howrah, (e) Shibpur, (f) Sarsuna, (g) Alipur, (h) Sonarpur, (i) Dum Dum, and (j) Rajarhat.**

Barabazar associated with PGA of 0.23g has a liquefiable layer below the ground level at a depth range of 5-10 m composed of non-plastic silty clay. The top 20 m soil sediments below the surface of Saltlake with PGA 0.29g has been found to be vulnerable to liquefaction which may have resulted due to the presence of very soft silty clay with decomposed wood or peat followed by non-plastic silty clay with fine sand and mica. On the other hand, Paikpara associated with PGA of 0.26g is underlain by non-plastic silty clay with sand followed by very soft silty clay with decomposed wood/peat and low plastic silty clay with SPT-N value ranging from 1-13 for the top 30 m soil column thus, making the region vulnerable to liquefaction hazard. However, both Howrah and Shibpur with PGA values of 0.22g and 0.25g respectively are underlain by alternate layers of low plastic silty clay with mica, sand and/or kankar & very high plastic silty clay with decomposed wood/peat which makes the top 20 m soil column prone to liquefaction. Sarsuna with PGA of 0.25g lies in the southwest corner of the study region and is underlain by sediments comprise of the alternate layers of non-plastic silty clay with mica, sand and/or kankar and very soft and high plastic silty clay with decomposed wood/peat making the whole top 30 m column vulnerable to liquefaction, whereas, Alipur with PGA 0.19g is underlain by very stiff silty clay with mica thus making the region safe from soil liquefaction hazard. The top 30 m sediments below the surface of Sonarpur comprise of soft silty clay with decomposed wood interbedded

with silty clay with mica and possess very low SPT-N values causing the top 23 m soil column to liquefy from the induced PGA of 0.21g. The sediments underlying in the top 30 m of the Dum Dum region are safe from liquefaction except for a layer at the depth range of 3.45-11 m comprising of silty clay with decomposed wood. Rajarhat has been found to be prone to liquefaction hazard at the depth range of 5-14 m below the ground level, this subsurface layer is comprising of silty clay with decomposed wood at a depth range of 3.45- 9.45 m interbedded with silty clay with mica.

To understand the behavior of liquefaction with respect to the lithology of the region Probability of Liquefaction and Factor of Safety has been plotted for the soil section A-B situated at eastern Kolkata extending from Bidhannagar to Central Park Metro Station (MS). As depicted in Figure 9.18, the cross section of litholog indicates the dominance of coarse grained sediments *viz.* Sand, Silt and Sandy Silt in the region along with the presence of fine grained sediments like clayey silt

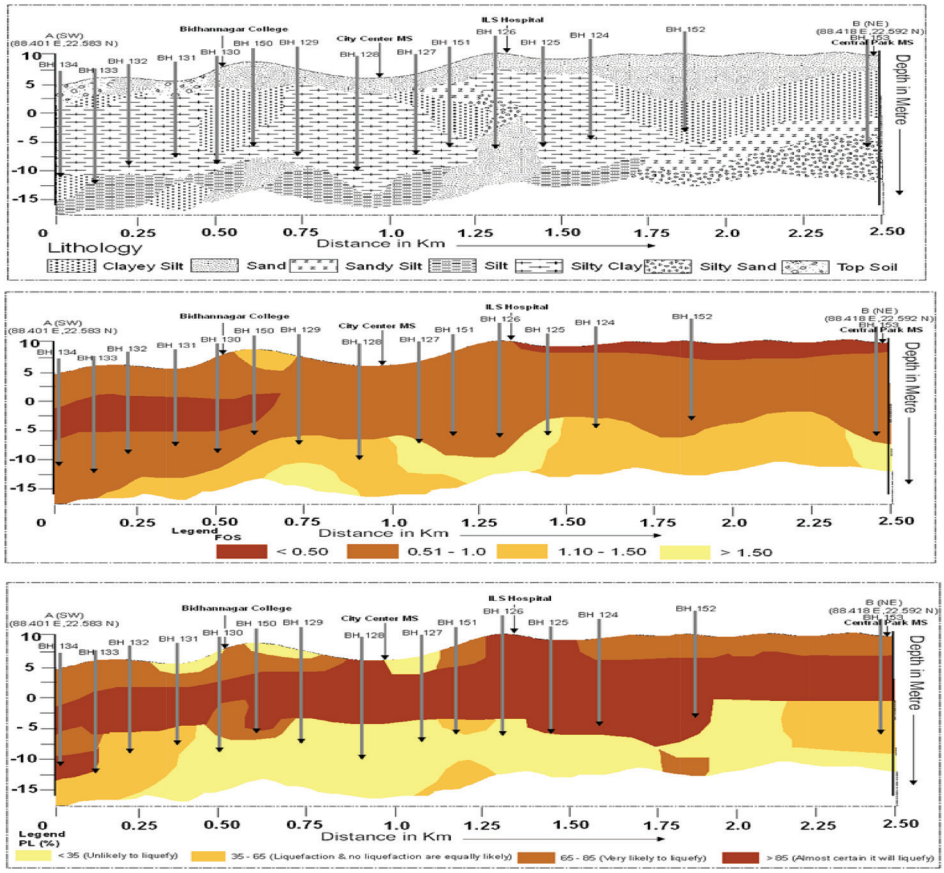


Figure 9.18 **(a) Soil profile of cross-section AB from Bidhannagar to Central Park MS derived from geotechnical data depicting the subsurface lithological conditions of the City, (b) Factor of Safety (FOS) against liquefaction induced due to PGA values for 10% probability of exceedance in 50 years with 475 years of return period at surface level along the cross-section indicating the vulnerability of coarse sediments towards liquefaction, (c) Liquefaction Probability (P_L) distribution due to PGA values for 10% probability of exceedance in 50 years with 475 years of return period at surface level along the cross-section suggesting the presence of liquefiable soil layer of varying thickness at the depth range of 5-15 m below the ground level. Coarse grained sediments *viz.* sand, silty sand and sandy silt associated with the cross-section AB are found to be more prone to liquefaction than fine grained sediments like silty clay and clay.**

and silty clay. The probability of liquefaction distribution indicates the vulnerability of soil layer of varying thickness lying in the depth range of 5-15 m. The presence of non-plastic sand and sandy silt has enhanced the hazard due to liquefaction in the region. Coarse grained sediments have larger pore size in comparison with the fine sediments, thus providing more space to retain water which may lead to the vulnerability of the soil layer getting liquefied under the influence of intense ground shaking due to high PGA.

The LPI and I_R values estimated for the aforementioned locations, presented in Table 9.13 places most of the locations *viz.* Saltlake, Paikpara, Howrah, Shibpur, Sarsuna and Rajarhat in Severe liquefaction zone and, therefore, are at very high liquefaction risk. On the other hand, Barabazar, Dum Dum and Sonarpur fall in low liquefaction zone while, Alipur falls in Non-liquefiable zone and these regions are, therefore, at low liquefaction risk.

Table 9.13 **Liquefaction Potential Index and Liquefaction Risk Index estimated by using PGA values for 10% probability of exceedance in 50 years with 475 years of return period at surface level for representative sites of Kolkata**

Location	Liquefaction Potential Index	Liquefaction Risk Index
Barabazar	2.1 (Moderate Susceptibility)	18.2 (Low Risk)
Saltlake	47.2 (Severe Susceptibility)	78.5 (Very High Risk)
Paikpara	33.7 (Severe Susceptibility)	58.8 (Very High Risk)
Howrah	19.8 (Severe Susceptibility)	36.5 (Very High Risk)
Shibpur	38.5 (Severe Susceptibility)	62.5 (Very High Risk)
Sarsuna	41.6 (Severe Susceptibility)	40.4 (Very High Risk)
Alipur	0 (Low Susceptibility)	0.04 (Low Risk)
Sonarpur	1.8 (Moderate Susceptibility)	14.4 (Low Risk)
Dum Dum	4.8 (Moderate Susceptibility)	17.8 (Low Risk)
Rajarhat	18.8 (Severe Susceptibility)	52.7 (Very High Risk)

The liquefaction susceptibility map of Kolkata generated on GIS platform by spatially distributing LPI values places most of the northern, northeastern and southeastern region encompassing Saltlake, Niccopark, Rajarhat, New Town, Dhapa, Dabpur, Bagdoba *etc.* in Severe liquefaction zone (LPI>15). In addition to these, parts of Howrah, Shibpur, Paikpara and Central Kolkata also fall in this classified zone. These regions are found to be underlain by very soft alternate layers of coarse grained, non-plastic silty clay and very high plastic silty clay with peat/ decomposed wood with very low SPT-N value. On the other hand, parts of southeastern, central, northwestern and northern region covering Jadabpur, Garia, Kalighat, Shobhabazar, Kashipur, Bagbazar, Kona, Bankra and Dharsa are in High liquefaction zone ($5<LPI\leq15$). However, northern region encompassing Dum Dum, Durganagar, Ganti *etc.* along with the southwestern region falls in Low liquefaction zone ($LPI<5$) except for a small patch of Severe liquefaction zone in southwestern corner of the City.

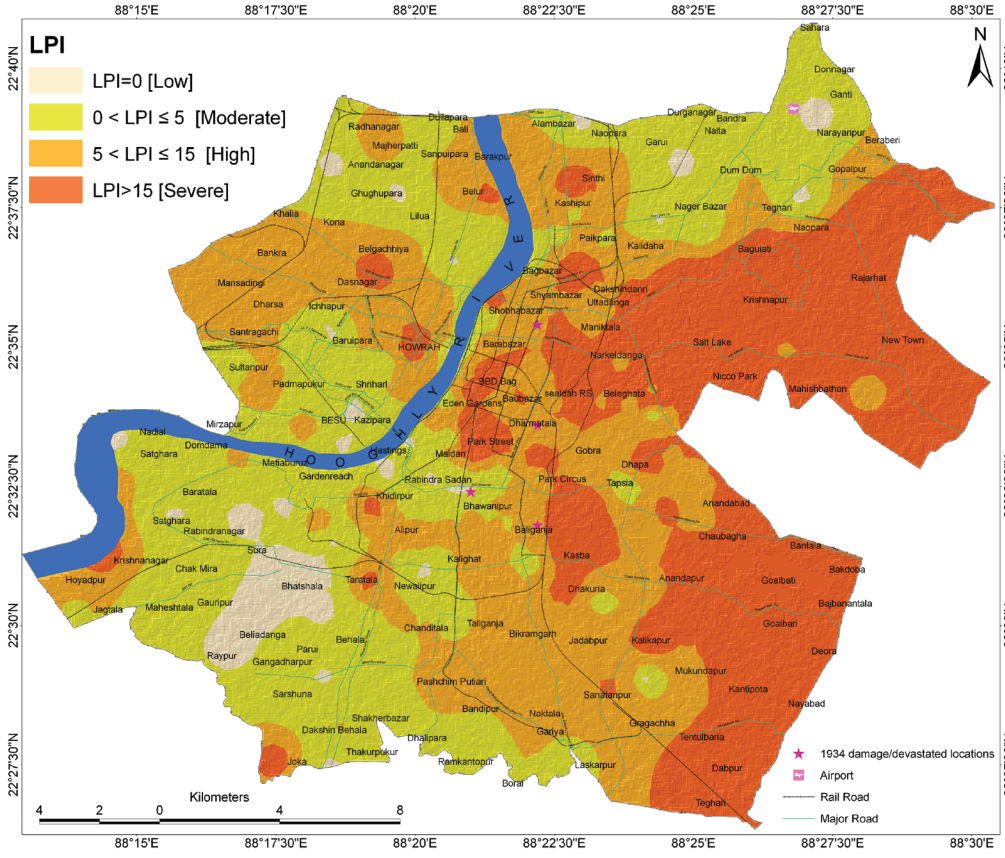


Figure 9.19 **Liquefaction Susceptibility Map of Kolkata due to PGA values for 10% probability of exceedance in 50 years with 475 years of return period at surface level prepared by spatially distributing Liquefaction Potential Index (LPI) values on GIS platform. An LPI>15 indicates a severe liquefaction hazard condition, an LPI between 5 and 15 indicates a tendency to liquefy, and LPI < 5 depicts a non-liquefiable condition.**

The Liquefaction Risk Map of Kolkata for the considered scenario has been generated and displayed in Figure 9.20 exhibiting regions at Extreme risk (I_R> 30), High risk (20<I_R ≤ 30) and Low risk (I_R<20) to soil liquefaction. It is evident that extremely high risk zones encompass the northeastern and southeastern parts of the City along with parts of central Kolkata and a small patch of the southwestern corner of the City. The rest of the City is at High liquefaction risk except for the two patches of Low risk areas in northern and southwestern corner of the City.

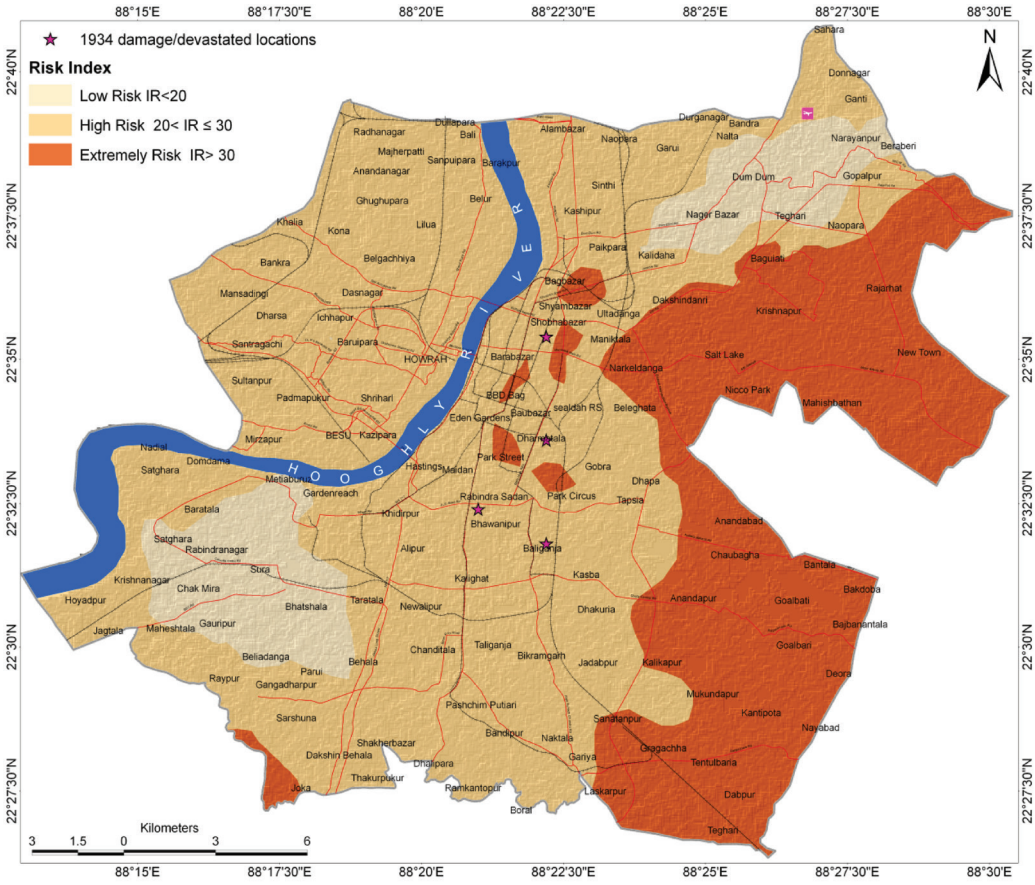


Figure 9.20 **Liquefaction Risk Map of Kolkata associated with PGA values for 10% probability of exceedance in 50 years with 475 years of return period at surface level prepared by spatially distributing Liquefaction Risk Index (I_R) values on GIS platform. An I_R< 20 indicates Low Risk Zone, I_R in between 20 to 30 is High Risk Zone whereas, I_R> 30 depicts Extremely High Risk zone. All the reported damage sites due to 1934 Bihar-Nepal Earthquake of M_w 8.1, marked as '★' falls in High and Extremely High Risk Zone.**

9.7 Concluding Remarks

Subsurface data from Kolkata indicates that the sedimentary deposits underlying the City consist predominantly of grain size favorable to liquefaction. Results of both field and laboratory analysis indicates that the shallow ground water level, geological & geomorphological conditions and the grain size of insitu soils, in conjunction with the active seismic shaking of the terrain make the conditions favorable for liquefaction which may eventually induce foundation failure, ground

settlement and structural damage. The present analysis indicates that the recently developed parts of the City formed on coarse grained, artificial non-engineered fill *viz*. Saltlake, New Town and portion of Rajarhat are more susceptible to soil liquefaction and are at High Risk to the induced hazard. In order to prevent the occurrence of possible soil liquefaction and attendant settlement of buildings, it has been recommended that a raft or deep footing of suitable thickness (below liquefiable zone) should be used to bear both static and dynamic stress (Yilmaz and Bagci, 2006). Both the liquefaction susceptibility map and the liquefaction risk map generated from the present analysis should be correlated with each other to understand the associated liquefaction hazard of the city of Kolkata. This site specific soil liquefaction analysis of Kolkata subdividing the City into various liquefaction hazard zones necessitates reclassification of the City site condition categorizing few E class zones into F classes.