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Liquefaction potential along the coastal regions of Karachi

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Abstract

This paper investigates liquefaction resistance of the coastal belt of Karachi stretched over 38 kms, the assessment is based on the scattered standard penetration test data of 120 bore logs. The liquefaction potential has been evaluated using simplified procedure developed by Seed and Idriss (1971) and modified by Youd et al. (2001). The results of analysis are transformed into maps, which are expected to serve as general guidelines for effective town-planning, designing efficient mitigation systems, ground-failure vulnerability and for future microzonation studies. This study endeavours to provide the basis on which a comprehensive microzonation map of Karachi can be developed after some modifications.

Keywords: Liquefaction potential; Coastal regions of Karachi; Bore logs; Effective town-planning.

1. Introduction

Liquefaction due to earthquake can cause widespread damage to life and property. One of the mitigation measures is early detection of liquefiable site with the help of generated maps. The coastal city of Karachi, Pakistan lies approximately 150 km east of the triple junction between the Arabian, Indian and Asian plates and within reach of earthquake on numerous tectonically active structures surrounding the city. Its population exceeds 18 million and is prone to catastrophic disaster in the event of a major earthquake. No concrete work has yet been witnessed to collect and analyse data for determination of liquefaction susceptibility of Karachi.In this study we devise a liquefaction hazard assessment tool using NCEER procedure while limiting our study area to the coastal belt of Karachi being most prone to subjected phenomenon.

2. Liquefaction

Liquefaction is a phenomenon which involves the transformation of a granular material from a solid to a liquefied state as a consequence of increased pore-water pressure and reduced effective stress under dynamic loading. Cyclic stresses as a result of earthquakes lead to the development of un-drained conditions in fully saturated granular soils activating liquefaction. Liquefaction causes the soil to lose its shear strength and thus it's bearing capacity, thereby losing its ability to support super imposed loads resulting in settlement, tilting, and/or overturning of structures and causing damage to lifeline systems.

3. Geological framework of Karachi

Karachi is located at 24°51′36″N and 67°00′36″E, on the coast of the Arabian Sea. This study is a concerted effort for seismic hazard assessment for a city that is the financial hub of Pakistan, covers an area of approximately 3,530 square kilometres, and is home to a population of about 18 million.

The city comprises largely of flat or rolling plains, with hills on the western and northern boundaries. Geologically, the region is outlined by the north-trending mountain ranges, namely, Mor Range, Pab Range and Bela ophiliolite/ mélange zone to the west, Kirthar Range to the north and to the east, and by the Indus Delta and the Arabian Sea creeks to the south-east and south. Rocks from Eocene age to recent are exists in the South mostly under marine conditions.Karachi lies between Ranpathani and Cape Monze in the east and west respectively and Mehar and Mol Babals (mountains) in the north and this region is part of synclinorium.The geology of the study area, DHA and Port Qasim consists of alluvial fan deposits, sand bar deposits, and coastal sand dune deposits.

3.1. Seismicity and tectonics of Karachi

The seismo-tectonic setting of Karachi presents a scary sight. Karachi has precarious seismo-tectonic settings as it lies in a close proximity of triple junction of Arabian, Indian, and Asian plates and has experienced numerous earthquakes in the past (Fig. 1). Convergent and tanscurrent rates of 28-33 mm/yr respectively has been measured in the western and north-trending arms of the triple junction (Apel et al. 2006).

The recent discovery of an active Sonne fault indicates fragmentation of the Arabian plate across the southwest corner of the triple junction defining a triangular Ormara plate. Ormara plate velocity relative to the Arabian plate increases subduction velocities by a few millimetres per year compared to the rate to the west (Bilham et al., 2007).

A thrust and folding belt parallel to the transform fault separating India and Asia and the intraplate system of Kachchh fault approaching the City (Fig. 1) exists in addition to the clearly defined plate boundaries have produced damaging earthquakes that have been felt in the city in the past 200 years.

3.2. Seismic history of Karachi

Although residents of Karachi feel occasional shaking from M 4-5 earthquakes on faults north and northwest of the city, and also felt shaking from the 1945 Makran and 2001 Bhuj earthquakes, no earthquake has ever produced documented damage in Karachi. A review of the known historical data on earthquakes with 500 km of the city shows that the historical record prior to 1800 is limited and unreliable (Bilham et al., 2007). The core issue is whether Karachi truly enjoys a seismic setting or whether the absence of damaging earthquakes is only due to Karachi's short and incomplete seismic history. However, Pakistan Building code – Seismic Provision 2007 (SCB) has placed Karachi in seismic hazard zone 2B, Table 1.

Karachi seems to have a very uncertain seismic history. Around 1800 earthquakes have been felt within 500 km most of them around M 4 – 5, including two major one i.e.1945 Makran and 2001 Bhuj earthquakes but no earthquake had ever produced any documented damage in the City. However, the data of seismicity is limited and unreliable (Bilham et al., 2007). Availability of reliable seismicity data with no record of damage places Karachi into an uncertain seismic hazard. Probably, due to this uncertainty, Pakistan Building Code – Seismic Provision 2007 (SCB) has placed Karachi in seismic hazard zone 2B, Table 1.

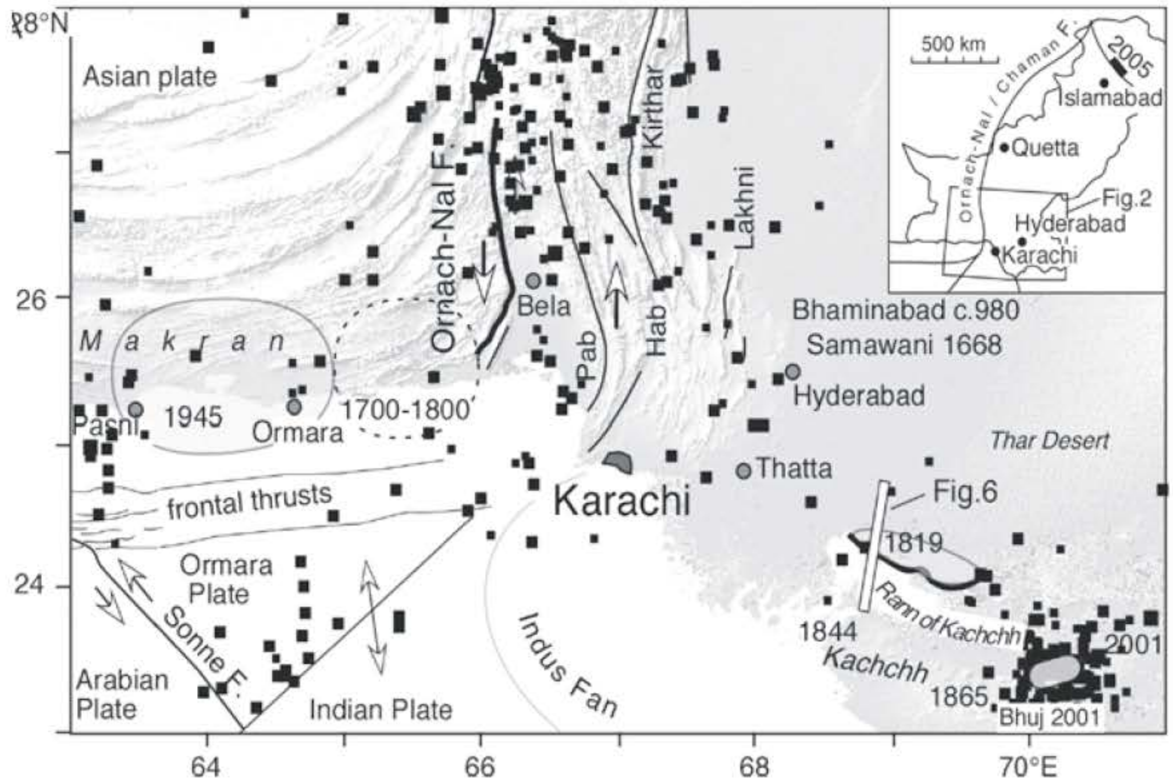

Fig. 1. Locations of active faults and dated historical earthquakes with inferred ruptures outlined. Locations of moderate events shown only by date; smaller shocks (3.8 <M < 5.5) as squares proportional to magnitude (Bilham et al., 2007).

Table 1. Seismic Zone Factors as prescribed by UBC-97.

Seismic Zone	Seismic Zone Factor (Z) $Z = a_{max}/g$
1	0.075
2A	0.15
2B	0.2
3	0.3
4	0.4

3.3. Study area

The study area is located along the coastal area of Karachi concentrated on Defence Housing Authority (D.H.A.) and Port Qasim Industrial Area (PQA) between the latitudes and longitudes as shown in Figure 1. The data has been collected from different soil laboratories who have conducted geotechnical studies in the subjected area for distinct projects along the coastal belt of Karachi, to include Sea Rock Driller and Constructors, Soil Testing Services, Consolidated Engineering Services, Soil Mat Engineers, Geotechnical Services, Soil Mechanics, Hasnain A. Bokahari etc. Samples of 120 borehole logs have been used for the analysis. The bore hole log locations are detailed in Table 2 and their locations are marked on Figure 2 for reference.

Table 2. Bore Log Information.

ID	Location	No. of Bore logs
A	Development of Crescent Bay, Phase VIII, D.H.A.	3
B	Khayaban-e-Qasim, Phase VII, D.H.A.	3
C	Foundation Public School, D.H.A.	4
D	Jinkwnagjaz (Pvt.) Ltd, D.H.A.	3
E	Bokhari Commercial , D.H.A.	2
F	Ittehad Lane No 6, D.H.A.	3
G	LNG Terminal, PQA	12
H	Al Huda Centre, D.H.A.	2
I	Clifton Block 1	3
J	AKD Tower, Clifton	8
K	Bridge at M.T. Khan road	4
L	Bahria Complex III, M.T. Khan Road	4
M	Children Museum for Peace and Human Rights, D.H.A.	9
N	Pakistan Mall, D.H.A.	7
O	Shahrah-e-Faisal	4
P	D.H.A. Mall	8
Q	PQA F-2 North West Industrial Zone	2
R	Plot # E-60 N.W.I.Z. PQA	4
S	Tuwairqi Steel Mills, PQA	35
T	Clifton Quarters	3
U	Karachi Grain Terminal, PQA	2
V	Fauji Fertilizer, PQA	21

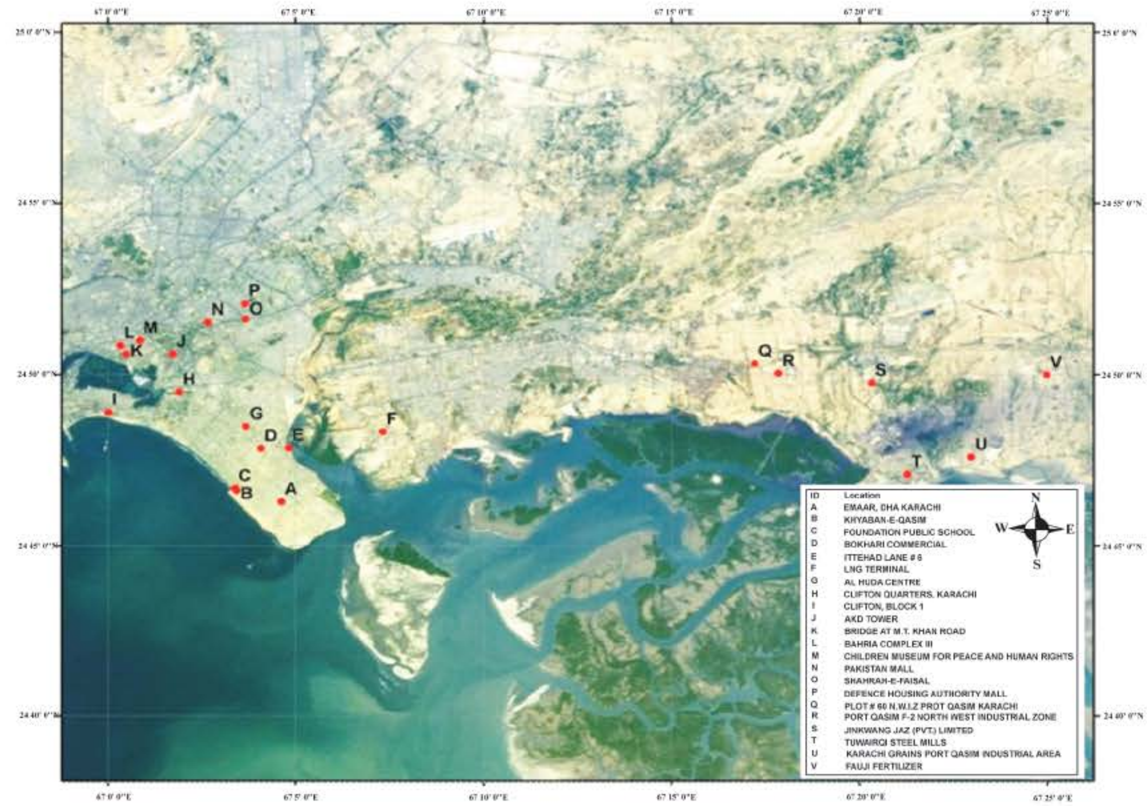

Fig. 2. Bore hole logs marked for reference of study area.

3.4. Hydrogeological condition

SPT bore records show ground water table very near to the ground surface in the study area, especially in Port Qasim area due to proximity to the sea. During 1970's Port Bin Qasim was constructed to provide an alternate to Karachi Port and tofacilitate newly developed industrial area in the south eastern part of the City. The navigational channel at Port Qasim connects Phitti Creek and is about 45 km long. However, over time this channel has caused severe coastal erosion and has resulted in destruction of barrierislands thus destroying the nature's first line of defence againstcoastal erosion.

Over the years due to pressure of increasing population and increase in land prices, Defence Housing Authority which is acoastline residential area was increased through reclamation of sea. This reclamation was done without giving due consideration to the implications of coastal dynamics.Sand from adjacent beach or dredged from depths as shallow as 5m was used for reclamation which led to coastal erosion and resulted in the development of water inlet due to changed pattern of energy dissipation on the beach face of affected areas.

Studies (ESCAP, 1996) show that sea level in rising at a rate of 1.1 mm/yr in the past 100 years. With this rate of rise of sea level it is expected that in the next 50 to 100 years, resulting rise could be from 20 to 50 cm.

It is observed throughout the Karachi particularly in the study area, that there is immense leakage and over flow from the sewerage and water supply systems, creating high groundwater table. Such conditions amplify the seismic intensity levels, affecting the area more severely even during low magnitude earthquakes. In view of freshwater shortages, a number of shallow and relatively deep tube wells have been installed. The pumping of groundwater from the wells should be monitored because over pumping may cause rapid seawater intrusion in areas along the coastal belt of Karachi. Very little is known regarding liquefaction potential along the coast of Karachi (Mahmud et al., 2008; Qureshi et al., 2001).

3. Research methodology

Liquefaction susceptibility of saturated sandy soils can be broadly classified into two groups i.e. laboratory methods and field methods. The major drawback of the laboratory methods is the extraction of undisturbed samples from the field, while correlating the laboratory results to the actual in-situ conditions is yet another issue. For accuracy of the analysis we chose field methods for this study.

4.1 Simplified procedure

An empirical based, field methodology known as the "Simplified Procedure", originally developed by Seed and Idriss (1971), has been improved over the years by different geotechnical experts (Seed and Idriss 1979; Seed 1982; Seed et al.,1985; Seed and Harder, 1990). In 1996 and 1998 National Science Foundation (NSF) and National Centre for Earthquake Engineering Research (NCEER) organised workshops to gain a consensus on the developments made in Simplified Procedure over the last decade. A research paper was published by 21 experts in the Journal of Geotechnical and Geo-Environmental Engineering, (Vol. 127, No. 10, October, 2001) which summarises the recommendations of that workshop, and the present study primarily is based on this research output. This simplified procedure, therefore, has been referred to as the NCEER procedure within this study and is shown below.

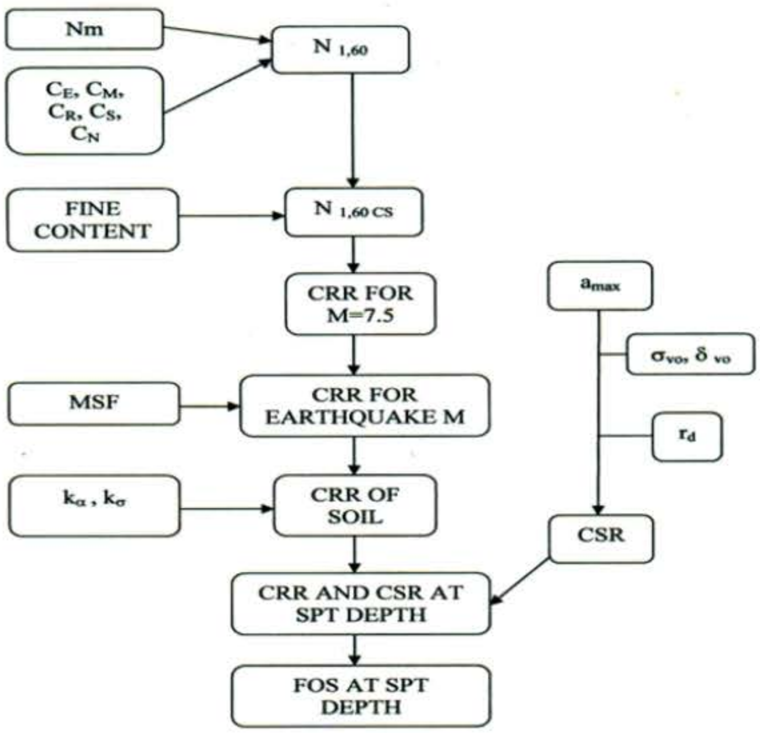

Fig. 3. The NCEER procedure.

Nomenclature

$CRR_{7.5}$	Cyclic resistance ratio at an earthquake magnitude of 7.5	r_d	Stress reduction coefficient
CSR	Cyclic stress ratio generated by earthquake shaking	z	Depth below ground surface in meters
MSF	Magnitude scaling factor	N_m	Measured standard penetration resistance
k_a	Correction factor for sloping ground	$(N_1)_{60cs}$	$(N_1)_{60}$ to an equivalent clean sand value,
k_s	Correction factor for extrapolate simplified procedure to soil layers with overburden pressure > 100kPa	(N1)60	SPT blow count normalized to an overburden stress of 100 kPa and a hammer efficiency of 60%.
$\tau_{\alpha\varpi}$	Average shear stress	FC	Fines Content
δ_{vo}	Effective vertical overburden stresses	C_E	Correction for hammer energy ratio (ER)
a_{max}	Peak horizontal acceleration at the ground surface generated by the earthquake shaking	C_N	Factor to normalize N_m to a common reference effective overburden stress
g	Acceleration of gravity	C_R	Correction factor for rod length
$\sigma_{\varpi o}$	Total vertical overburden stresses	C_S	Correction for samplers with or without liners
		C_B	Correction factor for borehole diameter

4.2. Cyclic stress approach

The NCEER procedure is based on the cyclic stress approach, the earthquake induced loading expressed in terms of cyclic shear stresses, is compared with the cyclic liquefaction resistance of the soil. At locations where the loading exceeds the resistance, liquefaction is likely to occur. NCEER procedure encompasses four methods:

1. Criteria based on standard penetration tests;
2. Criteria based on cone penetration tests;
3. Criteria based on shear-wave velocity measurements
4. Criteria based on the Becker penetration test for gravely soils.

This study uses the methodology based on the standard penetration test based on the market practices and accuracy of results. The objective of this study is to prepare liquefaction potential map on the basis of input through field test data.

Based on the computation of values of Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR), the methodology brings forth the values that depict the soil liquefaction susceptibility. Due to the absence of fines content data (passing sieve # 200), liquefaction potential has been determined by computation of factor of safety at different percentages of fines content i.e. 5%, 10%, 20%, 30% and 40%. The analysis is done on the basis of Standard Penetration Test values considering a sample size of 120 borehole logs. Depth of the bore logs used in the study is limited to 50 ft since NCEER procedure is only applicable to shallow depths of 50 ft.

In most of the cases sandy soil was found, however, at places traces of silt were also encountered along with sand (Sultan 2009). The analysis is made on the 7.5 magnitude of earthquake being the benchmark of analysis, which could be corrected on the basis of magnitude scaling factors based on the value of actual magnitude experienced. As recommended by Pakistan Building Code, Karachi has been analyzed in zone 2-B and Zone 4 for the worst case scenario. Based on the results generated, the liquefaction potential maps are developed using surfer software, which produces contour plans based on the values of factor of safety. The contour plan helps to categorize the areas susceptible to liquefaction; factor of safety in this study being cyclic resistance to cyclic stress ratio, (See Fig. 3). No specific value of factor of safety is recommended as safe, however, for soil having factor of safety less than 1 are highly susceptible to liquefaction and susceptibility for liquefaction varies inversely with factor of safety.

5. NCEER procedure

NCEER Procedure (Youd et al., 2001) has been used for determination of liquefaction potential for the coastal regions of Karachi, it is a deterministic procedure for determination of liquefaction potential. Figure 3 summarises the NCEER procedure.

Liquefaction susceptibility is determined on the basis of factor of safety (FOS) computed by taking the ratio of Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR).

$$FOS = \{CRR_{7.5} / CSR\}\ MSF\ (k_{\alpha})(k_{\sigma}) \qquad (1)$$

5.1. Computation of cyclic stress ratio

Following equation for calculating cyclic stress ratio has been used (Seed and Idriss 1971).

$$CSR = (\tau_{av} / \delta_{vo}) = 0.65(a_{max} / g)(\sigma_{vo} / \delta_{vo}) r_d \qquad (2)$$

For a_{max} the following assumption has been undertaken based on UBC 1997:

"PGA may be determined based on site-specific study taking into account soil amplification effects. In absence of such a study, peak ground acceleration maybe assumed equal to seismic zone factor."

No instrumental study has yet been undertaken to determine peak ground acceleration values for Karachi city. We make use of Table 1, for Zone 2B, amax= 0.2 g and for Zone 4, amax = 0.4g

r_d is a stress reduction coefficient which accounts for flexibility of the soil profile.

For routine practice and non-critical projects, the following equations may be used to estimate average values of rd:

$$r_d = 1 - 0.00765z \quad \text{for } z \leq 9.15\text{ m} \qquad (3a)$$
$$r_d = 1.174 - 0.0267z \text{ for } 9.15\text{ m} \leq z\ 23\text{ m} \qquad (3b)$$

T.F. Blake has given the following equation, which can be conveniently used for computations in a spreadsheet.

$$rd\ \left[\frac{(1.000\ 0.4113^{1.5}\ +0.04052z + 0.001753z^{1.5})}{(1.000\ 0.4177^{0.5}\ +0.05729z\ \ 0.006205z^{1.5}\ +0.001210z^{1.5})}\right] \qquad (4)$$

where z = depth beneath ground surface in meters. Equation (4) yields essentially the same values for rd as Equation (3a & 3b).

5.2. Computation of cyclic resistance ratio

The equation for cyclic resistance ratio is based on case history data from limited site conditions of shallow liquefaction and near level ground for a moment magnitude 7.5 earthquakes and the strength obtained for a given penetration resistance is termed CRR 7.5. It can be adjusted for actual site conditions by applying the corrections of MSF, K_d and K_r indicated in Equation (1).

$$CRR_{7.5} = \frac{1}{34-(N_1)_{60}} + \frac{(N_1)_{60}}{135} + \frac{50}{(10(N_1)_{60}+45)^2} - \frac{1}{200} \qquad (5)$$

where $(N1)_{60}$ is SPT blow count normalized to an overburden stress of 100 kPa and a hammer energy ratio or hammer efficiency of 60%.

5.3. Influence of fines content

The value of CRR increases with an increase in fines content. It is still unclear whether this increase is caused by an increase of liquefaction resistance or a decrease of penetration resistance.

The Equations (6) and (7) were developed by Idriss and Seed for correction of $(N1)_{60}$ to an equivalent clean sand value, $(N1)_{60cs}$

$$(N_1)_{60cs} = \alpha + \beta(N_1)_{60} \qquad (6)$$

where α and β are coefficients determined from the following relationships:

$\alpha = 0$ for $FC \leq 5\%$ (7a)

$\alpha = \exp[1.76 - (190/FC)]$ for $5\% < FC < 35\%$ (7b)

$\alpha = 5.0$ for $FC \geq 35\%$ (7c)

$\beta = 1.0$ for $FC \leq 5\%$ (7d)

$\beta = [0.99\ 1\ (FC/1,000)]$ for $5\% < FC < 35\%$ (7e)

$\beta = 1.2$ for $FC \geq 35\%$ (7f)

Sieve analysis results were missing for the 120 SPT bore logs data obtained from various geotechnical laboratories, therefore, the liquefaction potential has been determined by considering fines content to be equal to 5%, 10%, 20%, 30%, 40% for the study area and developing subsequent maps.

5.4. Other Corrections

Several factors in addition to fines content and grain characteristics influence SPT results. Equation (8) incorporates these corrections

$$(N_1)_{60} = N_m C_N C_E C_B C_R C_S \qquad (8)$$

where Nm = measured standard penetration resistance;

6. Results and discussion

Karachi is growing at a phenomenal pace. Careful planning and selection of safe area for future expansion remains a challenge urban planners, these maps will not help plan city's expansion in a safe manner but will also serve civil and geotechnical engineers, seismologist and architects in making decisions while selecting the land for new development projects along the coastal areas of Karachi. At the same time they will research in develop further at the universities. The methodology adapted shall pave way for mapping out vulnerable sites for future construction activity.

This study presents results of field tests that have been used to assess liquefaction susceptibilities of the soils of the coastal belt of Karachi city by considering Karachi in zone 2B and 4. Figures 4.1 to 4.10 show the results of this study determined on the basis of factor of safety (FOS) computed by the ratio of Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR) at different percentages of fines content i.e. 5%, 10%, 20%, 30% and 40%. The NCEER procedure is applied to the SPT data values consisting of 120 borehole logs located in the coastal areas of Defence Housing Authority and Port Qasim Industrial Area. Magnitude of earthquake considered in the analysis is 7.5. The study indicates that the coastal region of Karachi is highly susceptible to liquefaction in the event of an earthquake.

7. Conclusions

1. Liquefaction susceptibility exists for all FOS values less than 1, with severity increasing with decreasing values.

   Zone 2B: The graphs depict that the soil is highly susceptible to liquefaction with less fines content and severity decreases with an increment of the same due to an increment in porosity of the soil and generating drained conditions. Values ranging from 0.35 (highly susceptible) to 0.75(moderately susceptible) were observed.

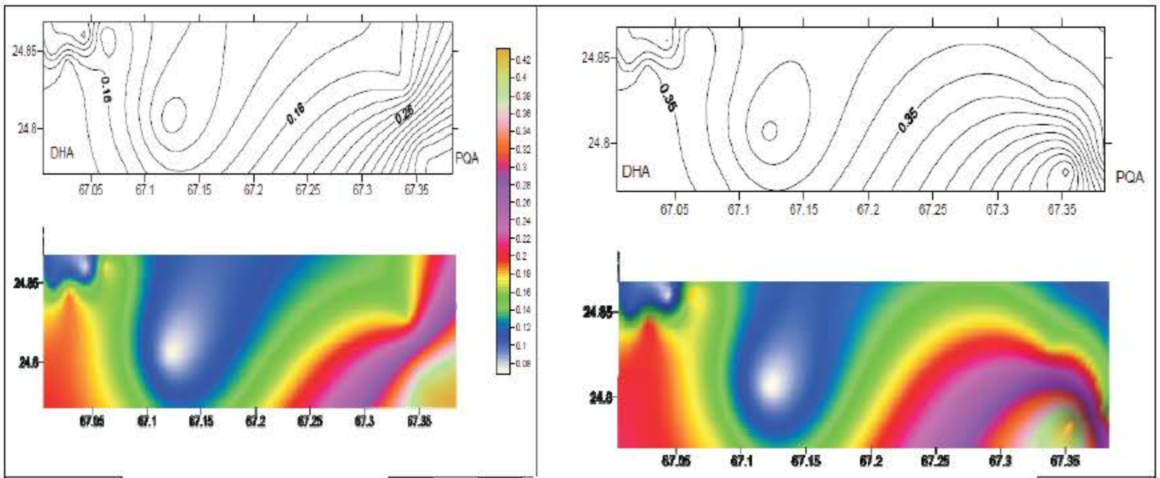

Fig. 4.1 Fig. 4.2

Fig. 4.1 and 4.2. Geospatial distribution of Factor of safety contours for coastal area based on consideration of Zones 4 and 2B with 5% fines content respectively.

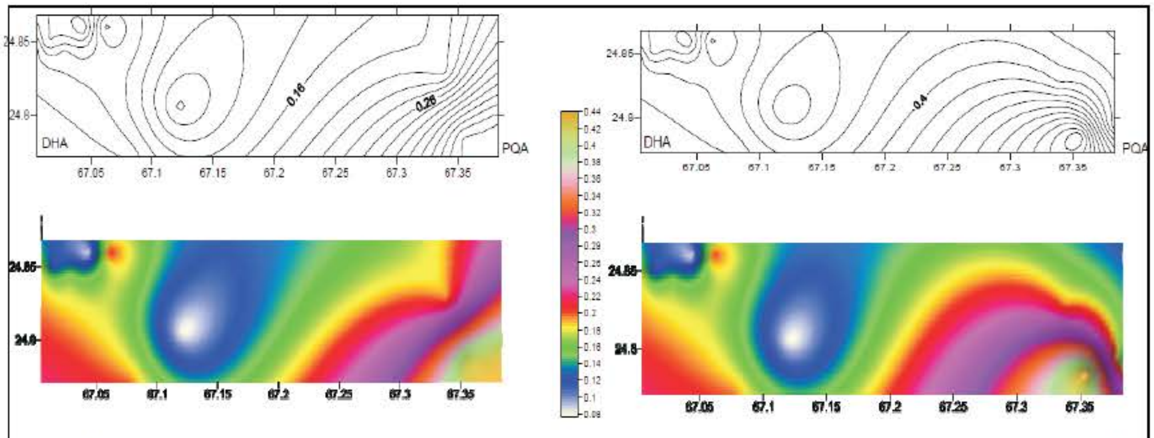

Fig. 4.3 Fig. 4.4

Fig. 4.3 and 4.4. Geospatial distribution of Factor of safety contours for coastal area based on consideration of Zones 4and 2B with 10% fines content respectively.

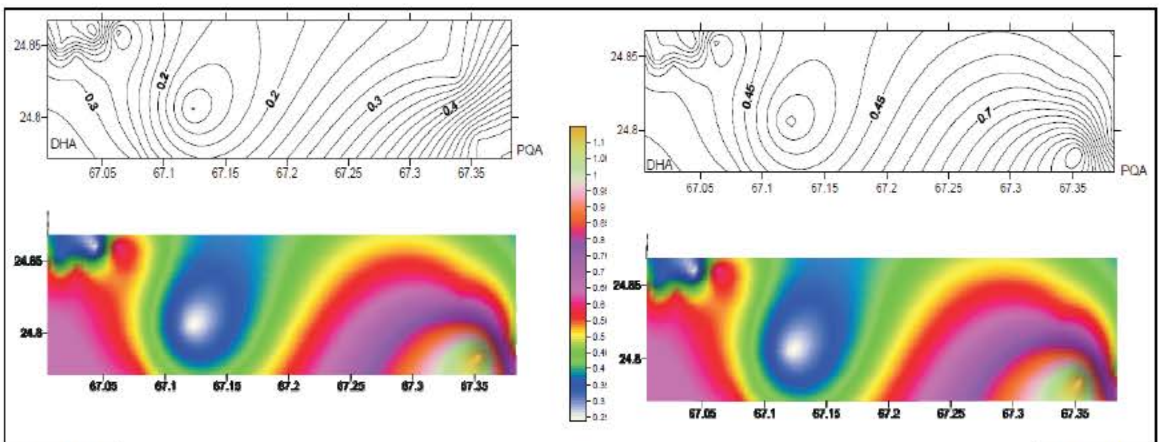

Fig. 4.5 Fig. 4.6

Fig. 4.5 and 4.6. Geospatial distribution of Factor of safety contours for coastal area based on consideration of Zones 4 and 2B with 20% fines content.

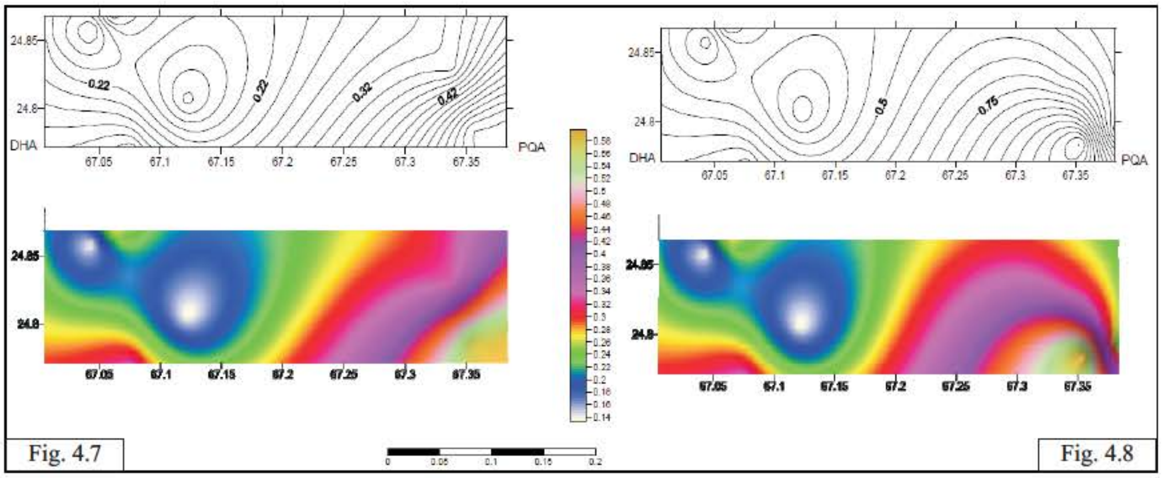

Fig. 4.7 and 4.8. Geospatial distribution of Factor of safety contours for coastal area based on consideration of zones 4 and 2B 30% fines content.

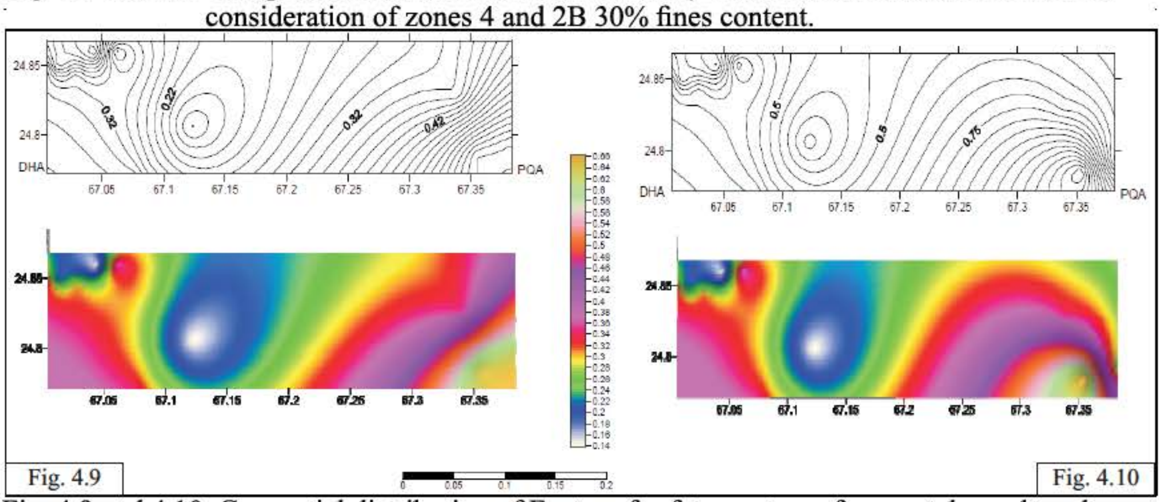

Fig. 4.9 and 4.10. Geospatial distribution of Factor of safety contours for coastal area based on consideration of zones 4 and 2B 40% fine content.

Zone 4: When considering the study area in Zone 4, it is highly evident from the results that however the FOS varies with an increment in percentage of fines content and variation of ground water table but the values range between 0.16 and 0.4 that depicts, study area is highly susceptible to liquefaction.

2. Both the high groundwater level and the grain size of the soils, in conjunction with the active seismic features of the region, result in conditions favourable to the occurrence of liquefaction.

3. Actual records of sieve analysis data if available will improve the quantification of results, though may not alter the prime finding

8. Recommendations

1. In order to prevent the occurrence of possible soil liquefaction and settlement of buildings, it is recommended that mitigation measures against liquefaction should be used to bear both static and dynamic stress. Soil liquefaction improvement techniques can be characterized as soil densification, drainage, reinforcement, mixing, or replacement.

2. Since damaged water and sewer lines tend to increase liquefaction potential; steps should be taken at micro and macro level to address and eradicate the issue.

3. As has been observed at various locations along the coastal belt of Karachi to include Bahria Icon Tower, Bin Qasim Park, Karachi Financial Tower etc., with soil retained through the secant pile wall and excavation in high water table has resulted in lateral spreading of soil with formation of large cavities behind the wall, thus

liquefaction, resulting in constructing a mass concrete wall behind the retention wall or a complete failure of retention mechanism. The reason being undue consideration for liquefaction hazard assessment. Preliminary and detailed soil investigation should mandatorily include liquefaction potential and seismic hazard assessment to augment the factor of safety and save undue costs.

4. The lithology of soil in Karachi is highly variable with non-uniform variation pattern as has been observed during the research, concerted efforts needs to be done pre-construction for correct assessment of soil classification to reduce liquefaction hazard.

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