Mapping of Liquefaction Susceptible Sands of Punjab Province in Pakistan

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Abstract-Liquefaction is hazardous for existing and new developments because the saturated loose sands lose their bearing capacity under shaking due to earthquake. In Pakistan, lesser database is available about the presence of liquefiable sands and local codes are also silent about its origination/mapping especially in Punjab Province. Historically, Punjab has been facing low to high intensity earthquakes. The developments on liquefiable sands faced numerous losses of lives and property after earthquakes in recent decades. An attempt has been made to evaluate liquefaction susceptibility of sand deposits in different districts of Punjab for future record in terms of mapping. There are lots of procedures available for analysis, identification and quantification of liquefaction potential of sands. The analysis is done based on two of the most recognized techniques i.e. Standard Penetration Test (SPT) parameter and grain size characteristic. Analysis resultant parameters like cyclic resistance ratio (CRR) and cyclic stress ratio (CSR) are plotted on the base curves available in literature about liquefiable sands. Based on analysis, a map is proposed for liquefiable sands in Punjab.

Keywords-Sands, Liquefaction, Standard Penetration Test, Map, Grain Size Characteristics, Punjab, Pakistan

I. INTRODUCTION

Liquefaction is a phenomenon which mostly occurs in granular soils under saturated and poor drainage conditions. These granular soils are like sands or silty sands[i]. During seismic loadings, the volume of loose sands decreases resulting increase in pore water pressure. Due to rise in pore water pressure, shear strength decreases and subsequently reduction of effective stress occur [ii]. Evaluation of liquefaction potential for a soil deposit can be determined by a combination of factors like properties of that soil, environmental conditions and earthquake characteristics. Although, we cannot determine some factors directly but for liquefaction evaluation procedure, the effects of these factors can be incorporated. Two methods are commonly available to evaluate the liquefaction potential of soils i.e. through field Standard Penetration Test (SPT) and laboratory gradation parameters. The liquefaction potential of soil is normally referred interns of Cyclic stress ratio (CSR), Cyclic resistance ratio (CRR) and respective Factor of Safety (FOS). The details of these methods are discussed below.

After massive damages due to severe earthquakes of Alaska and Niigata Japan in 1964, two methods of liquefaction assessment were developed one from SPT data proposed by [iii] also named as "simplified procedure" and other from laboratory gradation parameters by [iv]. Since, then the “Simplified procedure” was continuously improved by different researchers like [v],[vi],[vii] Fig. 1 shows the latest status of the procedure.

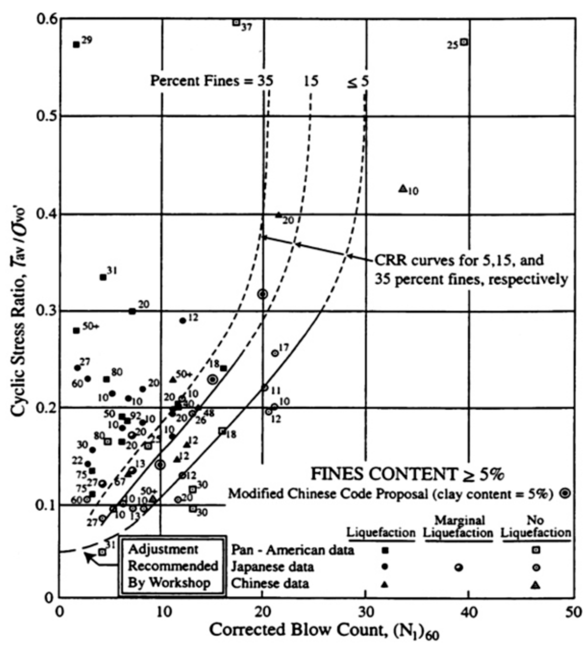

Fig. 1. Simplified base curves for determination of CRR from SPT (Seed et. al 1985)

To prepare liquefaction maps of soils is a common practice in developed countries for its possible consideration during development on such soils. The maps developed for liquefaction susceptibility differentiates the zone of low or high liquefaction potential. Mapping of liquefaction susceptibility is raised in order to identify that how the liquefaction hazard is different from one place to another on the basis of different earthquake characteristics.

Distribution of different geologic strata, depth of ground water table, bore hole logs and predicted levels of shaking during future earthquakes are parameters which are used for development of these maps.

Although the liquefaction susceptibility mapping for the areas are increasing around the world, but the method for the development of such kinds of maps has remained the same. The basic parameter used in most of the previous and existing liquefaction susceptibility maps is geotechnical engineering data and surface geology.

One of the available maps of liquefaction susceptibility of San Francisco Bay Area of USA is shown in Fig. 2. In this map, interpretation of Liquefaction susceptibility has been done on the basis of geotechnical engineering data and surface geology. References [viii], [ix], [x], [xi]& [xi] also used geotechnical engineering data / geological data for liquefaction susceptibility mapping in past.

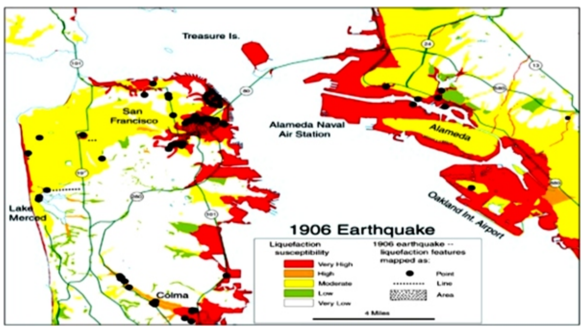

Fig. 2. Liquefaction susceptibility map of San Fransico Bay area USA

Almost no work has been done regarding mapping of liquefaction susceptible sands of Punjab Province in Pakistan. In this research, a basic liquefaction map has been developed after identification and analysis of sands prone to liquefaction. The purpose of this research was to provide the basic guidelines to the geotechnical and structural engineers for carrying out design in the liquefaction susceptible areas.

II. MATERIALS AND METHODS

Identification of liquefaction prone soils in Punjab was carried out initially. For that purpose detailed literatures / documents in form of geotechnical engineering reports / geological formations were collected / consulted from different organizations like Soil Survey of Pakistan, Geological Survey of Pakistan, Communication and Works Department Government of Punjab, NESPAK, Berkley Associates, etc. The basic base in identification of potentially liquefiable soil areas was seismic zoning map of Pakistan as shown in Fig. 3.

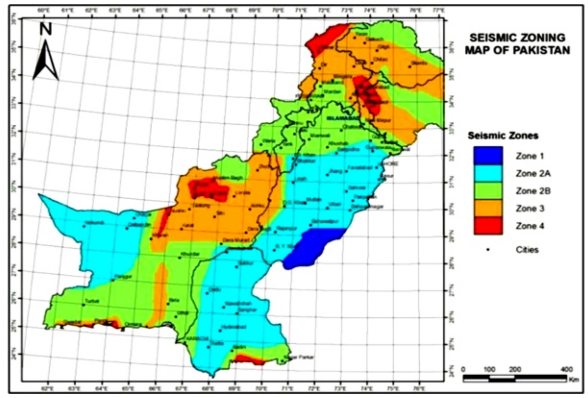

Fig. 3. Seismic Zoning Map of Pakistan

The geotechnical engineering reports/geological formations of all districts of Punjab were evaluated based on the criteria of gradation parameters and Standard penetration tests data. After identification of liquefiable soils, the in-situ geotechnical parameters like SPT blows (N) were further corrected to $(N_1)_{60}$ as recommended [xiii] and analyzed to determine the liquefaction properties like CRR (Cyclic Resistance Ratio) which is a measure of liquefaction resistance of soil, CSR (Cyclic Stress Ratio) which is induced by earthquake and respective factors of safety. These factors were calculated from mathematical expressions/equations described from Eq. (1) to Eq. (7).

$$CSR = 0.65 a_{max} / g r_d \sigma_v / \sigma'_v \quad (1)$$

0.65 = Reduction factor converting the (single/one time) peak cyclic to the "equivalent uniform shear stress

a_{max} = The peak ground acceleration in units of g.

r_d = Stress reduction factor accounting for the flexibility of the soil profile.

σ_v = Total vertical overburden stress.

σ'_v = Effective vertical overburden stress.

Stress reduction factor assumes a linear relationship of r_d versus depth as shown in Eq. 2 [xiv]

$$r_d = 1 - 0.012z \quad (2)$$

z = Depth in meters below the ground surface where the liquefaction analysis is being performed

The N-value is the blow counts for the last 30 cm of penetration and 50 times is the maximum value. However, for harder soil penetration cases, there often happens that penetration depth does not reach 30 cm or counts need more than 50 times for 30 cm penetration. For practical use of N-values for earthquake engineering purpose, the corrected N-value of "N_{SPT}" is used.

The measured SPT blow count (N_{SPT}) is first normalized for the overburden stress at the depth of the test and corrected to a standardized value of $(N_1)_{60}$. Equation (3) is used for the calculation of corrected SPT $(N_1)_{60}$ using the recommended correction factors.

$$(N_1)_{60} = N_{SPT} \times C_N \times C_E \times C_B \times C_R \times C_S \quad (3)$$

C_N = Correction applied for overburden
C_R = Correction applied for rod length
C_B = Correction applied for borehole diameter
C_E = Correction applied for hammer energy
C_S = Correction applied for sampler whether it is with or without liner

$$CRR = 1/[34 - (N_1)_{60}] - (N_1)_{60}/135 + 50/[(10(N_1)_{60} + 45)]^2 - 1/200 \quad (4)$$

Equation (4) for the calculation of CRR is valid for $(N_1)_{60} < 30$ and earthquake magnitude of 7.5 (ii). For $(N_1)_{60} > 30$, Clean granular soils are too dense to liquefy and are classed as non-liquefiable. If the magnitude of earthquake is other than 7.5 then CRR value is further corrected using a factor named as Magnitude Scaling Factor (MSF) and its mathematical expression is shown as Eq. (6) [ii]

$$CRR = CRR_{7.5} \text{ x } MSF \quad (5)$$

$$MSF = 10^{2.24} \text{ x } (M_w)^{2.56} \quad (6)$$

M_w is the anticipated earthquake magnitude

$$FOS = CRR / CSR \text{ x } MSF \quad (7)$$

An Excel spreadsheet based on "simplified procedure" was developed to calculate these liquefaction properties in steps mentioned by [xv].

Then the calculated values of $(N_1)_{60}$ and factors of safety were checked against the limits defined by researchers. The soils having $(N_1)_{60} < 30$ the soils were considered liquefiable and for soils having value of $(N_1)_{60} > 30$, considered as non-liquefiable [xvi]. After calculation of $(N_1)_{60}$, CRR and CSR values at a particular depth of given soil stratum, factor of safety against liquefaction was calculated [iii]. For the soils having factor of safety less than or slightly greater than 1.0 i.e. 1.2 (xvii), the soils were declared liquefiable.

Then the calculated parameters like $(N_1)_{60}$, CRR, CSR and factor of safety were plotted against depth to interpret the behavior of liquefaction susceptible sands of Punjab. Also, the parameters like CRR, CSR and $(N_1)_{60}$ were plotted on the curves (ii) to show the compatibility of this research with previous researchers. Correlations between $(N_1)_{60}$, CSR and CRR were also proposed.

Liquefiable soils identified at different sites were also verified through gradation parameters obtained from geotechnical engineering reports. Based on the findings of research, the mappings of liquefiable soils for the province of Punjab were made using ARC GIS software.

III. Results and Discussion

For the identification of liquefiable soil areas; geological data, geotechnical reports/ data from various Government and Non-Government organizations were reviewed. Initially the surface soils data present in all districts of Punjab were evaluated based on the criteria of gradation parameters and Standard penetration tests data. After initial evaluation the methodology explained by [iii] and [iv] as shown in Fig. 4 was adopted.

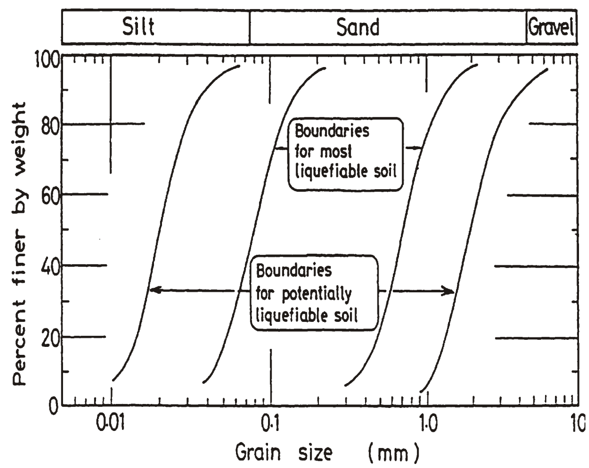

Fig. 4. Liquefaction soil boundaries based on gradations (Tsuchida 1970)

Characterizations of districts in Punjab Province are listed in Table I based on basic geological surface data obtained from Soil Survey of Pakistan & Geological Survey of Pakistan. It was observed that tehsils Attock, Haroonabad, Minchanabad, Bahawalnagr, Daryakhan, Wazirabad, Karorlaliesam, Malikwal, Muzafargarh, Liaqatpur, Sargodha, Bahalwal and Sialkot tehsils of these districts have distinguishable alluvial sands deposits. Liquefaction susceptible sands were also observed at different other districts of Punjab at scattered locations particularly along the fine major river routes. Presence of loose sands at the top strata and shallow depth of ground water table was the criteria for preliminary scrutiny. In order to further scrutinize the initial data formation for the analysis only tehsils having distinguishable formations of alluvial sands (with liquefaction susceptibility) were only selected as summarized in Table I.

TABLE I
SUMMARY OF DISTRICTS IN PUNJAB WITH RESPECT TO SOILS FORMATIONS

Sr.	District Name	Dominant soils formations in most parts of districts	Liquefaction susceptible tehsils in districts used in analysis
1	Attock	Alluvial sands	Nartopa
2	Bahawalnagar	Alluvial sands	Haroonabad, Minchanabad, Bahawalnagar.
3	Bahawalpur	Loams	-
4	Bhakkar	Alluvial sands	Daryakhan
5	Chakwal	Pothohar Belt with Expansive Soils	-
6	Chiniot	Clayey stratum	-
7	Dera Ghazi Khan	Expansive Soils (xviii)	-
8	Faisalabad	Clayey stratum	-
9	Gujranwala	Clayey stratum with Alluvial Sands and Expansive Soils (xviii)	Wazirabad
10	Gujrat	Clayey stratum	-
11	Hafizabad	Clayey stratum	-
12	Jhang	Clayey stratum	-
13	Jehlum	Clayey stratum	-
14	Kasur	Clayey stratum	-
15	Khanewal	Clayey stratum	-
16	Khushab	Clayey stratum with Expensive Soils	-
17	Lahore	Clayey stratum	-
18	Layyah	Alluvial sands	Karorlaliesan
19	Lodhran	Clayey stratum	-
20	Mandi Bhahuddin	Alluvial sands	Malikwal
21	Mianwali	Clayey stratum	-
22	Multan	Clayey stratum	-
23	Muzafargarh	Clayey stratum with Alluvial Sands	Muzafargarh
24	Narowal	Clayey stratum	-
25	Nankanasab	Clayey stratum	-
26	Okara	Clayey stratum	-
27	Pakpattan	Clayey stratum	-
28	Rahimyarkhan	Clayey stratum with Alluvial Sands	Liaqatpur
29	Rajanpur	Clayey stratum	-
30	Rawalpindi	Pothohar Belt	-
31	Sahiwal	Clayey stratum	-
32	Sargodha	Clayey stratum with Alluvial Sands	Sargodha, Bhera
33	Sheikhupura	Clayey stratum	-
34	Sialkot	Clayey stratum with Alluvial Sands	Sialkot
35	Toba Tek Singh	Clayey stratum	-
36	Vehari	Clayey stratum	-

The database in forms of geotechnical testing reports were collected from different organizations in these thirteen identified tehsils of Punjab Province for the verification of the presence of liquefaction soils. The summary of which is presented in Table II.

TABLE II
PROJECT NAME WITH THEIR SOURCE OF COLLECTION

Sr.	Tehsil	Title of geotechnical engineering report	Reference
1	Minchinabad	Govt. Boys High School	
2	Haroonabad	Govt. Islamia Rizvia	
3	Bahawalnagar	Distt. Jail Residences	
4	Bahawalnagar	Separate Emergency Block in DHQ	
5	Muzaffargarh	Executive Engineer Residence	
6	Liaqatpur	Riverine Post	
6A	Liaqatpur	Govt. Boys High School	
6B	Liaqatpur	Govt. Girls Primary School	
7	Layyah	Police Station	Building Research Station(BRS), Communication &Works Department, Lahore, Govt. of Punjab
8	Layyah	Police Station	
9	Bhakkar	Govt. Boys Degree College	
10	Bhakkar	Govt. Boys Degree College	
11	Attock	Govt. Girls Elementary School	
12	Attock	Govt. Girls Elementary School	
13	Attock	Govt. Girls Elementary School	
14	Sargodha	Govt. Degree College for Girls	
15	Sargodha	Govt. Degree College for Girls	
16	Sargodha	Govt. Degree College for Girls	
17	Bhera	Govt. Degree College for girls	
18	Bhera	Govt. Degree College for Girls	
19	Mandi bahauddin	Construction of Judicial Complex	
20	Mandi bahauddin	Construction of Judicial Complex	
21	Mandi bahauddin	Construction of Judicial complex	
22	Marala	Lucky Hydropower	Barqaab Consulting Services (Pvt.) Ltd. Lahore
23	Wazirabad	New Khanki Barrage	Berkley Associates Lahore

From the database of geotechnical investigation reports of projects tabulated in Table II the SPT profiles and gradation parameters have been extracted for further analysis. A liquefaction phenomenon was observed in sandy soils. Fig. 5 presents the grain size analysis of soils encountered in regions reported in Table II.

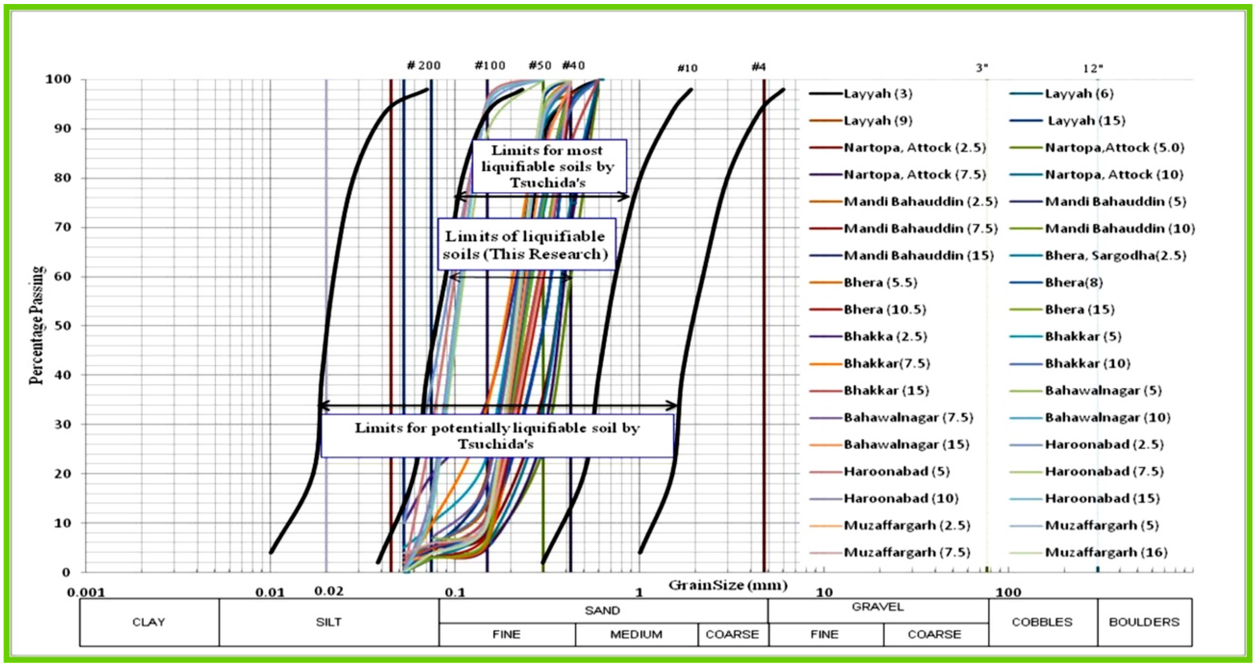

Fig. 5. Gradations profiles of soils

It can be seen in Fig. 5 that most of the soils are medium to fine sands in nature. Sands are more susceptible to liquefaction. The gradations of sands found in all the tehsils fall well within the boundaries of the liquefiable soils proposed [iv].

Hence, based on the analysis of gradations curves the soils encountered in all tehsils are categorized as liquefiable. The SPT profile with depth for all twenty three projects is shown in Fig. 6.

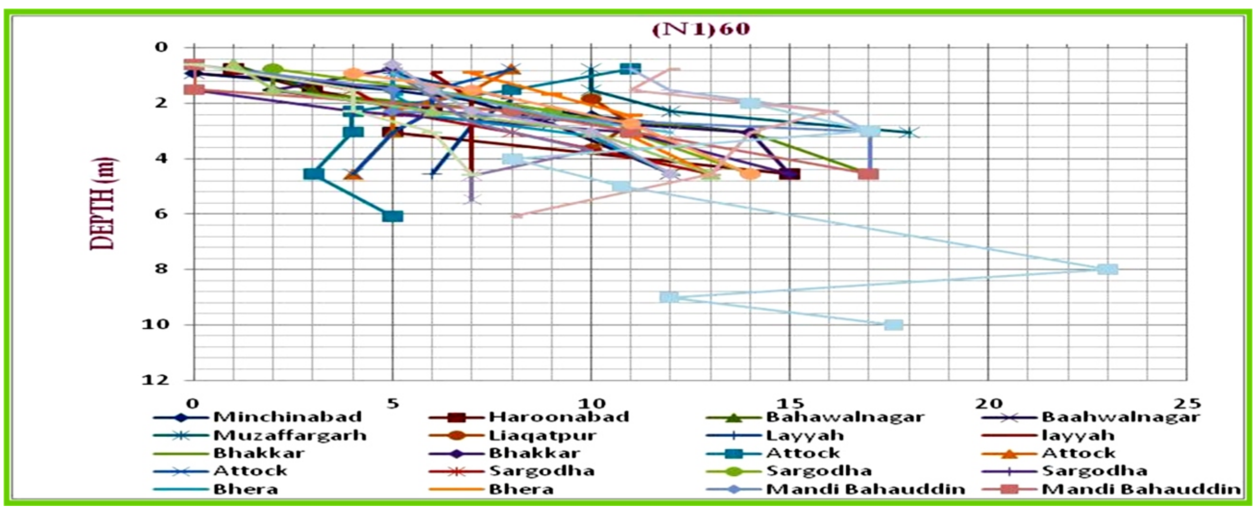

Fig. 6. SPT blows profile with depth

It can be seen from Fig. 6 that the value of $(N_1)_{60}$ is less than 20 in almost all the soils up to an average depth of 6 m. Hence, the soils showing $(N_1)_{60} < 30$ are declared as liquefiable soils [ii]. CRR and CSR were determined using SPT blows against moment magnitude (Mw) of 7.5 intensity and maximum value of Peak Ground Acceleration (PGA) for a particular zone as reported in Seismic code of Pakistan (SP-2007). Moment magnitude of intensity 7.5 and maximum value of Peak Ground Acceleration (PGA) is taken to consider the critical condition for analysis. Figs.7 & 8 show the profiles of CRR and CSR with depth.

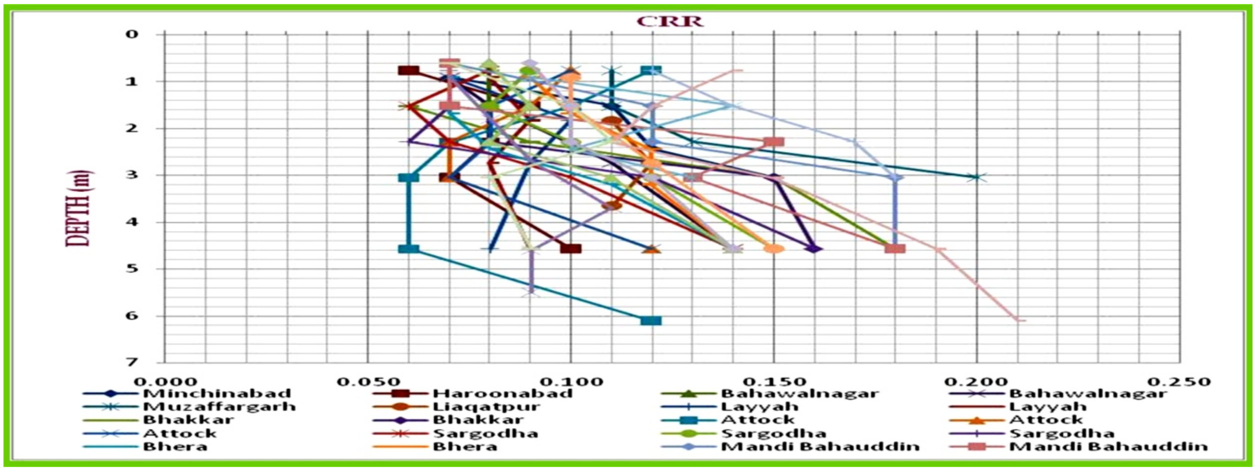

Fig. 7. CRR profiles with depth

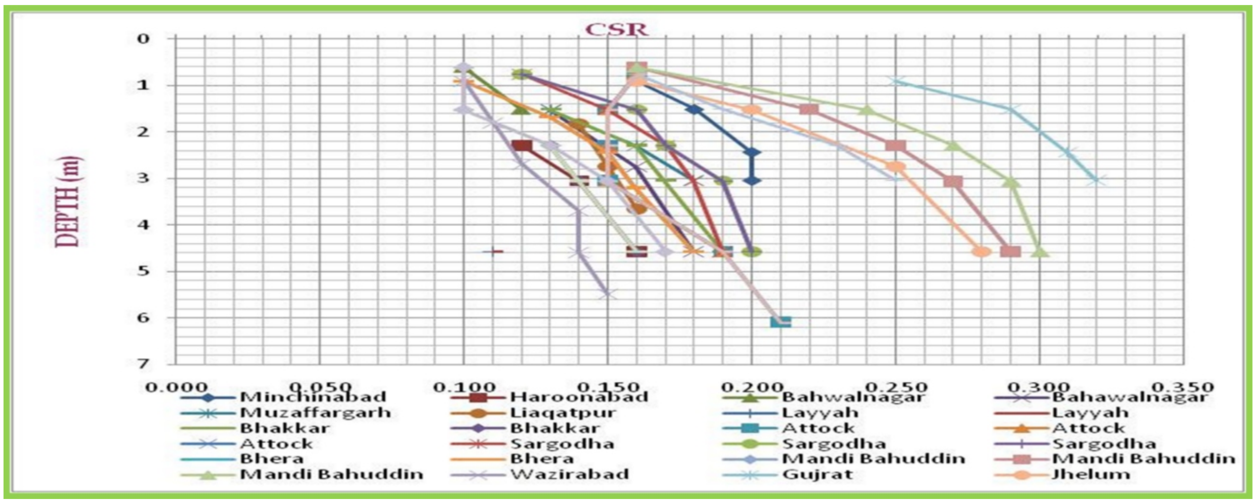

Fig. 8. CSR profiles with depth

It is eminent from Fig. 7 that CRR increases with the depth. The typical range of CRR observed in all location varies from 0.06 to 0.2. The CSR shows an increase with depth in typical range of 0.1 to 0.3 as shown in Fig. 8. The corresponding FOS profiles with depth are presented in Fig. 9.

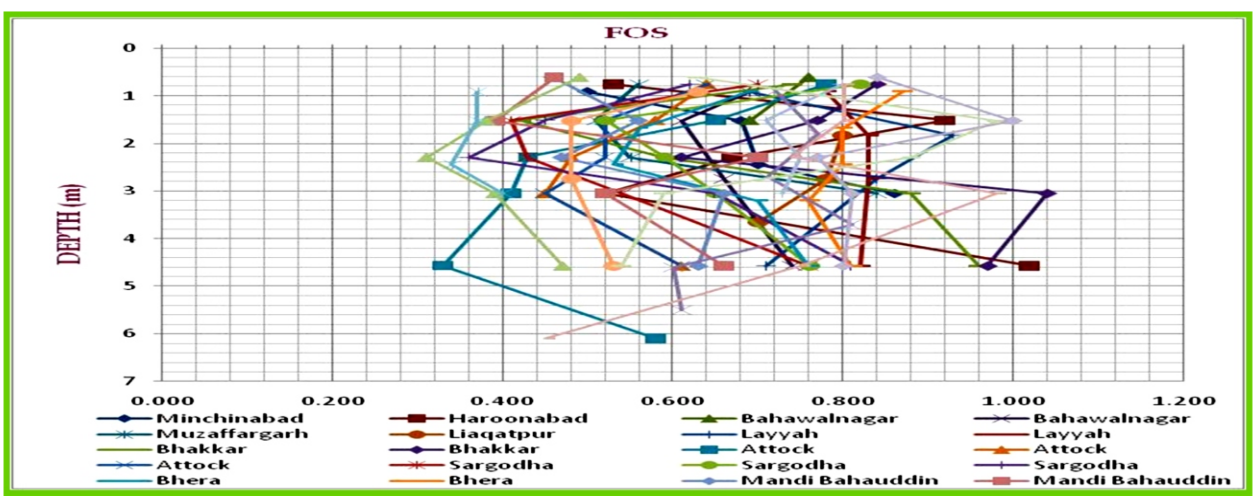

Fig. 9. FOS profiles with depth

In almost all the locations the Factor of Safety (FOS) ranges well below 1 as shown in Fig. 9. For further evaluation of the liquefaction susceptibility in soils i.e. $(N_1)_{60}$, CRR and CSR were also plotted on the original curve proposed by [iii] with future subsequent modifications as shown in Fig. 10.

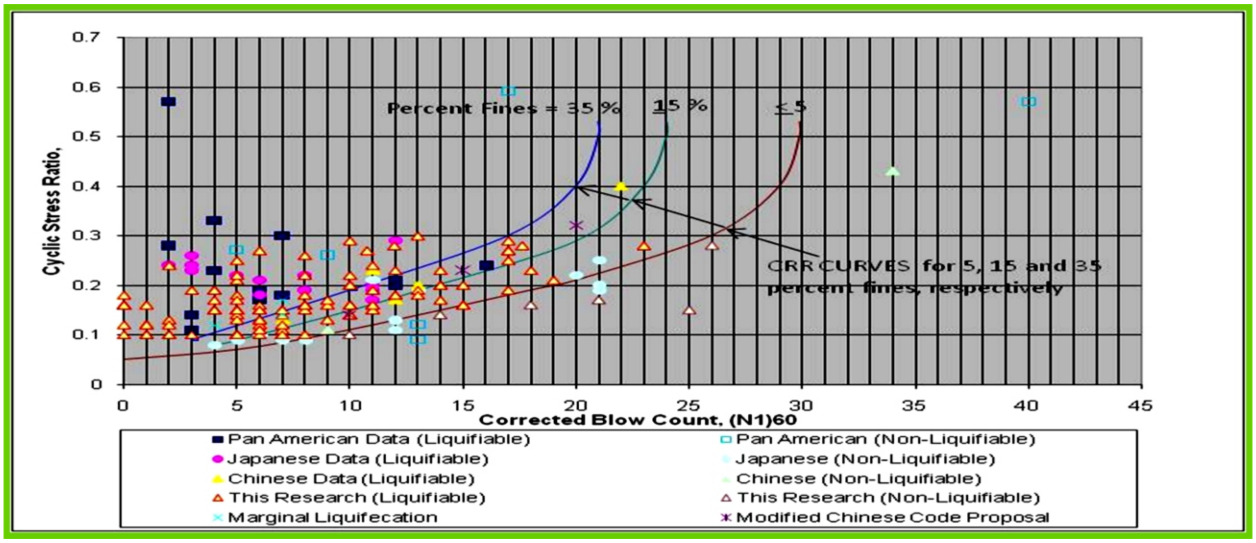

Fig. 10. CSR & CRR and $(N_1)_{60}$ plotted on Seed & Idriss Curve

The sands under study has been observed typically well within the typical zones of liquefiable soils as depicted in Fig. 10. Hence, the in-situ geotechnical engineering data of all 23 projects of all thirteen tehsils under study proved as liquefiable sands.

There are number of relationships reported in literature between CRR, CSR and $(N_1)_{60}$ for different type of soils. Two strong correlations between CRR, CSR and $(N_1)_{60}$ have also been obtained during data analysis of the subject study as shown in Figs. 11 & 12.

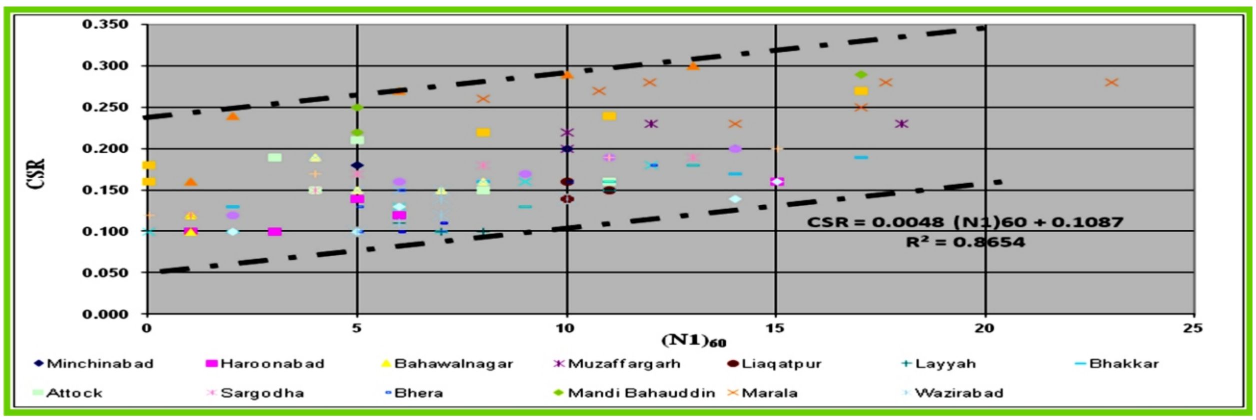

Fig. 11. Correlation between CSR and $(N_1)_{60}$

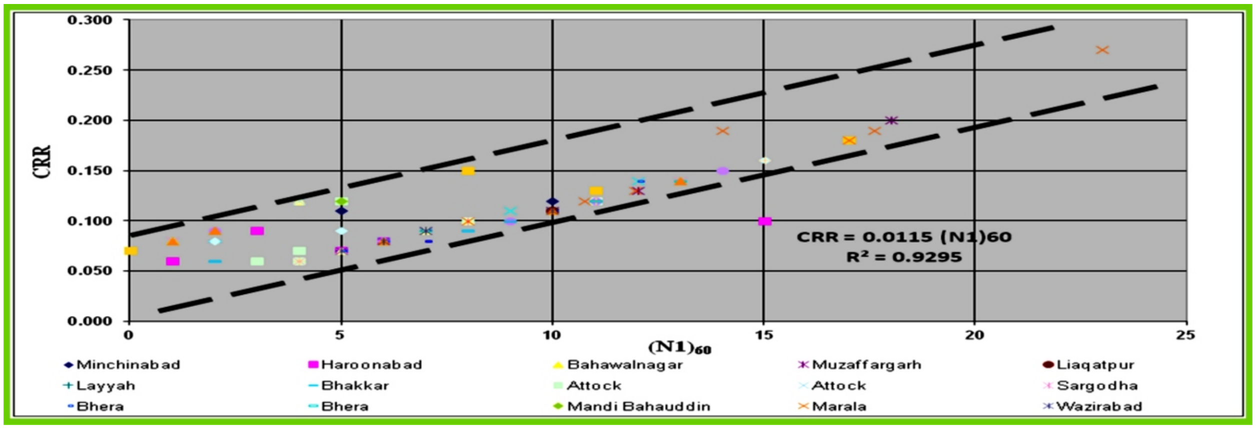

Fig. 12. Correlation between CRR and $(N_1)_{60}$

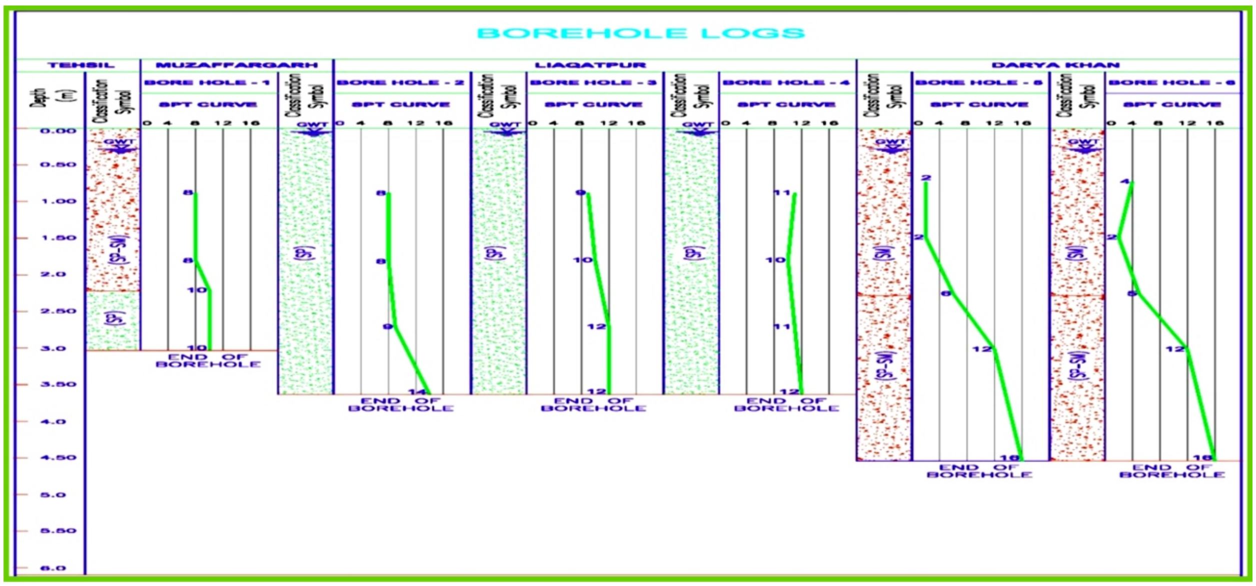

Fig. 13. Typical Bore Hole Log plot of different liquefiable tehsils

Both correlations reported in Figs.11&12 have strong coefficient of determination. The correlations between CRR, CSR and $(N_1)_{60}$ reported in Figs.11 & 12 are helpful for the direct determination of CSR and CRR after carrying out only SPT test at site. Further validations of correlations are recommended. Boreholes 2D plots of liquefiable tehsils like Muzaffargarh, Liaqatpur and Darya Khan has been plotted side by side as shown in Fig. 13 which shows higher water table and presence of poorly graded sands / silty sands in the upper strata.

Also the SPT-N values are less than 15 even at a depth of 3m. A map of Punjab province was developed using ARC GIS software as shown in Fig.14. On the map using coordinates districts, tehsils and locations of the projects were marked. Based on $(N_1)_{60}$ the magnitude of liquefaction on the map was subdivided into two parts as proposed [ii].

$(N_1)_{60}$ = 0 20 High liquefiable soils
$(N_1)_{60}$ = 21-30 Intermediate liquefiable soils

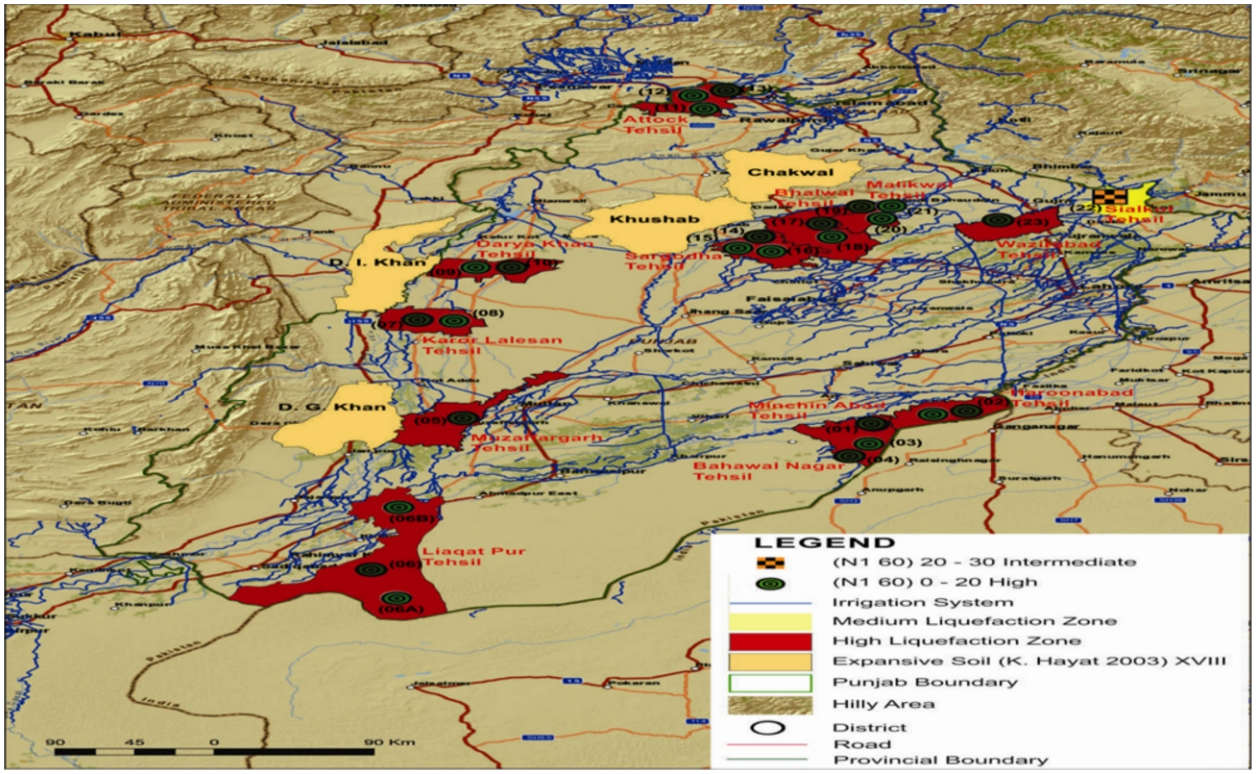

Fig. 14. Map of Punjab showing liquefiable soils

IV. CONCLUSIONS

The main object of mapping is to introduce the trend adopted worldwide in the practice of Pakistan. Further, it has been one of the key considerations to propose the idea through the subject research to local government and non government organizations dealing in codes of practice, researchers and professionals engaged in the practice of engineering to be adopted for identification of liquefiable soils. Following conclusions can be drawn from the above findings:

High liquefiable sands zones in Punjab are identified in Liaqatpur, Bhawalnagar, Muzzafargarh, Layyah and Minchanabad tehsils in southern Punjab. Attock tehsil in northern Punjab. Malikwal, Waziarabad, Bhalwal and Sargodha tehsils in eastern Punjab. Darya Khan tehsil in western Punjab.

Medium liquefiable sands zones in Punjab province are as following Marala tehsil in eastern Punjab.

Any geotechnical / structural engineering investigation or development works carried out in liquefiable susceptible zones identified above need to incorporate special considerations in design of footings.

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