Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)
© 2016 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-1-0

Standard Penetration Test-Based Assessment of Seismic Soil Liquefaction Potential of Urmia, Iran

H. Bahadori & A. Hasheminezhad
Department of Civil Engineering, Urmia University, Urmia, Iran

ABSTRACT: Soil liquefaction phenomenon has been observed for many years, but was brought to the attention of researches after Alaska and Niigata (Japan) earthquakes in 1964. There is no direct way to measure the liquefaction potential in soil, yet. What can be measured directly or indirectly are the various parameters that control soil's propensity to liquefy on seismic loading. For this purpose, various penetration test methods such as SPT, CPT and DMT are examined. These methods are completely empirical in nature and have worked well to date. Since Iran is located in an area with high seismic probability, there is a need for the liquefaction potential assessment in coastal areas like Urmia due to its proximity to Urmia Lake. In this paper, with the collected borehole data, an attempt was made to assess in detail the liquefaction potential of Urmia soil using SPT-based method. The Liquefaction potential was expressed in terms of the liquefaction potential index and calculated using standard penetration test profiles. Furthermore, a liquefaction hazard map of Urmia has been presented.

1 INTRODUCTION

Liquefaction is one of the most interesting but complex and controversial topics in geotechnical engineering. Soil liquefaction has been a major cause of damage to soil structure, lifelines and building foundation. It occurs when the structure of loose, saturated sand breaks down due to some rapidly applied loadings. As the structure breaks down, the loosely-packed individual soil particles attempt to move into a denser configuration. In an earthquake, however, there is not enough time for the water in the pores of the soil to be squeezed out. However, the water is trapped and prevents the soil particles from moving closer together. This is accompanied by an increase in water pressure which reduces the contact forces between the individual soil particles, thereby softening and weakening the soil deposit, results in settlement, tilting and rupture of structures in urban areas. Liquefaction potential of a soil deposit is dependent on the magnitude of a probable earthquake, grain-size distribution and soil type, relative density, earthquake loading characteristics, vertical effective stress and over-consolidation, age and origin of the soils, seismic strain history, degree of saturation and thickness of sand layer. Therefore in its assessment, these factors must be considered. However, some of the studies about these factors could not be ascertained, but their effects probably are assessed by means of cyclic loading test on undisturbed samples or in field tests such as SPT, CPT and DMT.

2 ASSESMENT OF LIQUIFICATION POTENTIAL

Several methods have been proposed to evaluate the liquefaction potential of soils due to earthquakes. The different types of methods can be classified into four groups including topographical and geological features, standard penetration test (SPT), Laboratory cyclic shear testing of undisturbed samples; and in-situ blasting or laboratory shake table testing. Nevertheless, conventional method based on the standard penetration test (SPT) has been commonly used in most countries and Iran. Seed and Idriss (1971) proposed a simplified procedure based on SPT-N values for the evaluation of liquefaction resistance of soils after two large and catastrophic earthquakes occurred in Alaska and Niigata (Japan) in 1964. The original simplified procedure based on empirical rules has been modified and improved over the years (Seed 1983).The standard penetration test is a method that can be used in the empirical correlation with liquefaction potentials of the sub-surface materials. Previous studies indicated that the liquefaction characteristic of soil is depended on a larger number of factors (Seed 1983). Although, it may not be possible at this stage to specify a single parameter, Christian and Swiger (1975) have shown that the SPT value, N, may ultimately solve this problem. Standard penetration test (SPT) is widely used as an economic, quick and convenient method to investigate the penetration resistance of non-cohesive soils. This test is an indirect means to obtain important parameters for non-cohesive soils. The cyclic stress ratio, developed at a particular depth beneath the ground surface may be estimated using the relation developed by Seed and Idriss (1971):

$$\frac{\tau_{av}}{\sigma_0'} = 0.65 \frac{a_{max}}{g} \frac{\sigma_0}{\sigma_0'} r_d \quad (1)$$

Where τ_{av} is the average cyclic shear stress during a particular time history, σ_0 is the effective overburden stress at the depth in question, σ_0' is the total overburden stress at that depth, a_{max} is the peak horizontal ground acceleration generated by the earthquake at the ground surface, g is the acceleration of gravity, and r_d a stress reduction factor which is a function of depth and the rigidity of the soil column. The second part of the Seed and Idriss procedure requires the determination of the cyclic strength of the soil deposit. This is estimated either through empirical correlation with the SPT Nm value (Seed et al., 1985), or cone penetration resistance, q_c allowing the effects of soil fines content. Empirical charts have been prepared to determine the cyclic strength based on corrected SPT blow count $(N_1)_{60}$. Based on $(N_1)_{60}$ then, the cyclic stress ratio required to induce liquefaction for a magnitude 7.5 earthquake, $(\tau_{av}/\sigma_0)1, M = 7.5$ is given by several relationships. For earthquakes of other magnitudes, the appropriate cyclic strength was obtained by multiplying a magnitude scaling factor.

As an index for the assessment of liquefaction potential, the liquefaction index (P_L value) is adopted in earthquake damage assessment of many countries. The liquefaction index is calculated from the safety rate to liquefaction (F_L value) for every depth derived from drilling data, geology sections and conditions of geo-morphological unit. The possibility of liquefaction and the safety rate to liquefaction (F_L value) or a liquefaction index (P_L value) are generally connected as follows. In next two parts, these two methods are explained in detail.

- $F_L > 1.0$ -- There is little possibility of liquefaction in the depth.
- $F_L \leq 1.0$ -- There is the possibility of liquefaction in the depth.
- $P_L = 0$ -- Liquefaction potential is quite low.
- $0 < P_L \leq 5$ -- Liquefaction potential is low.
- $5 < P_L \leq 15$-- Liquefaction potential is high.
- $P_L > 15$ -- Liquefaction potential is very high.

1.1 *F_L Method*

This method was first developed by Architectural Institute of Japan in 1988. In this method input data include JMA Magnitude of the earthquake, peak ground acceleration (PGA), depth from the ground, N-value, granule part content (Clay part content, Plastic index), groundwater level, total upper load pressure (calculated from unit weight of stratum) and effective upper load pressure (calculated from the unit weight of a stratum, the unit weight of groundwater, and groundwater level). The output of the method is rate of safety to liquefaction (F_L value). Saturated soil shallower than 20m, the granule part content F_c is 35% or less of stratum. Even if F_c is 35% or more, the clay part content P is 10% or less or the plastic index I_p is a 15% or less of silt layer with low plasticity. The stratum in which clay part content exceeds 20% can be estimated from the object for an assessment. First, the ratio of equivalent cyclic shear stress generated for every depth in the ground of an examination point is calculated using Equation 1. At the last, the rate F_L of safety to liquefaction generating in every depth is calculated using Equation 2 as follows:

$$F_L = \frac{\left(\frac{\tau_{av}}{\sigma_0'}\right)_M}{\left(\frac{\tau_{av}}{\sigma_0'}\right)} \quad (2)$$

1.2 *P_L Method*

This method was first proposed by Iwasaki et al. (1978) and used for liquefaction damage assessment during earthquakes. The method is similar to the Seed and Idriss (1971) approach. The input and output of the method are the distribution of $F_L$value to a depth of 20 m and Liquefaction index, (P_L value), respectively. The liquefaction potential of the ground is not assessed with F_L method although it assesses the generating possibility of the liquefaction in a certain depth. Iwasaki et al., (1984) defined the value (a liquefaction index, P_L value) acquired from the weighted integration of F_L value for depth, and made it as the index for liquefaction potential of soil (Equations 3).

$$P_L = \int_0^{20} F.w(z)dz$$

$$F = \begin{cases} 1 - F_L & F_L < 1.0 \\ 0 & F_L \geq 1.0 \end{cases} \quad (3)$$

$$w(z) = 10 - 0.5.z$$

(z: depth from earth surface [m])

Where $w(z)$ is a weight function for the depth, and has given bigger weight to the shallow portion. The result depends on the method that derives F_L value.

The main objective of this study is to determine the areas with the greatest liquefaction potential in Urmia.

3 ASSESMENT OF LIQUIFICATION POTENTIAL OF URMIA

Figure 1. Borehole locations in the study area in Urmia

Urmia is the second largest city in the north-west of Iran and the capital of West Azerbaijan Province, Iran. The study area in this research is Urmia with an area of about 105 km^2 and Gholman Khaneh suburb of Urmia which has an area approximately 30 km^2. The location map of the study area has been illustrated in Figure 1.

Urmia Lake is one of the world's largest salt lakes, which is situated in the east of the city and the mountainous borders of Turkey are located in west. Urmia is exposed to significant seismic hazards and it is a coastal area due to the proximity to Urmia Lake. Both the high groundwater level and the grain size of the soils, along with the active seismic features of the region, result in favourable conditions for the occurrence of liquefaction in Urmia. When the surface and near surface geological conditions were taken under consideration, it became clear that due to having a moderate liquefaction susceptibility, the study area's geology is prone to liquefaction. If geologic and geomorphologic criteria are considered, it can be seen that the study area as discussed under the region's geology is susceptible to liquefaction. All the above mentioned facts are sufficient to study the liquefaction potential of sediments in Urmia to determine the zones of major risk. The determination of absolute susceptibility requires site specific geotechnical studies. Therefore, In order to increase our knowledge about the susceptibility of the region, it was necessary to use geotechnical information. This information has been acquired through Standard Penetration Tests (SPT) performed in 108 borehole data which has been drilled during Urmia seismic microzonation studies by Sahra Kav Consulting Engineers (SKCE) in 2009-2014. This research uses the database of boreholes and data from a recently completed extensive geotechnical site investigation to assess liquefaction susceptibilities of the soils in Urmia and analyzes it in the framework of GIS. Liquefaction potential of Urmia has been assessed using standard penetration test (SPT) in conjunction with established methods such as those of Seed (1979), F_L method and P_L method.

Initially, geological mapping was carried out, and based on field observations and drilled logs, soil profiles were constructed. As a part of microzonation study of Urmia, SPT was carried out according to D1586-99 ASTM and Designation E-21 User Earth manual. Grain size distribution and saturated unit weight of the sample soils were determined by means of laboratory testing. In addition, groundwater level was an important parameter in assessing regional liquefaction potential. Regarding the significant number of drilled boreholes (108 boreholes) and the adequate coverage of the Urmia, by the use of groundwater level in these boreholes, ground water situation has been determined. Based on these studies, ground water level (GWL) map has been prepared for Urmia (Figure 2). According to this map, groundwater level varies between 1 to 33 m in Urmia. This considerable difference in the groundwater level is related to sediments' thickness and materials, changes in surface topography in different parts of the city and faults probability performance that is in need of more research. Using corrected N values and adopting an average saturated unit weight at the magnitude of earthquake of M=7, the liquefaction potentials of the soils in the study area have been estimated. Finally, the potential liquefiable zone has been quantified. The data obtained have been mapped according to susceptibility, and the susceptibility maps based on the geotechnical data indicated a moderate to high susceptibility to liquefaction for the magnitude of earthquake (M=7) for Urmia.

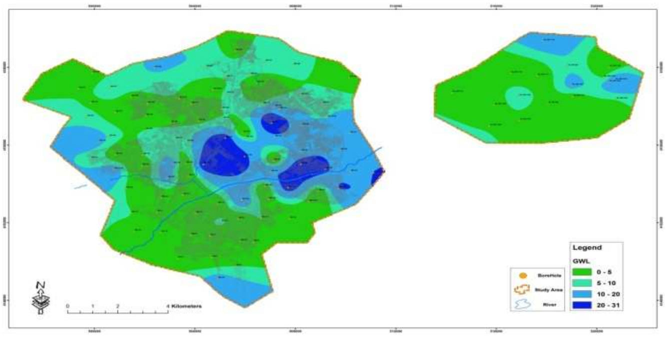

Figure 2. GWL map of the study area in Urmia

4 RESULTS AND DISCUSSIONS

The general soil profile of the study area consists of sand, silt, clay and gravel. Figure 3 indicates the typical soil profile for the borehole NO.85. Nevertheless, the main constituent is loose to medium dense sand which is a susceptible to liquefaction soil type. According to SPT results, SPT values in the most drilled boreholes in Urmia are more than 50. According to Terzaghi and peck (1967) as shown in Table 1, most of alluvial layers in points of density view in Urmia are dense to very dense and small part of those have medium dense and loose. In addition, most of the clay layers are in the very stiff and hard density and only small part of those are medium stiff and soft. According to Das, Braja M. (1941) as shown in Table 3, main parts of sands in Urmia have relative density of approximately 30-60 percent and angle of internal friction encompasses 35-42 degree. Other considerable parts of soils have relative density of approximately 95 percent and angle of internal friction is more than 42 degree.

Table 1. Urmia Soil classification based on SPT value in Boreholes (SKCE, 2013)

SPT Value	Classification	Percentage of Boreholes %
0-4	Very Loose	0
4-10	Loose	13.9
10-30	Medium	21.3
30-50	Dense	8.1
>50	Very Dense	56.7

Table 2. Urmia Fine-grained Soil classification based on SPT value in Boreholes (SKCE, 2013)

SPT Value	Classification	Percentage of Fines in Boreholes %
<2	Very Soft	2.5
2-4	Soft	4.9
4-8	Firm	7.9
8-15	Stiff	8.8
15-30	Very Stiff	11.9
>30	Hard	64

Table 3- Urmia soil classification based on SPT value In Relative density and angle of internal friction (SKCE, 2013)

Modified SPT Value	Relative Density (D_r%)	Angle of Internal Friction	Sandy Soils in Boreholes %
0-5	0-5	26-30	8
5-10	5-30	28-35	5.8
10-30	30-60	35-42	42.3
30-50	60-95	38-46	4.9
>50	-	-	39.1

In this part, the results of liquefaction potential analysis have been presented. In assessment of the liquefaction potential, the groundwater level in meter, peak ground acceleration for return period of 475 years in g, magnitude of region's seismicity as 7 and experimental results up to 20 m depth for each borehole have been considered. The collected data from the soil characteristics including soil grading, natural density, passing from sieve NO.200 and SPT results has been utilized in analyzing liquefaction of each borehole. In the case in which passing percent of sieve NO.200 and plastic index were more than 35 and 15 percent respectively, the soil was classified as non-liquefiable, according to seed et al., 1983. The boreholes with less than or equal 20 groundwater level can be used for liquefaction potential assessment. Rests of the boreholes due to groundwater level of more than 20 m were considered as non-liquefiable. The summary of liquefaction analysis has been presented in Table 4.

Table 4. Summary of liquefaction analysis of Urmia

Number of BH	Criteria	Liquefaction Potential
7	PL>15	Very high
5	5<PL≤15	High
7	2<PL≤5	Medium
14	0<PL≤2	low
75	PL=0	Very Low

The liquefaction potential in Urmia varies from very low to very high. Cohesive clay and hard silty soils as well as the clay sands with high plastic index have been classified as non-liquefiable soils in study area. Silty soils, silty sands with clay in high density have been classified as low to medium liquefaction potential soils. Sandy soils with silt in medium to low density had high liquefaction potential.

According to Table 4, among 108 drilled boreholes only 7 samples had very high liquefaction potential, 5 boreholes had high liquefaction potential, 7 boreholes had medium liquefaction potential, 14 boreholes had low liquefaction potential and 75 boreholes has been recognized as the lack of liquefaction potential. That is, 29 boreholes due to lack of groundwater level, 5 boreholes due to groundwater level more than 20 m and 5 boreholes due to fines percent of more than 35 percent and plastic index of more than 15 and 36 boreholes after calculating F_L and P_L which their liquefaction index was 0 and did not have any liquefaction potential.

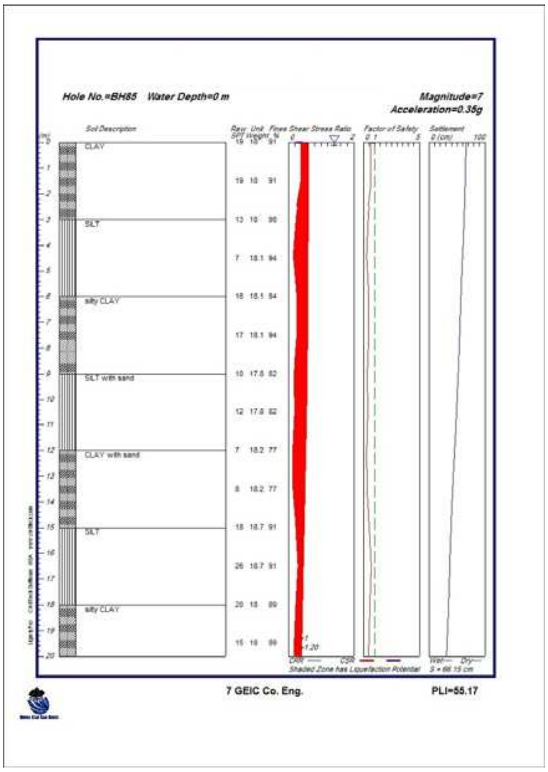

Figure 3.The soil profile for BH NO.85 (SKCE, 2013)

5 LIQUEFACTION POTENTIAL MAPPING OF URMIA

Liquefaction potential mapping of the study area was obtained by linear interpolation of the liquefaction potential index using F_L and P_L methods for probable earthquake. Liquefaction hazard map for Urmia has been presented in Figure 4. The map indicates that the boreholes which have very high liquefaction potential are mostly in the North, the Eastern-North and the Western-North and near to the center of Urmia. Other parts of the study area, including the center part and south because of low groundwater level and also existence of fine-grained soil are non-liquefiable potential soils. According to Figure 4, it’s concluded that liquefaction danger in the center of Urmia to the north, the Eastern-North and the Western-North is considerable. So, in order to emphasize on dispersion of liquefaction soils in the determined limitations, the detailed and explanatory researches are essential.

6 CONCLUSIONS

Urmia is in one of the highest seismic zones of the world and due to its proximity to Urmia Lake, the evaluation of liquefaction potential is of utmost importance. In this paper, with the collected borehole data, an attempt was made to assess in detail the liquefaction potential of Urmia soil using SPT-based method. Results addressed an extensive analysis for determination of liquefaction hazard of Urmia. The Liquefaction potential was expressed in terms of the liquefaction potential index and calculated using standard penetration test profiles. Furthermore, a liquefaction hazard map of Urmia has been presented. The results indicated that the study area has highly susceptible regions to liquefaction and is in need of appropriate mitigation to reduce the risk. Thus, It is hoped that this paper will serve as a guideline for the geotechnical engineers as well as seismologists, architects and urban planners in making rational decisions while developing projects in the Urmia.

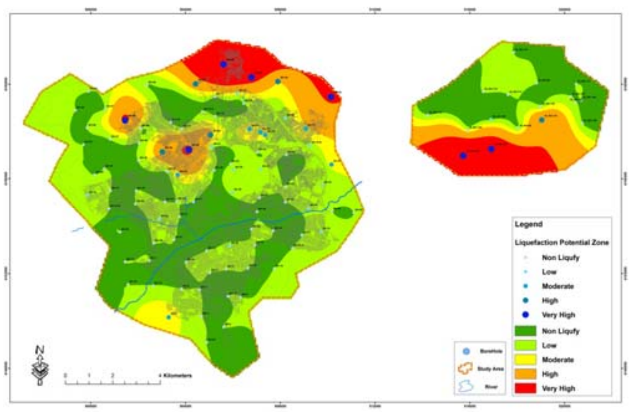

Figure 4.Urmia Liquefaction potential map

7 ACKNOWLEDGMENTS

The authors would like to thank Sahra Kav Consulting Engineers (SKCE) and khak & Rah Azma Consulting Engineers for providing the SPT data and other geotechnical properties of this study.

8 REFERENCES

Das, B. M. (2010). Geotechnical Engineering Handbook. J. Ross Publishing.

Iwasaki, T., Tatsuoka, F., Tokida, K.-I., & Yasuda, S. 1978. “A practical method for assessing soil liquefaction potential based on case studies at various sites in Japan.” Proc., 2nd Int. Conf. on Microzonation, San Francisco, National Science Foundation, Washington, D.C. 885–896.

Iwasaki, T., Arakawa, T., & Tokida, K. I. (1984). Simplified procedures for assessing soil liquefaction during earthquakes. International Journal of Soil Dynamics and Earthquake Engineering, 3(1), 49-58.

Sahra Kav Consulting Engineers (SKCE).(2013), “ Urmia city geology studies report”, Urmia Microzonation Studies Project, Islamic Republic of Iran - Ministry of Roads & Urban Development.

Seed, H. B. and Idriss, I. M. (1971). “Simplified procedure for evaluating soil liquefaction potential.” Journal of the Soil Mechanics and Foundations Division, ASCE, 97(SM9), 1249-1273.

Seed, H. B., Idriss, I. M., & Arango, I. (1983). “Evaluation of liquefaction potential using field performance data.”

Journal of Geotechnical Engineering Division, ASCE, 109(3), 458-482.
Terzaghi, K. & Peck, R.B. (1967) "Soil Mechanics in Engineering Practice," John Wiley, New York. 729.