Liquefaction evaluation based on CPTu soil classification chart

Évaluation de la liquéfaction basée sur le graphique de classification du sol de CPTu

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ABSTRACT

Liquefaction is one of the most serious geotechnical hazards that may cause irreparable and financial damages. Based on in-situ testing results, several methods have been developed to evaluate the liquefaction potential. Due to continuous and repeated records, the piezocone (CPTu) has gained wide acceptance among other in-situ tests in geotechnical practice. In this paper, a new approach is proposed for liquefaction potential evaluation based on CPTu results. The new approach is verified by ten CPTu soundings (case histories) derived from different sites. By analyzing the liquefied sites, an area on the soil classification charts was introduced in this paper, showing the soil types which are most susceptible to liquefaction. The results of liquefaction prediction by this proposed approach demonstrate good accuracy and consistency with other current methods.

RÉSUMÉ

Liquéfaction est l'un des plus graves dangers géotechniques qui pourrait causer des dommages irréparables et financiers. Suivant les résultats des tests in situ, plusieurs méthodes ont été développées pour évaluer le potentiel de liquéfaction. En raison des données continues et répétées, la piézocône (CPTu) a acquis dans la pratique une large acceptation parmi d'autres tests géotechniques réalisés in situ. Dans cet article, une nouvelle approche basée sur les résultats de CPTu est proposée pour l'évaluation du potentiel de liquéfaction. La nouvelle approche est vérifiée par dix sondages de CPTu (étude sélective) provenant de différents sites. En analysant les sites liquéfiés, une zone sur les graphiques de classification du sol a été introduite dans le présent article, indiquant les types de sol qui sont plus aptes à la liquéfaction. Les résultats de prévision de la liquéfaction par cette approche proposée prouvent sa bonne précision et sa cohérence avec les autres méthodes actuelles.

Keywords: liquefaction, cone tip resistant, sand, soil behavior classification

1 INTRODUCTION

The Cone Penetration Test (CPT) has gained wide acceptance as an important in-situ test for the characterization of soils where penetration is possible. The standard cone penetrometer is cylindrical in shape having a conical tip with a base area of 10 cm^2 (diameter = 35.7 mm) and 60 degree tip apex angle. The friction sleeve, located behind the conical tip, has a surface area of 150 cm^2 (Youd et al. 2001).

The CPT is pushed into the ground with a constant velocity of 20 mm/s. During pushing, excellent near-continuous profiles of cone tip resistance (q_c) and friction sleeve (f_s) are measured, from which soil type, detailed stratigraphy, and soil mechanical properties can be determined. More advanced cone penetration tests (CPTu) also measure pore pressure (u) during sounding and its dissipation, if needed, during pause in penetration. In addition, the test can measure soil shear wave velocity which has increased its application in geotechnical earthquake engineering.

This paper is concerned with CPTu based evaluation of soil liquefaction potential. Liquefaction is defined as the transformation of a granular material from a solid state to a liquefied state as a consequence of increased pore water pressure and reduced effective stress due to seismic shaking. In general, two different approaches are employed to evaluate the liquefaction potential of a site. These two approaches are categorized as based on a) analytical, and b) descriptive. But in this paper a new approach based on soil classification chart is introduced.

2 CURRENT LIQUEFACTION EVALUATION METHODS

Generally there are two different approaches for liquefaction evaluation a) analytical approach and b) descriptive approach. In the following, these approaches are described briefly:

2.1 *Liquefaction Evaluation Based on Analytical Approach*

An analytical approach for evaluation of liquefaction potential consists of calculation of a factor of safety (FS). This can be achieved by dividing CRR by CSR as follows:

$$FS_L = \frac{CRR}{CSR} \qquad (1)$$

Where CSR is the Cyclic Stress Ratio induced in the soil by an earthquake, and CRR is the Cyclic Resistance Ratio. The earthquake demand is calculated by using Seed's method, first introduced in 1971 (Seed and Idriss, 1971). It has since evolved and been updated through summary papers by Seed and his colleagues. The equation is as follows:

$$CSR = \left(\frac{\tau_{ave}}{\sigma'_{v0}}\right) = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) r_d \qquad (2)$$

Where, 0.65 is a weighing factor, introduced by Seed (1971), to calculate the number of uniform stress cycles required to produce the same pore water pressure increase as an irregular

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earthquake ground motion. σ'_{v0} and σ_{v0} are the effective vertical overburden stress and total vertical overburden stress respectively. The parameter a_{max} is the Peak Horizontal Ground Acceleration, PGA, in units of g, and r_d is a stress reduction coefficient determined as recommended by NCEER (Youd et al. 2001).

There are several methods to evaluate the $CRR_{7.5}$ from CPT data (such as Seed (1986), Suzuki (1997), Robertson-Wride (1997, 1998), Andrus (2004), etc). As an example, in the modified Robertson-Wride method, the soil behavior type index I_c is utilized for normalization of q_c, and after determination of the normalized qc [i.e. $(q_{c1n})_f$], a formula is used for the calculation of CRR.

Having determined CSR and CRR, FS_L is calculated by using (Eq.1). If $FS_L < 1$, the soil will liquefy during earthquake and if $FS_L > 1$, then the soil will not liquefy during earthquake.

2.2 *Descriptive methods*

Descriptive methods are those which evaluate the liquefaction potential by investigation of particular soil parameters from CPTu test data (such as pore water pressure (u_2) or cone tip resistance (q_c)). Examples of soil parameters are electrical resistivity, soil dilation angle, or relative density. Most of these methods are not able to absolutely specify liquefaction susceptibility, and only present a primary liquefaction evaluation. Assessment of liquefaction potential by Vibropiezocone test results is an example for this approach (Tokimatsu 1988).

3 CASE HISTORIES

CPTu data from sites that were struck by earthquakes, and have shown or have not shown liquefaction during these earthquakes were collected from ten various sites (PEER 2000, Ku et al. 2004). Data are selected from ground surface to 10 meter depth with 20 cm intervals. The soil layers located above the ground water table are not considered because only saturated soils have the potential for liquefaction

The Clayey soil layers were also eliminated in the data base because these layers do not show liquefaction. The selected data, then, are used for introducing the liquefiable soil zone over the soil classification charts. Table 1 shows the site location, peak horizontal ground acceleration, earthquake magnitude, average grain size, and other pertinent information for each site considered in this study.

Table 1: Site location and other related data in this study

Test	Site location	a_{max} g	M_w	γ kN/m^3	D50 mm	Soil profile	GWT m
CPT PS5	Adapazari,Turkey	0.37g	7.4	17.2	1.6	(SM)	1
CPT SF5	Adapazari, Turkey	0.4g	7.4	16.9	1.6	(SM)	1
CPT YH3	Adapazari,Turkey	0.37g	7.4	17.7	0.29	(SP-SM)	1
CPT C4	Adapazari,Turkey	0.4g	7.4	18.2	0.12	SM to ML	0.44
CPT E1	Adapazari,Turkey	0.4g	7.4	17.87	0.51	(SP)	0.5
CPT F1	Adapazari,Turkey	0.4g	7.4	17.9	0.09	(SM)	0.5
NT 1	Nantou,Taiwan	0.38g	7.6	18.5	0.08	(SP-SM)	1
WF 4	Wufeng ,Taiwan	0.6g	7.6	18.5	0.17	(SM)	1.2
YL 2	Yuanlin ,Taiwan	0.25g	7.6	18.5	NA	(SP)	0.56
LW-C1	Chang-bin,Taiwan	0.4g	7.5	19.5	NA	(SP-SM)	1

4 PROPOSED METHOD BASED ON SOIL BEHAVIOR CLASSIFICATION CHARTS

The analytical methods presented in the literature generally require long computational analyses. In this paper, a new approach to evaluate the liquefaction potential with an acceptable accuracy and speed of calculation is presented. .

Soil classification based on CPT and CPTu data have been considered by many researchers. Fellenius and Eslami (2000) compared and evaluated about 20 soil classification methods based on CPT and CPTu data. From these methods, the Robertson soil classification chart (1990), which is generally used in practice, and Eslami- Fellenius method (2004), which is the new approach, will be compared for the determination of liquefiable soil zone. Both methods are based on CPTu data. However determination of such zone is also possible over the other soil classification charts based on CPT data. Robertson (1990) modified his suggested previous chart by normalizing the CPT data measurements (Normalized Q_t versus Normalized R_f).The numbered areas in the Robertson profiling chart separate the soil types in nine zones, as follows:

1. Sensitive, Fine-grained Material, 2. Organic Material - Peat, 3. Clays – Clay to Silty Clay, 4. Silt Mixtures – Clayey Silt to Silty Clay, 5. Sand Mixtures – Silty Sand to Sandy Silt, 6. Gravelly Sand to Sand, 7. Silty Sand to Sandy Silt, 8. Very Stiff Sand to Clayey Sand, 9. Very stiff, fine-grained over consolidated or cemented soil.

Eslami and Fellenius (2004) also introduced a chart for soil classification. As an advantage, it is based on effective cone resistance q_E (that is $q_E=q_t-u_2$) versus friction sleeve. For granular soils, q_E is not much different from q_t, as pore pressures generated are generally small. However, in fine grained soils the difference between q_E and q_t can be large. Also the Eslami-Fellenius chart identifies numbered areas that separate the soil types in five zones, as follows.

1. Sensitive and Collapsible Clay and/or Silt, 2. Clay and/or Silt, 3. Silty Clay and/or Clayey Silt, 4. Sandy Silt and/or Silty Sand, 5. Sand and/or Sandy Gravel

Comparison between Robertson method (1990) and Eslami-Fellenius method (2004) shows good conformity for granular soils, i.e. soils with high q_c.

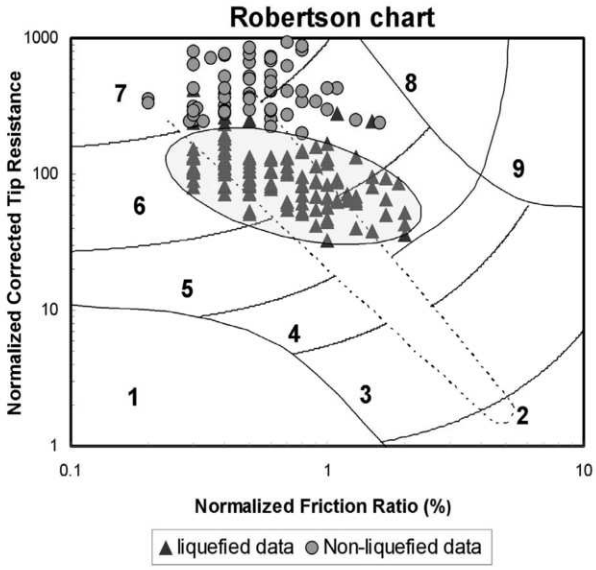
In the selected data base, the data points associated with liquefaction occurrence during earthquake were considered. Also considered were the data points not associated with liquefaction. The data were first verified using the modified Robertson-Wride liquefaction evaluation method. Since these data were affected by earthquakes with magnitude other than 7.5, magnitude scaling factors were introduced to normalize for a corresponding 7.5 magnitude earthquake.

Analyses were performed using Robertson-Wride method, and the associated FS_L were determined for all of the data points. The data points with FS_L less than 1 were considered as the data associated with liquefaction. Also those data that did not liquefy during earthquake and their FS_L based on analytical method were more than 1 were selected as points associated with the condition of a non-liquefied point.

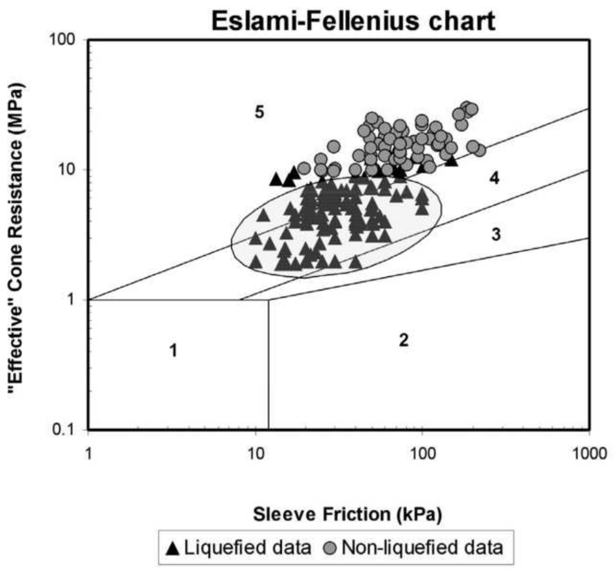
The data points were then introduced on both Robertson and Eslami – Fellenius soil classification charts. An investigation of the data distribution on both of these charts shows that most the data points corresponding to occurrence of liquefaction are located on the normally consolidated sand zone. Specifically speaking, in Robertson soil classification chart, the concentration of data point associated with liquefaction is on the normally consolidated sand zone, and in the proposed Eslami-Fellenius soil classification chart, it is in the zone of sand, silty sand, and fine sand.

As over consolidation ratio increases, the concentration of the data decreases. Also with the increase of soil grain size, the number of data points associated with liquefaction is decreased. Also, as is shown in Figure 1, the existence of silt does not appear to affect the liquefaction potential.

As demonstrated by various researchers (Youd & Gilstrap 1999), saturated loose sands have highest potential for liquefaction. It was previously mentioned that clayey soil data were eliminated because they required very limited conditions for liquefaction.



(a)

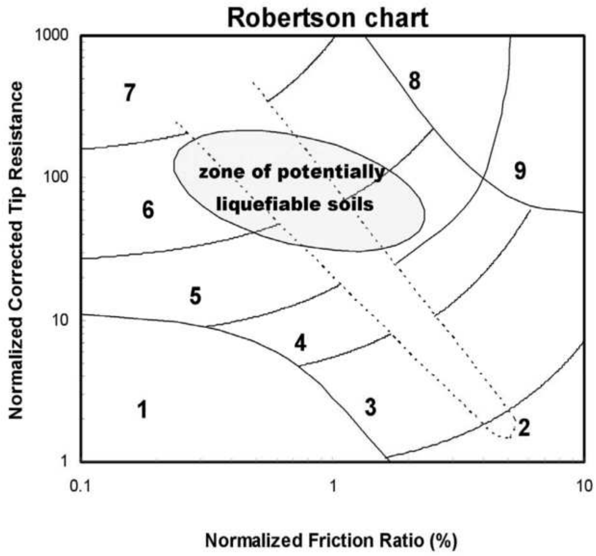


(b)

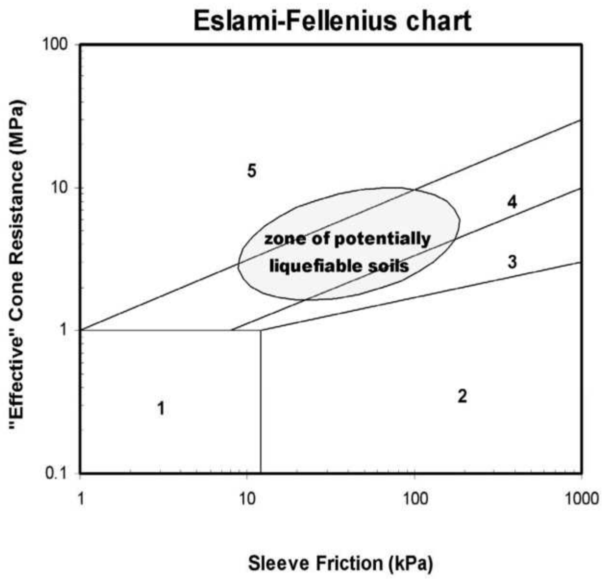
Figure 1. Liquefied data distribution on a) Robertson chart b) Eslami –Fellenius chart.

With this liquefied data distribution, it seems that a zone related to the soil with high potential of liquefaction could be identified over these soil classification charts. This zone is shown separately in Figure 2 (a) and (b) for each chart.

This zone can readily be used for liquefaction evaluation of saturated soils. In other words, using Robertson or Eslami-Fellenius charts, if CPTu data points associated with a saturated granular soil is located in the zone circled in Figure 2, this soil has a high potential for liquefaction.



(a)

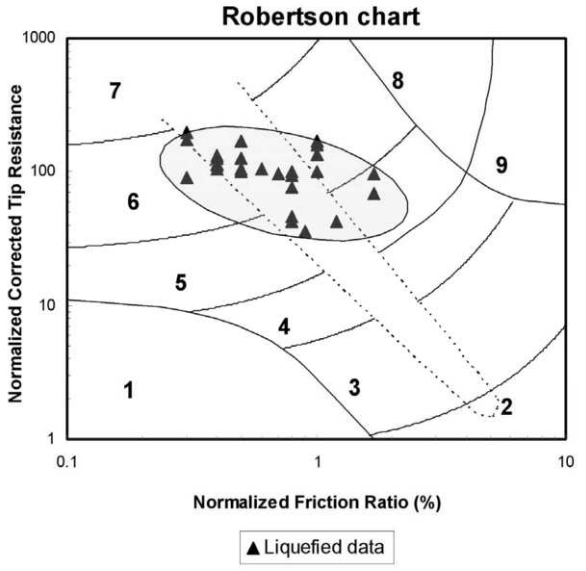


(b)

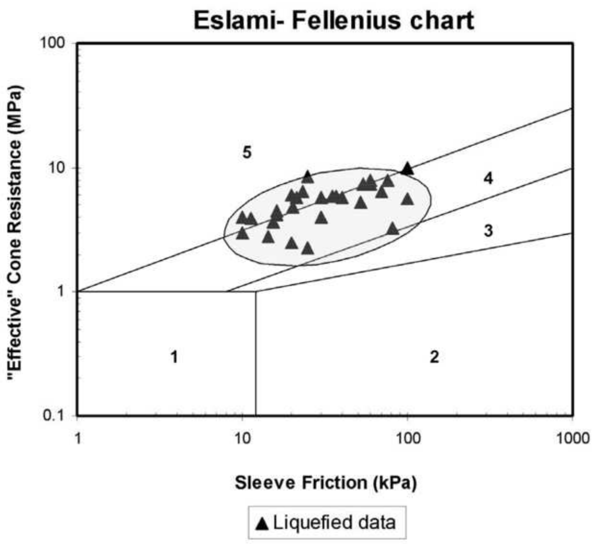
Figure 2. Zone of potentially liquefiable soil over a) Robertson chart b) Eslami –Fellenius chart.

The selected data were introduced on both Robertson and Eslami-Fellenius charts. The results of these analyses are shown in Figure 3. As is shown in Figure 3, nearly all of the actually liquefied data points are located in this zone; therefore it can be concluded that this zone has the potential to identify the liquefied layers of soils.

It should be mentioned that the new proposed approach can predict the liquefaction potential of granular soils. However, this does not mean that other CPTu data points not located on the suggested zone do not show liquefaction during earthquake.



(a)



(b)

Figure 3. Proposed zone of potentially liquefiable soil over a) Robertson chart b) Eslami –Fellenius chart.

5 CONCLUSION

In this study, 10 CPTu tests from ten various sites were investigated and analyzed. The analyses were performed for a depth of up to 10 meter, and in 20 cm intervals. The results are briefly as follows:

Determination of liquefiable soil zone over the Robertson chart and Eslami-Fellenius chart, in addition to including rational results, can be used for primary liquefaction evaluation. Thus if a CPTu data point associated with a saturated soil is located on this zone, it may have a high potential for liquefaction during earthquake.

Proposed zone over the soil classification chart is proposed for an earthquake with 7.5 magnitude. Performing liquefaction analyses and comparison of data that obtained from liquefied sites showed the proposed method, which is based on soil behavior classification chart, is a quick and dependable method.

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