Seismic Liquefaction Susceptibility and Ground Deformation Evaluation using Geotechnical Characterization

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Abstract- Earthquake shaking can trigger the complex phenomenon of seismic liquefaction. The purpose of this study is to assess the Liquefaction Potential Index (LPI) and liquefaction-induced ground deformations (LGD) during earthquakes in Karachi, Pakistan. Karachi, home to over 20 million inhabitants, is located in one of the most tectonically active regions in the world. To date, no comprehensive studies have evaluated LPI and LGD for this city or produced detailed maps for various earthquake scenarios, leaving a significant research gap that this study aims to fill. The Standard Penetration Test (SPT) is a commonly used geotechnical field method to evaluate the penetration resistance of the subsurface strata and can be used for assessing LPI and LGD. For this study, SPT bore data was collected from 100 sites across Karachi. Analyses were conducted for earthquake magnitudes of 6.5 and 7.5, using peak ground accelerations (a_{max}) of 0.16g, 0.2g, and 0.24g. Results revealed that coastal areas of Karachi are particularly susceptible to LGD, with settlements exceeding 30 cm and lateral displacement indices greater than 100 cm at most of these locations. Specifically, the greatest LGD is expected in the coastal regions of Clifton Cantonment, Korangi Creek Cantonment, Jamsheed Town, and Korangi Town for earthquake magnitudes of 6.5 and 7.5 at a_{max}=0.2g.

***Keywords*-** Liquefaction potential index, Soil Settlement, Lateral Displacement Index, Standard Penetration Test, Liquefaction-induced deformation

I. INTRODUCTION

Earthquakes can cause tremendous infrastructure damage, which leads to life losses and economic losses. Dollet and Guéguen, (2022) determined that among natural hazards, earthquakes are the most destructive causing 78% of life losses and 45% of economic losses, between the years 1967-2018.

Earthquake shaking may lead to seismic liquefaction. Typically, higher the earthquake magnitude, and smaller the epicentral distance, the greater the area susceptible to liquefaction. However, studies have shown that liquefaction phenomena have been observed for earthquake magnitudes as low as 5.2 (Olancha Earthquake,2009), seismic intensity as low as VI (Wenchuan Earthquake, 2008) and epicentral distances of over 400 km (Tohoku Earthquake, 2011) (Huang and Yu, 2013). Liquefaction-induced failures are manifested in the form of ground deformations that can distress man-made structures, vertically and horizontally (Youd et al 2018). Examples includes slope failures, vertical soil settlements, sand boils, and lateral spreads (Jafari et al. 2022; Siddarthan and Bukhary, 2011; Siddarthan et al. 2011). Lateral spreads are common forms of ground failures caused by liquefaction, particularly on gentle slopes or nearly level ground with exposed surfaces such as river banks or road cuts. This lateral displacement is typically in the range of less than a meter, but can be several meters large for high magnitude earthquakes and highly susceptible terrain. Buildup of excess pore water pressure during earthquakes in loose sandy soils leads to undrained conditions and the phenomena of liquefaction. After, the dissipation of the excess pore water pressure starts, which becomes the primary reason for the resulting decrease in volume of the soil that manifests itself on the ground surface in form of non-uniform soil settlement

Numerous techniques are available for assessing horizontal and vertical ground movements caused by liquefaction including laboratory-based methodologies, numerical approaches, and in-situ testing methodologies. Difficulties encountered in obtaining undisturbed soil samples of loose sandy soils limit the practical utilization of numerical and laboratory-based techniques. Thus, geotechnical field-test-based approaches that include standard penetration test (SPT), and cone penetration test, emerge as simple yet effective means of estimating liquefaction-induced ground deformations (LGD) for projects with low to medium levels of risk. Several publications have applied these methodologies for investigation of liquefaction hazard (Rehman et al. 2015; Cetin et al. 2002; Wu and Seed, 2004).

Ortiz-Hernández et al. (2022) utilized 23 SPT profiles to calculate the LPI of the coastal city of Portoviejo, Ecuador by considering maximum acceleration (a_{max}) of 0.5 g. The study showed that the urbanized Portoviejo has a high likelihood of liquefaction compared to the southeast region (Ortiz-Hernández et al. 2022). Cetin et al. (2002) examined the impact of liquefaction-induced vertical and horizontal deformation on the Hotel Sapanca site during the 1999 Turkey earthquake of magnitude 7.4. The study utilized various in situ tests including 5 SPT profiles to analyze and compare the predicted ground settlements and lateral deformations with reported ground movements. Wu and Seed, (2004), evaluated the reliability of a SPT-based method for predicting liquefaction-induced ground settlements in level or nearly level ground by comparing observed and calculated estimates for case histories. The results showed that the estimated settlements were mostly within the range of 50-200 % of the observed settlements. Amoroso et al. (2020) utilized 10 SPT soil profiles of a bridge embankment to determine lateral displacements for the 7.8 magnitude earthquake in Ecuador in 2016. The estimated lateral displacements found in the range of 0.58-1.32 m were in good agreement with the observed values.

The current study focused on the coastal city of Karachi, Pakistan to analyze the LPI and LGD by estimating liquefaction-induced vertical settlements (LVS) and lateral displacement index (LDI) which is the novel aspect of this work. Review of existing literature indicated that there are no known comprehensive studies that estimated the LPI and LGD and produced detailed maps for this city, for different earthquake scenarios, and this research gap is covered by the present work. The current study conducted the analysis for earthquake magnitude 6.5 and 7.5, for a_{max} 0.16g, 0.2g, 0.24g. The current study would benefit Karachi land-use planners as well as structural and earthquake engineers for mitigating the effects of damage that can potentially be caused by liquefaction.

II. STUDY AREA

Karachi city is located on the Arabian Sea coast in the southern part of Pakistan. Karachi was founded as a fishing village in the 18th century, however, over the next 200 years, by the late 20th century, it became one of the most populated cities of the world. Today, Karachi has a population of over 20 million (PBS, 2024). Karachi is the leading financial and commercial hub of the country, contributing around 25% of the country's GDP (ADB, 2023).

Geologically, the city is bounded by the north-trending mountain ranges to the west, including the Mor Range, Pab Range, and Bela ophiolite mélange zone; to the north and east by the Kirthar Mountain Range; and to the south-east and south, by the Indus Delta and Arabian Sea streams. Low flat-topped hills and ridges devoid of vegetation is characteristics of Karachi's physical environment. Overall, the geology of Karachi is dominated by sedimentary rocks of varying ages that have been deposited by a combination of fluvial, deltaic, and marine processes. In terms of hydrogeology, Karachi is located within the Malir River basin, with the Hub River forming its western boundary and the Malir River flowing on the eastern side. The drainage system in the Malir basin is primarily composed of the ephemeral Lyari and the Malir River, both carrying sewage and industrial effluent. On the western margin of the city, runs the ephemeral Hub River, but it is free from human-induced contamination. The coastal aquifers in Karachi receive their main recharge from either the Malir or Lyari Rivers, with a similar contribution from the Hub River. The Hub River recharges the confined aquifers of Tertiary age, specifically the Nari and Gaj formations. On the other hand, the Malir and Lyari Rivers primarily recharge the alluvial aquifers of Quaternary age in the coastal areas of Karachi city.

Karachi is situated in one of the most tectonically dynamic environments in the world (Bilham et al. 2007). It is situated close to plate boundaries and numerous tectonically active structures that make it vulnerable to earthquakes (Figure 1). Karachi is situated roughly 150 km to the east of the point where the Arabian, Indian, and Eurasian plates meet at a triple junction. Indications of fragmentation of the Arabian plate over the southwest corner of the triple junction, which defines a triangular Ormara plate, include the recent finding of an active Sonne fault. Subduction velocities rise by a few millimeters per year faster on the Ormara plate than on the Arabian plate when compared to the pace to the west (Bilham et al. 2007). The active Chaman transform fault, which delineates the boundary between the Indian and Eurasian plates, is located at 120 km northwest of Karachi. Additionally, Karachi is positioned at the southern end of the Kirthar active foreland thrust-fold belt, which trends in a north-south direction and lies along the western deformed edge of the Indian plate. The Pakistan Building Code Seismic Provision 2007 places Karachi in seismic danger zone 2B (a_{max}=0.2g). Near Karachi, six earthquakes exceeding a magnitude of 7.0 have occurred within the last 20 decades, with epicentral distances ranging between 165 km-590 km (Waseem et al, 2019) (Table 1).

Examinations of Quaternary sediments through lithological investigation conducted by Nabi et al. (2019), revealed an absence of neotectonic deformation features, surface ruptures and paleo-liquefaction for Karachi. This suggests that there have been no significant earthquakes in the Quaternary period in Karachi. Bilham et al. (2007) noted that the seismic setting of Karachi is similar to Los Angles, USA, which is also an earthquake-prone city. However, unlike Los Angles, in the last 20 decades of reported history, none of the earthquake have caused notable damage to the city of Karachi. Nevertheless, it is possible that the absence of significant earthquake damage in Karachi is due to its limited and incomplete seismic history (of < 200 years) (Bilham et al. 2007). Based on the deterministic seismic hazard analysis, Waseem et al. (2019) reported the PGA ranges for Karachi city to vary between 0.19-0.99 g, with the highest values clustered around the Nagar Parker fault.

In this study, the estimates of LPI, LDI, and LVS were determined by utilizing 100 SPT soil profiles that were performed for various districts of Karachi (Figure 2).

III. METHODOLOGY

For evaluating the susceptibility of soils to liquefaction, a widely adopted approach known as the "simplified procedure" has emerged as a standard method (Youd and Idriss 2001). The procedure involves the computation of cyclic stress ratio (CSR), cyclic resistance ratio (CRR), and the resulting factor of safety (FS) which is the ratio between CRR and CSR. If FS is less than 1, then liquefaction can occur. This factor FS is corrected by magnitude scaling factor to account for earthquake magnitudes less than or greater than 7.5. The value of FS is utilized for estimating the parameter of LPI (Iwasaki et al. 1984). LPI quantifies the extent of damage to structures caused by soil liquefaction based on the severity of liquefaction (Table 2). For quantification of LGD, the parameters of LDI and LVS were used. LDI parameter is utilized for the assessment of the susceptibility of the soil to lateral displacement brought on by liquefaction phenomena during an earthquake. Vertical settlements were assessed by quantification of LVS (Table 2).

Methodology to compute the parameters of LPI, LVS and LDI is added in the supplementary material, and has been utilized by several studies (Rahman et al. 2020; Lombardi and Bhattacharya, 2014; Lu et al. 2023).

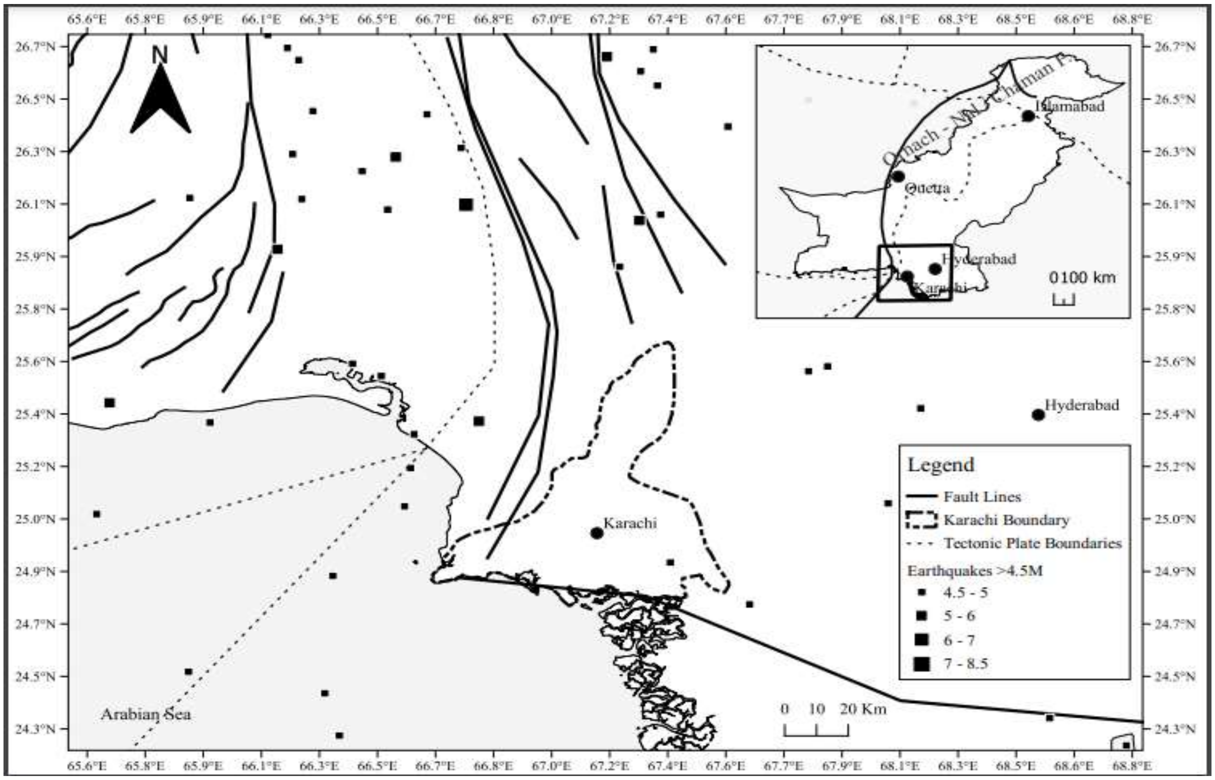


Figure 1: Fault map of the study area as well as the surroundings seismicity from 1907 to 2022, modified from the information available at United States Geological Survey, (2023)

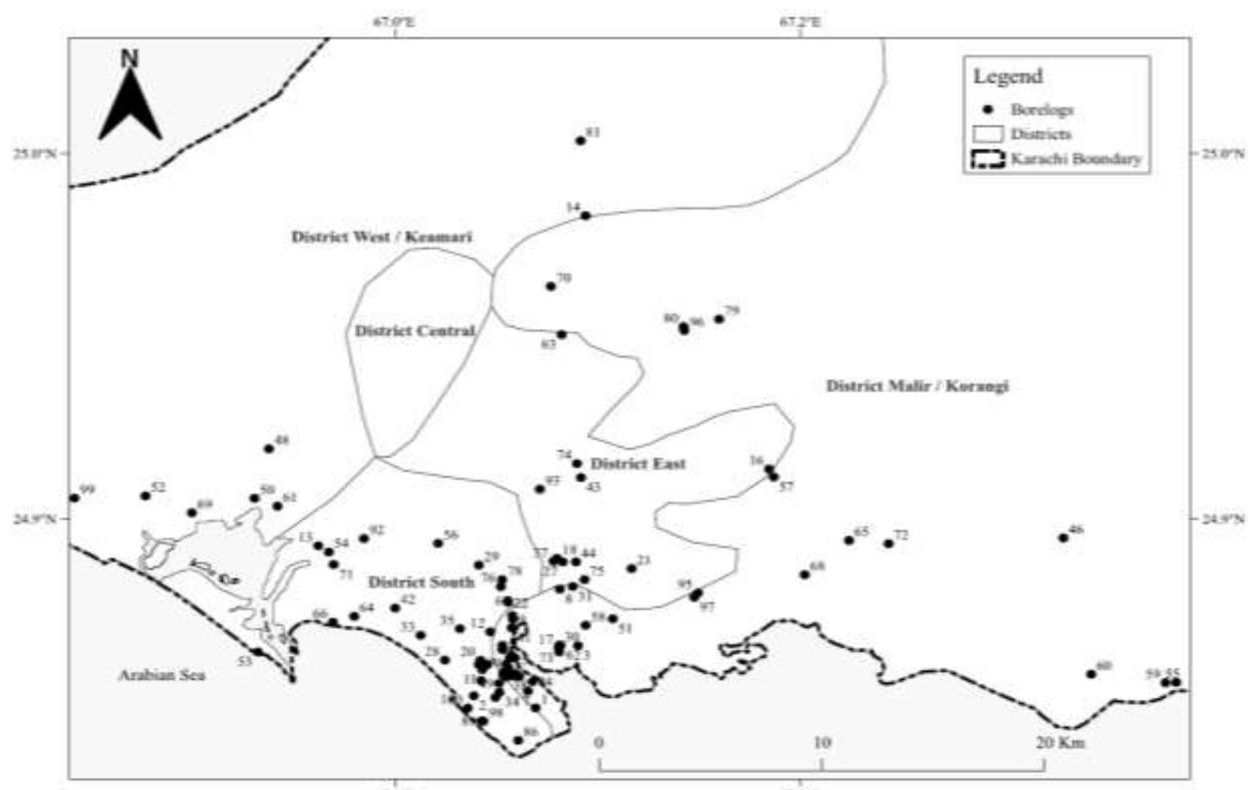


Figure 2. Location map of the 100 SPT bore logs for Karachi in the current study. Map showcasing Karachi's five districts: District East, District West, Karachi District Central, Karachi District South, and District Malir (Number of SPT bores in District South, Central, East West and Malir are thirty, zero, eleven, nine and fifty, respectively).

Table 1. List of historical earthquakes that occurred in the vicinity of Karachi (Waseem et al. 2019).

Date	Name of Earthquake	Magnitude (Richter)	Epicenter distance from Karachi (Km)
June 16, 1819	Allah Bund Earthquake	7.9	165
August 27, 1931	Mach Earthquake	7.3	550
May 31, 1935	Quetta Earthquake	7.6	590
November 28, 1945	Makran Earthquake	8.2	410
January 26, 2001	Bhuj Earthquake	7.7	300
January 19, 2011	Dalbandin Earthquake	7.2	518

Table 2. LPI classification for liquefaction risk indication (Iwasaki et al, 1984) and vertical soil settlement classification based on the extent of the liquefaction-induced damage (Ishihara and Yoshimine, 1992)

	Range	Extent of damage	Liquefaction indication
Liquefaction Potential Index (LPI)	LPI = 0	No damage	very low liquefaction risk.
	0 -5	Light damage	Low liquefaction risk. A detailed analysis is warranted for important structures.
	5 -15	Medium Damage	High liquefaction risk. A detailed analysis is warranted for the structures. Application of mitigation strategies is required.
	LPI > 15	Extensive Damage	Very high liquefaction risk. A detailed analysis is warranted for the structures. Application of mitigation strategies is required.
Liquefaction-induced Vertical Settlement (LVS) (m)	0 – 0.1	No damage to light damage	Minor Cracks
	0.1 – 0.3	Medium Damage	Small cracks, oozing of sand
	0.3 – 0.7	Extensive Damage	Large cracks, spouting of sand, large offsets, lateral movement

The Pakistan Building Code Seismic Provision 2007 places Karachi in seismic zone 2B corresponding to a_{max} values of 0.2g. In this study, LPI, LDI and LVS were estimated using a_{max} values of 0.16g, 0.2g and 0.24g for earthquake magnitude 6.5 and 7.5.

IV. RESULTS AND DISCUSSION

This section details the results of the LPI, LDI and LVS estimations for Karachi and are displayed in Figure 3-8.

Figure 3 displays LPI results using a_{max} = 0.16g, 0.2g and 0.24g, for earthquake magnitude 7.5. Fifty District Malir and Korangi SPT bore logs were collected. Using a_{max} = 0.2g, the LPI value was found to be zero for 24 bore logs, while thirteen SPT locations showed LPI<5, LPI ranges of 5-15 were found for eight SPT locations while five SPT bore logs resulted in LPI>15 (Figure 3). From District South, thirty bore logs were collected, and by utilizing a_{max} = 0.2g, fourteen SPT locations showed LPI = zero, while seven locations showed LPI values between 5-15, and six bore logs displayed LPI values >15. From District East, eleven bore logs were collected. Using a_{max} = 0.2g, LPI value ranges of 5-15 were found for only one SPT location, and none of the locations displayed LPI values >15. Nine District West and Kaemari bore logs were collected. Using a_{max} = 0.2g, the LPI value was found to be zero for eight bore logs, while one SPT location showed LPI values up to 5. Overall, fifty-two locations displayed LPI zero values when using a_{max} value of 0.2g, however, when using a_{max}=0.24g, thirty-six SPT locations displayed LPI zero values, while sixty-two soil profiles showed LPIs greater than zero.

LGD was assessed and mapped for those forty-eight SPT locations that showed LPIs greater than zero, for earthquake magnitude 7.5 in the form of inform of LVS (Figure 4) and LDI (Figure 5) using the a_{max} values of 0.16g, 0.2g and 0.24g. When using a_{max} =0.2g, twenty-five locations estimated LVS between 10-30 cm showcasing medium damage, while eight locations estimated LVS in the range of 30-100 cm indicating extensive damage during an earthquake (Figure 4). However, fifteen SPT locations estimated LVS<10 cm showing that level of damage during an earthquake at these sites would likely be small. Scenarios were also plotted for a_{max}=0.16g and a_{max}=0.24g. For LDI, when using a_{max}=0.2g, out of the forty-eight locations, twenty-five of the SPT locations estimated LDI >100 cm, eighteen locations estimated LDI values in the range of 30-100 cm, four locations estimated LDI values in the range of 10-30 cm, and only one location showed LDI < 10 cm (Figure 5).

Figure 6 illustrates the LPI results achieved with varying a_{max} values of 0.16g, 0.2g, and 0.24g, considering an earthquake magnitude of 6.5. A total of fifty SPT bore logs were gathered from Districts Malir and Korangi. When employing a_{max} = 0.2g, no liquefaction potential (LPI) was observed in thirty-eight bore logs, three bore logs displayed LPI values ranging from 5-15, and one bore log showed LPI>15 (Figure 6). In District South, thirty bore logs were collected, and with a_{max} = 0.2g, twenty bore logs showed an LPI of zero, four bore logs showed LPI values ranging from 5-15, and three bore logs had LPI values>15. From District East, eleven bore logs were gathered. Utilizing a_{max} = 0.2g, eight bore logs indicated an LPI of zero, while three bore logs exhibited LPI values between 0-5. Additionally, nine bore logs were collected from Districts West and Kaemari, and for a_{max} = 0.2g, all nine showed an LPI of zero, Overall, for magnitude 6.5 earthquake when utilizing an a_{max} value of 0.2g, seventy-five locations indicated an LPI of zero. However, with a_{max} = 0.24g, sixty SPT locations displayed an LPI of zero, while the remaining exhibited non-zero LPI values. Twenty-two bore logs had LPI values between 0-5, twelve bore logs showed LPI values ranging from 5-15, and six bore logs had LPI values>15, when using a_{max}=0.24g.

LVS and LDI were mapped using a_{max} values of 0.16g, 0.2g, and 0.24g, for magnitude 6.5, as shown in Figure 7 and 8, respectively. For district South, 24, 2 and 4 SPT locations, displayed LVS up to 10 cm, between 10-30 cm, and exceeding 30 cm, respectively, for a_{max}=0.2g. Settlements in District East and West locations were not shown to exceed 10 cm. For district Malir, out of the fifty locations analyzed, forty-three locations estimated settlements were<10 cm, six showed settlements ranging between 10-30 cm, and one location showed LVS>30 cm. For a_{max} = 0.2g and 0.24g, overall, eight and eighteen locations demonstrated LVS ranging from 10-30 cm, indicating moderate damage, respectively, while five and seven locations displayed LVS>30 cm, respectively, during liquefaction event. In terms of LDI, utilizing a_{max}=0.2g, among the twenty-five locations analyzed, eleven SPT locations estimated LDI >100 cm, seven locations estimated LDI between 30-100 cm, while five locations estimated LDI between 10-30 cm. Alternative scenarios were explored for a_{max} values of 0.16g and 0.24g, as depicted in Figure 8. Notably, with a_{max}=0.24g, nineteen SPT locations estimated LDI >100 cm, compared to eleven locations when using a_{max}=0.2g, while thirteen locations estimated LDI values between 30-100 cm with a_{max}=0.24g.

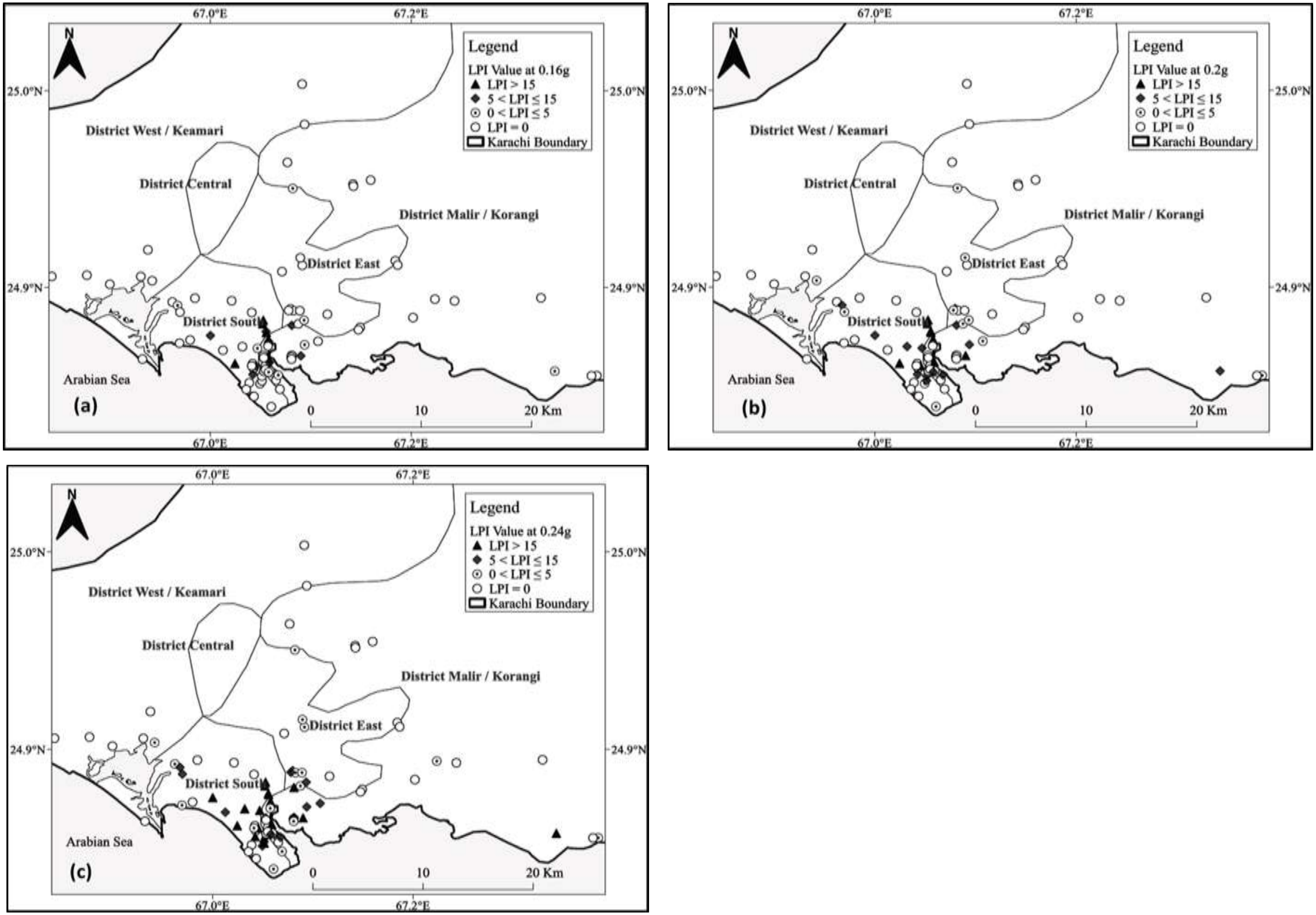
Results indicated that the greatest LGD is expected to develop at the coastal areas of Karachi particularly the areas of Clifton Cantonment, Korangi Creek Cantonment, Jamsheed Town, and Korangi Town (a_{max}=0.2g for earthquake magnitude 6.5 and 7.5) (Figure 4 and 5). Lodi et al. (2015) reported similar findings for liquefaction risk for Defense Housing Authority and Port Qasim Industrial areas of Karachi, through determination of FS which is the ratio between CRR and CSR. Khan et al. (2017), conducted a similar study based on the ratio between CRR and CSR, for the Defense Housing Authority area of Karachi, and found it to be vulnerable to seismic liquefaction. Mahmud and Sheikh, (2008) studied the vertical sinking of a water tank in Defense Housing Authority, Karachi. A comprehensive geotechnical investigation revealed that the settlement potentially occurred as a result of liquefaction triggered by seismic activity in the area.

Present study for the determination of liquefaction-prone areas is conducted for Karachi, Pakistan, which is located in South Asia. Similar studies have also been reported for other cities of the South Asian region, e.g. cities located in the countries of India, Bangladesh and Nepal. Rehman et al. (2015) prepared a liquefaction hazard map for Dhaka, Bangladesh, another major city of South Asia, using the liquefaction potential index (LPI) and cumulative frequency distribution of LPI for 53 SPT profiles. The hazard map categorized the city into three liquefaction hazard zones based on geological characteristics, with Zone 3 having the highest risk. The study showed that for an earthquake magnitude of 7.0 and a peak ground acceleration (PGA) of 0.15 g, 72% of Zone 3 is expected to display liquefaction phenomena (Rehman et al. 2015). Khanal et al. (2019) assessed the liquefaction-induced probability of ground failure, for Kathmandu valley Nepal, by utilizing a probabilistic model based on SPT data from 113 borehole logs for earthquake moment magnitude of 7.8 and peak ground acceleration of 0.16g. About 55% of the study area was found to be at very high and high risk of liquefaction.

Bhuj 2001 earthquake of magnitude 7.9, in India, caused widespread liquefaction phenomena in the Kutch region, particularly around the epicentral area, manifested on the surface in form of sand blows and lateral spreading. Karachi, having an epicentral distance of 300 km from the epicenter, did not experience any seismic-induced damage, however, Ahmedabad city in India, having an epicentral distance of 240 km from the Bhuj mainshock witnessed widespread liquefaction damage due to the 2001 earthquake (Hazarika and Boominathan, 2009). Some seismic-induced damage and liquefaction phenomena was reported in other locations in the province of Sindh, Pakistan (e.g. at locations in Mithi, Badin, Nangarparkar, Islamkote, Chilyan, Demo Dahdal, Diplo, Chachre, Sanghi), within the epicentral distance of 300 km (Khan et al. 2002; Lodi and Rafeeqi, 2007). Although Karachi city did not experience seismic-induced damages, after the 2001 Bhuj earthquake, Karachi was classified into seismic hazard zone 4, representing the highest seismic hazard level. This decision was strongly opposed by some members of the local engineering community, due to the use of unreliable data for the zoning assignment. This classification was subsequently revised to zone 2B, by the Building Code of Pakistan 2007, due to the absence of significant earthquakes in the immediate vicinity of Karachi over the preceding 200 years.

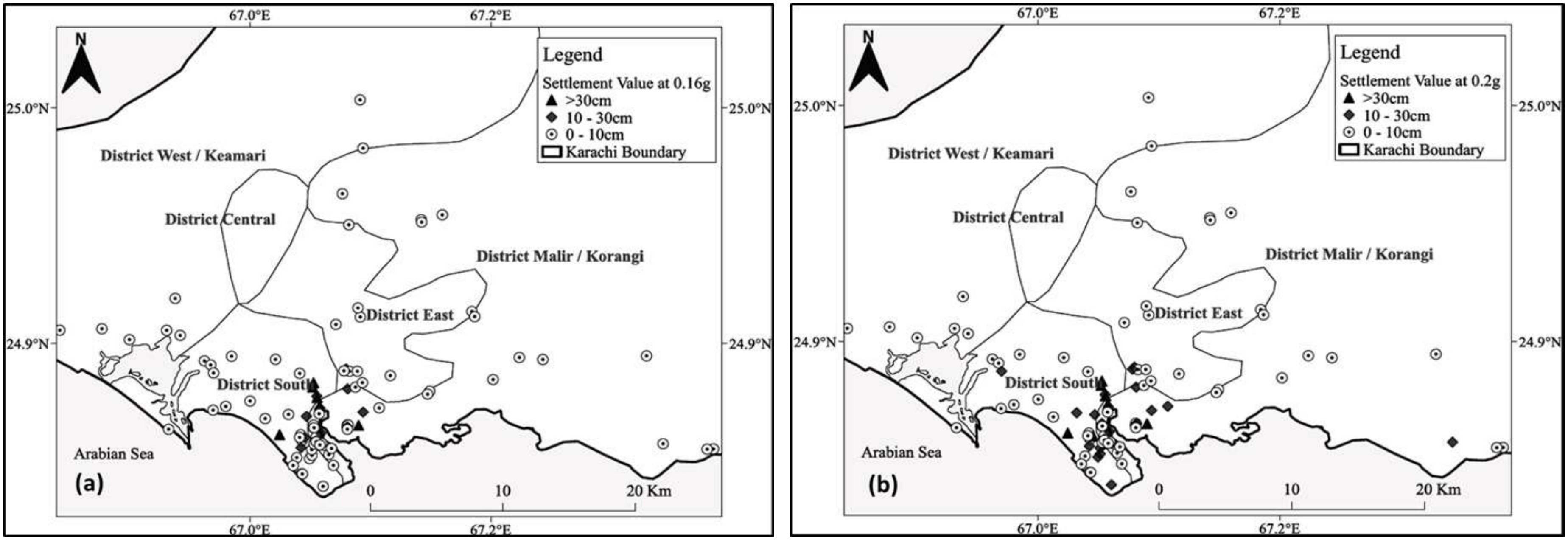
V. CONCLUSION

The objective of the current study was to evaluate the liquefaction potential index and liquefaction-induced ground deformations (lateral displacement index, and vertical settlements) by making use of SPT profiles of selected locations for the city of Karachi. Estimates were generated for earthquake magnitude 6.5 and 7.5 for a_{max}=0.16g, 0.2g and 0.24g. Largest values of LPI were determined to be concentrated along the coastal regions of Karachi. Likewise, liquefaction-induced ground deformation estimates were found to be largest for the coastal areas of Karachi including the areas of Clifton Cantonment, Korangi Creek Cantonment, Jamsheed Town, and Korangi Town. Results showed that the coastal areas of Karachi are more prone to liquefaction-induced ground deformations, compared to other areas in Karachi, with settlements exceeding 30 cm and LDI greater than 100 cm for earthquake magnitude 6.5 and 7.5, for a_{max}=0.2g.



Legend
LPI Value at 0.16g
LPI > 15
5 < LPI ≤ 15
0 < LPI ≤ 5
LPI = 0
Karachi Boundary
District West / Keamari
District Central
District Malir / Korangi
District East
District South
Arabian Sea
(a)
Legend
LPI Value at 0.2g
LPI > 15
5 < LPI ≤ 15
0 < LPI ≤ 5
LPI = 0
Karachi Boundary
(b)
Legend
LPI Value at 0.24g
LPI > 15
5 < LPI ≤ 15
0 < LPI ≤ 5
LPI = 0
Karachi Boundary
(c)
67.0°E
67.2°E
25.0°N
24.9°N
0
10
20 Km
N

Figure 3. Liquefaction potential index (LPI) map for Karachi for magnitude 7.5 and (a) a_{max}=0.16g; (b) a_{max}=0.2g; (c) a_{max}=0.24g



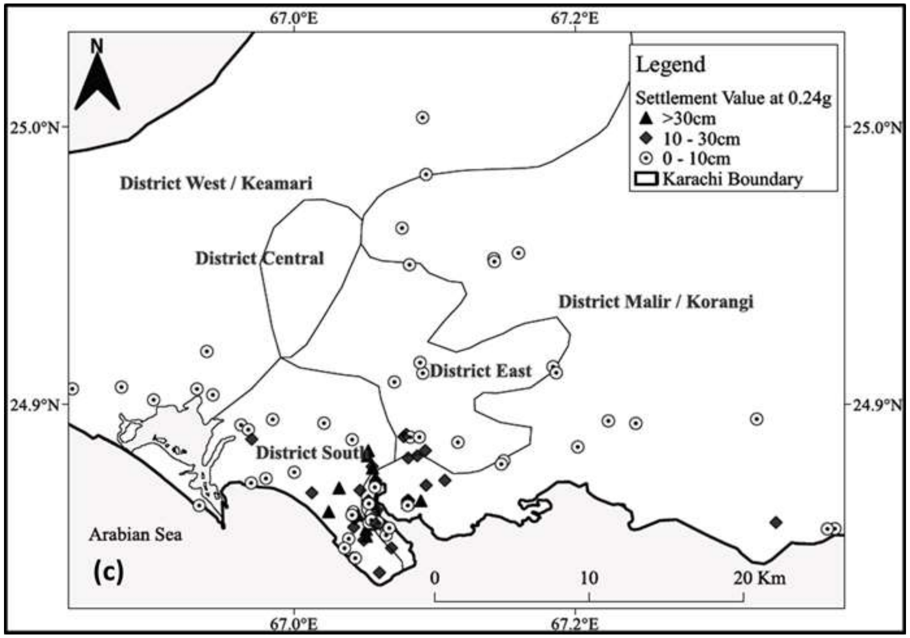


Figure 4. Liquefaction-induced soil settlement map for Karachi for magnitude 7.5 and (a) a_{max}=0.16g; (b) a_{max}=0.2g; (c) a_{max}=0.24g

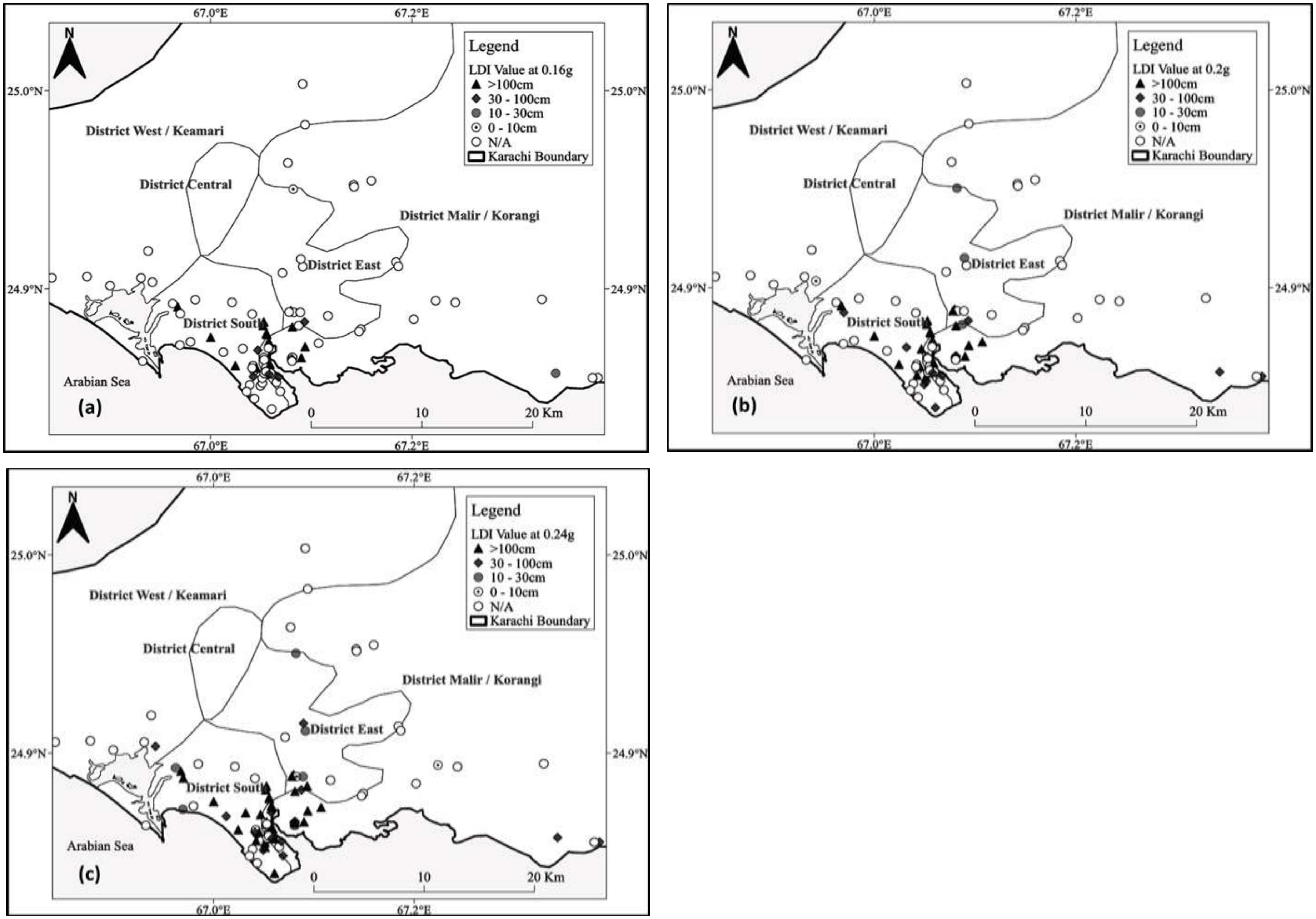

67.0°E
67.2°E
25.0°N
24.9°N
N
Legend
LDI Value at 0.16g
>100cm
30 - 100cm
10 - 30cm
0 - 10cm
N/A
Karachi Boundary
District West / Keamari
District Central
District Malir / Korangi
District East
District South
Arabian Sea
(a)
0
10
20 Km
LDI Value at 0.2g
(b)
LDI Value at 0.24g
(c)

Figure 5. Liquefaction displacement index (LDI) map for Karachi for magnitude 7.5 and (a) a_{max}=0.16g; (b) a_{max}=0.2g; (c) a_{max}=0.24g

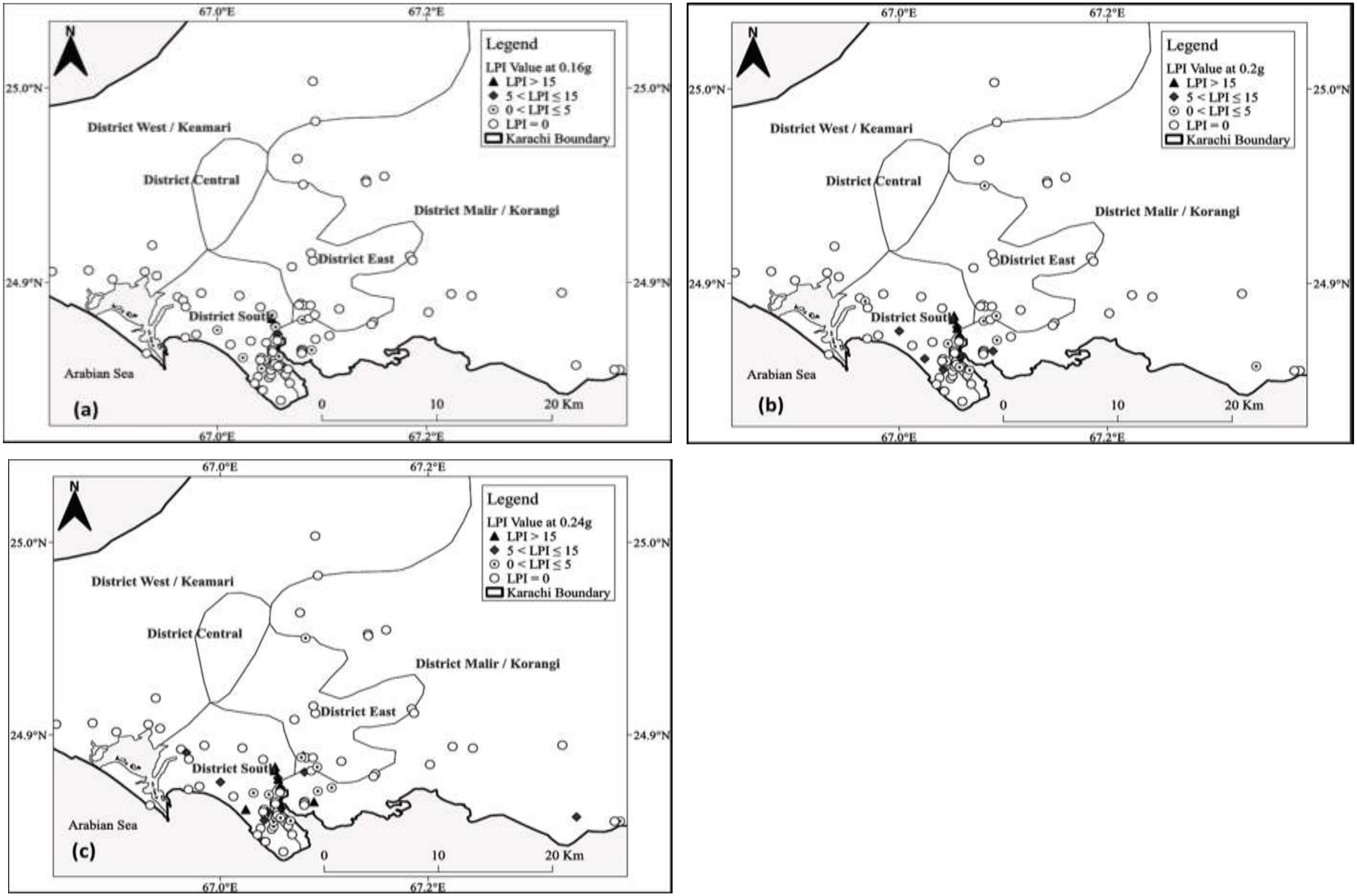
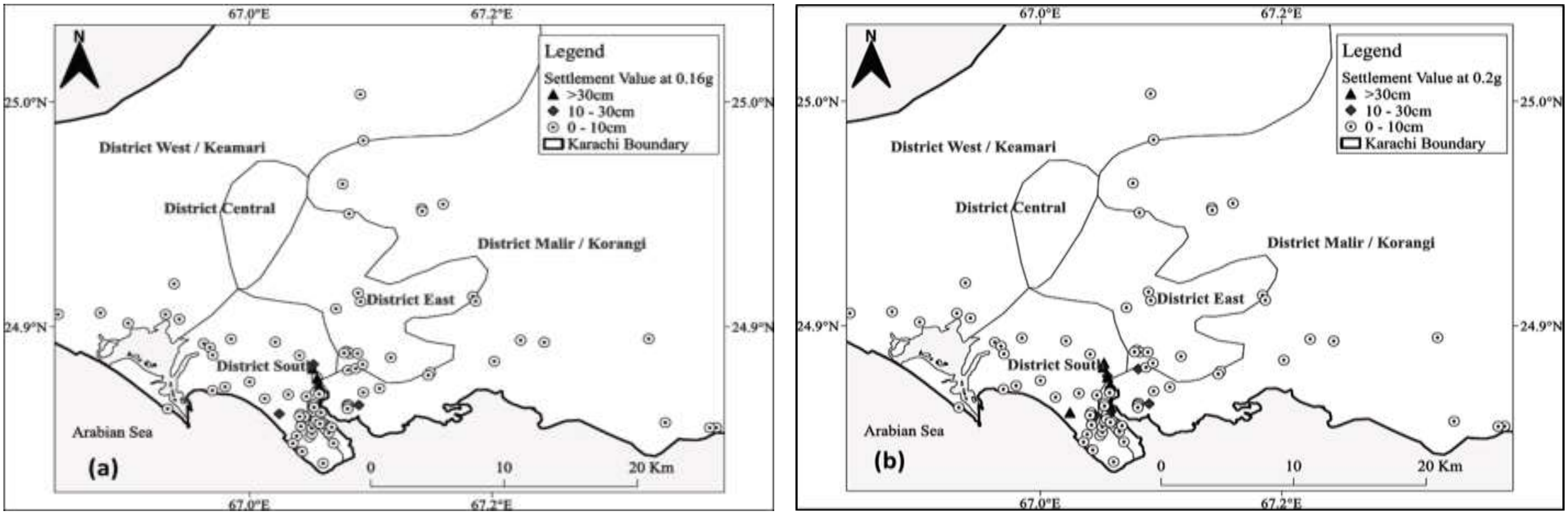


Figure 6. Liquefaction potential index (LPI) map for Karachi for magnitude 6.5 and (a) a_{max}=0.16g; (b) a_{max}=0.2g; (c) a_{max}=0.24g



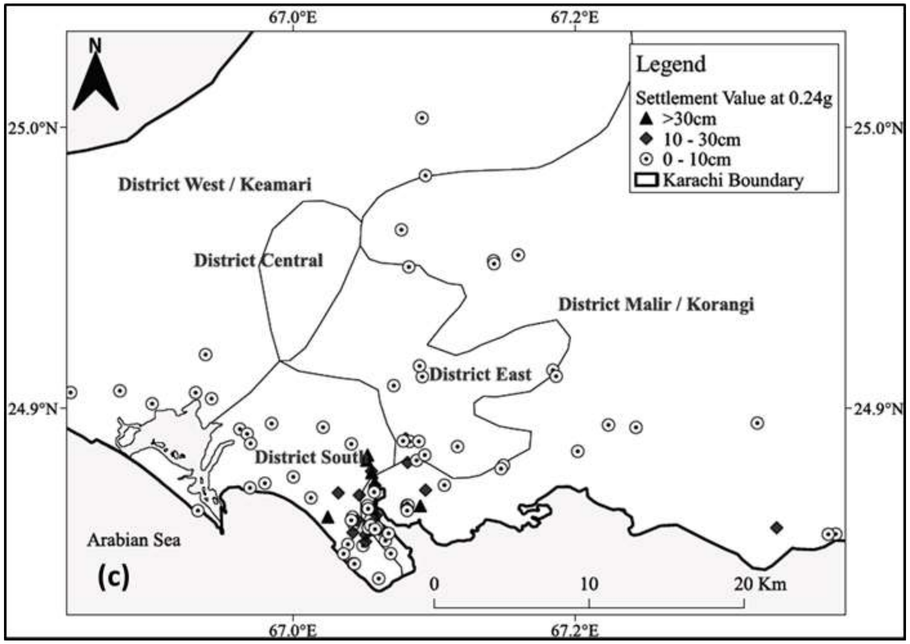


Figure 7. Liquefaction-induced soil settlement map for Karachi for magnitude 6.5 for (a) a_{max}=0.16g; (b) a_{max}=0.2g; (c) a_{max}=0.24g

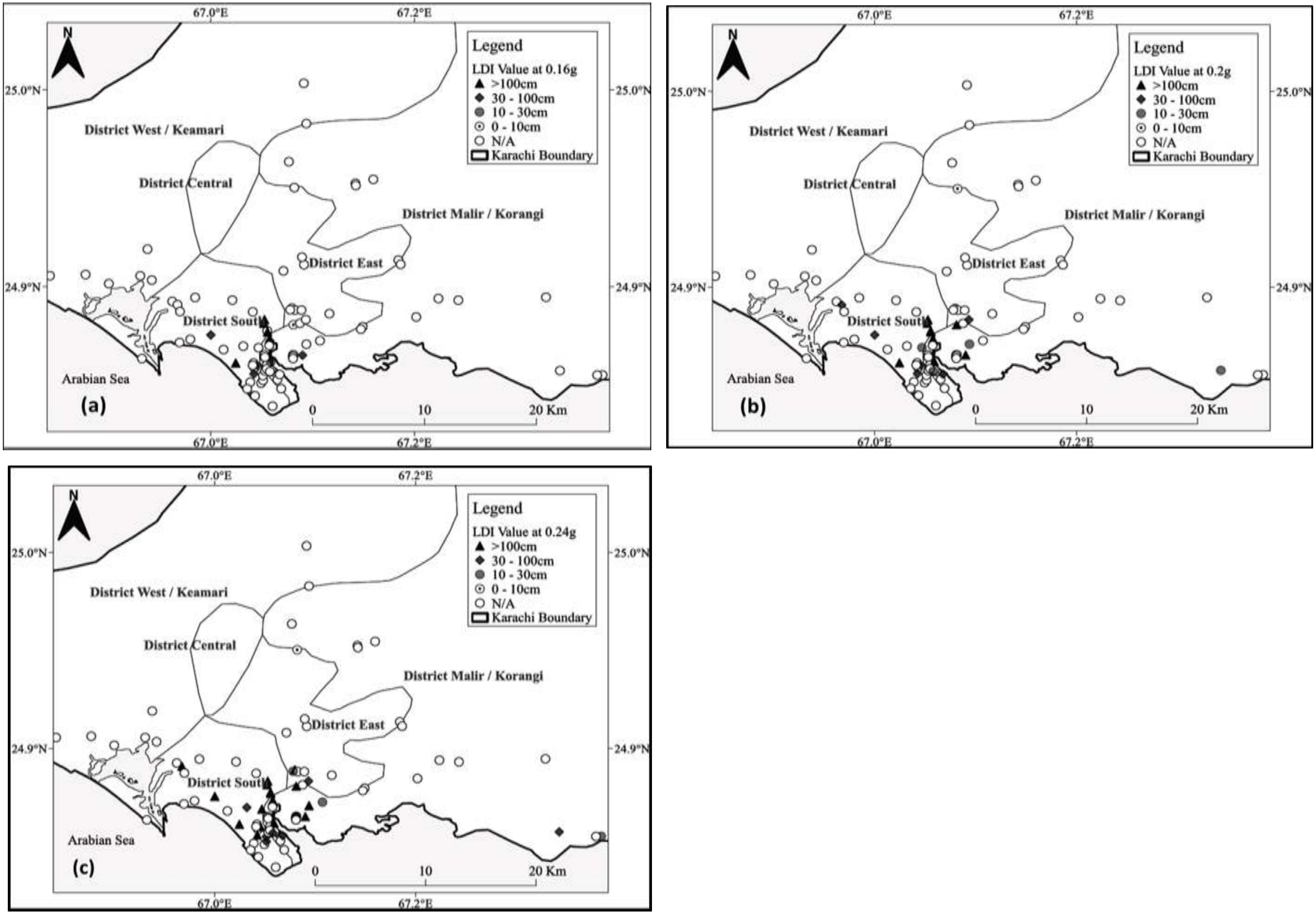

67.0°E
67.2°E
25.0°N
24.9°N
N
Legend
LDI Value at 0.16g
>100cm
30 - 100cm
10 - 30cm
0 - 10cm
N/A
Karachi Boundary
District West / Keamari
District Central
District Malir / Korangi
District East
District South
Arabian Sea
(a)
0
10
20 Km
LDI Value at 0.2g
(b)
LDI Value at 0.24g
(c)

Figure 8. Liquefaction displacement index (LDI) map for Karachi for magnitude 6.5 for (a) a_{max}=0.16g; (b) a_{max}=0.2g; (c) a_{max}=0.24g

The current work can be enhanced by adding to the pool of SPT datasets to obtain a more comprehensive assessment of the liquefaction potential and the resulting ground deformation. Karachi is situated in one of the most dynamic tectonic settings, however, in the last 200 years of recorded history, Karachi has not experienced any earthquake to cause noticeable damage. Thus, validation of the estimated ground deformation in the present study is not possible. Nevertheless, the evaluation of liquefaction-induced deformation in the current study provided valuable information for engineering design and construction practices in Karachi. It also highlighted the importance of considering seismic hazards in urban planning and risk management. Future work can focus on comprehensive estimations of liquefaction-induced lateral displacements for Karachi city by collection of relevant data.

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