CPT-based liquefaction screening: effect of non-plastic silt content

Criblage de liquéfaction à base de CPT: effet de la teneur en limon non plastique

Sabanayagam Thevanayagam, Umaipalan Sivaratnarajah, Qiqi Huang

Dept of Civil Engineering, University at Buffalo, SUNY, USA, theva@buffalo.edu

ABSTRACT: Liquefaction screening of non-plastic silty soils is a difficult problem. Based on observations of past performances at sites where earthquake-induced liquefaction and no-liquefaction occurred, methods have been developed for liquefaction screening using normalized cone penetration resistance q_{c1N}. Demarcation lines indicating the relationship between cyclic resistance ratio (CRR) of a soil and q_{c1N} have been developed. The CRR determined in this manner depends on the silt content of the soil for a given q_{c1N}. Different demarcation lines have been developed for CRR-q_{c1N} relationship for non-plastic silt content less than 5, 15 and 35%, respectively. While this approach has been routinely used in liquefaction screening practice, a rational understanding of this procedure has been lagging. This paper presents recent understanding on the effects of silt particles in a silty sand on CRR and q_{c1N} of silty sands. Experimental data on the effect of silt content on CRR, and the additional effect of reduced coefficient of consolidation c_v on q_{c1N} for silty sands are presented and compared with data for clean sand. Based on such data, a relationship between CRR, q_{c1N}, and T (where T = vd/c_v, d = cone diameter d, and v = penetration rate) is presented and compared against current screening charts.

RÉSUMÉ : Le criblage de liquéfaction de sols limoneux non plastiques est un problème difficile. Sur la base des observations des performances passées sur des sites où la liquéfaction induite par le séisme et la non-liquéfaction se sont produites, des méthodes ont été développées pour le criblage par liquéfaction utilisant la résistance à la pénétration normale du cône q_{c1N}. Des lignes de démarcation indiquant la relation entre le rapport de résistance cyclique (CRR) d'un sol et q_{c1N} ont été développées. Le CRR déterminé de cette manière dépend du contenu en limons du sol pour un q_{c1N} donné. Différentes lignes de démarcation ont été développées pour la relation CRR-q_{c1N} pour la teneur en limon non plastique de moins de 5, 15 et 35%, respectivement. Bien que cette approche ait été couramment utilisée dans la pratique de dépistage de la liquéfaction, une compréhension rationnelle de cette procédure a été en retard. Cet article présente les connaissances récentes sur les effets des particules de limon dans un sable limoneux sur CRR et q_{c1N} de sables limoneux. Les données expérimentales sur l'effet de la teneur en limon sur le CRR et l'effet additionnel du coefficient de consolidation réduit cv sur qc1N pour les sables limoneux sont présentés et comparés avec les données pour le sable propre. Sur la base de ces données, une relation entre CRR, q_{c1N} et T (où T = vd /c_v, d = diamètre du cône d, et v = taux de pénétration) est présentée et comparée aux cartes de criblage actuelles.

KEYWORDS: Liquefaction, sand, silty sand, cone penetration, cyclic resistance.

1 INTRODUCTION

1.1 Soil Liquefaction and Screening

Current liquefaction screening techniques rely on knowledge from extensive laboratory research conducted on liquefaction resistance of clean sands, and extrapolations of observed field performances during past earthquakes (Youd et al. 2001). Such observations have been documented in the form of normalized penetration resistances (SPT $(N_1)_{60}$, CPT q_{c1N}) (Seed et al. 1983, Robertson and Wride 1998, Boulanger and Idriss 2014), and shear wave velocity (v_{s1}) (Andrus and Stokoe, 2000) versus cyclic stress ratio (CSR) induced by the earthquakes, corrected for a standard earthquake magnitude of 7.5, for many soil deposits where occurrence or non-occurrence of liquefaction were recorded during the earthquakes (Fig.1). For liquefaction screening applications, the cyclic resistance ratio (CRR) of a soil deposit, applicable for number of cycles and frequency content relevant for a standard earthquake magnitude of 7.5, with a known value of $(N_1)_{60}$, q_{c1N} or v_{s1} for the site is obtained from a demarcation line drawn between the past field-observation-based data points which correspond to liquefied deposits and those that did not liquefy in Fig.1. This is denoted as $CRR_{7.5}$. This $CRR_{7.5}$ value is compared against the anticipated cyclic stress ratio (CSR) for that deposit due to a design earthquake of the same magnitude to determine whether or not that deposit would liquefy.

The $CRR_{7.5}$ determined in this manner depends on silt content of the soil for a given $(N_1)_{60}$, q_{c1N} or v_{s1}. For the same values of $(N_1)_{60}$, q_{c1N} or v_{s1}, silty sands show higher $CRR_{7.5}$ than for sands (Fig.1). Demarcation lines have been developed for silt content less than 5, 15 and 35%, respectively. In the case of cone penetration, an equivalent cone index I_c which is considered to represent the apparent effects of silt content has been introduced to obtain these demarcation lines (Fig.1). While this approach has been routinely used in practice, a rational understanding of this procedure has been lagging.

One of the main sources of uncertainty is that the effects of presence of silt among sand grains on liquefaction resistance (CRR), q_{c1N}, and the interrelationship between silt content, silt-soil characteristics (such as permeability k, and coefficient of consolidation c_v), CRR, and q_{c1N} remain largely unexplored and unknown.

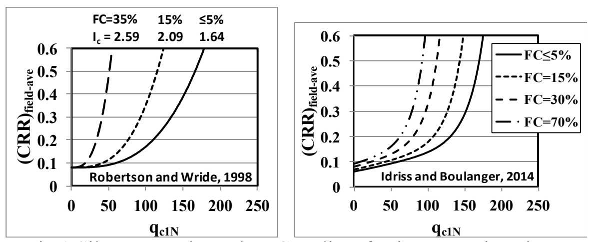


Fig.1 Silt-content-dependent CPT-liquefaction screening charts

1.2 Recent Research and Key Results

Recent research shows that the silt-phenomenon affecting the liquefaction screening relationship (CRR versus q_{c1N}) is as follows (Thevanayagam and Martin 2002, Thevanayagam et al.

2016):

- Silt particles in a silty sand do not fully contribute to the intergranular contacts and associated force chains. Therefore, they do not fully contribute to the cyclic strength ratio CRR and cone resistance q_{c1N} as much as they contribute to the density of the silty sand. For this reason, a silty sand may appear dense and can have low void ratio. But it may not be as resistant to liquefaction and as resistant to cone penetration as a clean sand at the same void ratio.
- Silt particles in a silty sand matrix contribute to the reduction in porosity and pore opening size and therefore contribute to a reduction in k and c_v. Therefore, a cone penetration process in a saturated silty sand produces sizable excess pore pressure around the cone that does not dissipate rapidly (due to low k and c_v) during penetration, and as a result contribute to a reduction in q_{c1N}. On contrary, a clean sand is highly permeable, and therefore cone penetration produces low excess pore pressure, due to rapid dissipation of pore pressures around the cone (due to large k and c_v) of the sand, leading to somewhat higher q_{c1N}. Furthermore, the pore pressure regime and its dissipation rates during penetration in sands and clays have been shown to depend on cone diameter (d) and penetration velocity (v) (Thevanayagam et al. 2008, Schneider et al. 2007). Therefore, they also affect the measured q_{c1N}.
- The above combined effects influence the CRR-q_{c1N} relationship to a different degree for silty sand than for a clean sand. This phenomenon is not just a function of the amount of silt content only, but rather highly depends on k and c_v as well, if v and d are kept the same.

A refined and more rational liquefaction screening method could be developed taking into account the effects of c_v, which can be measured using piezo-cone tests, on q_{c1N} and appropriately accounting for the effect of silt content on CRR, based on intergranular void ratio concept (Thevanayagam 1998, Thevanayagam et al. 2002). Progress to date (presented below) indicates that it is highly likely there exists a rational relationship between CRR-q_{c1N}-T (where T = vd/c_v).

2 EFFECT OF SILT CONTENT ON CRR, c_v, AND q_{c1N}

2.1 Intergranular Void Ratio Concept

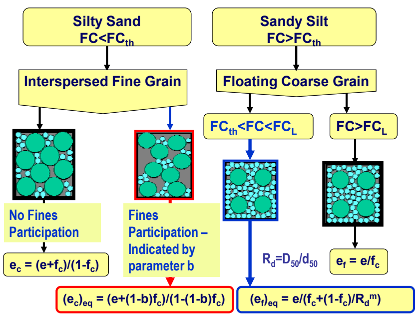
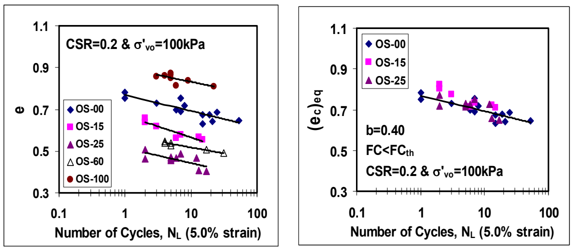


Fig. 2 Intergranular void ratio concept

The equivalent intergranular void ratio concept (Fig2) proposes that mechanical properties such as liquefaction resistance (CRR), steady state strength, shear wave velocity, stress-strain characteristics, and the likes of soils are influenced by intergrain contact density of a soil, among other factors. Silty sand and sand at the same global void ratio e are not expected to have the same intergrain contact density. Sand-silt mixes and host sand are expected to show similar mechanical behavior if compared at a same contact density index. To this effect, two approximate measures for contact density, namely equivalent intergranular void-ratio indices, $(e_c)_{eq}$ and $(e_f)_{eq}$, were introduced for soils at silt content (FC) less than a threshold silt content FC_{th} and more than FC_{th}, respectively. fc = fines content by weight, R_d= ratio of the d_{50}'s of the host sand and silt in the soil mix; b and m are soil parameters depending on gradation and grain size characteristics of the soil. In order to broaden the application of the concept, an equivalent intergranular relative density $(D_{rc})_{eq}$ has been defined as: $(D_{rc})_{eq} = ((e_{max})_{HS} - (e_c)_{eq})/((e_{max})_{HS} - (e_{min})_{HS})$, where HS=host sand.

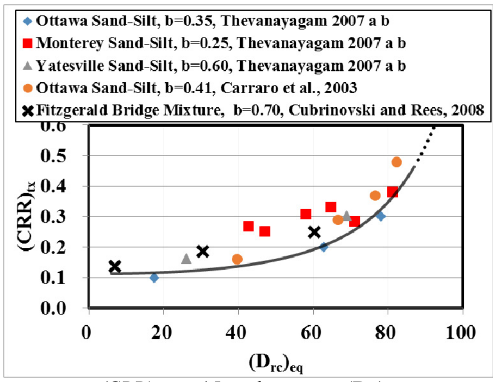
2.2 Effect of $(D_{rc})_{eq}$ on Cyclic Resistance Ratio CRR

Fig.3a shows the number of cycles (N_L) required to reach liquefaction versus e for Ottawa sand/silt mix obtained from undrained cyclic triaxial tests conducted at a constant stress ratio (CSR) of 0.2 and initial confining stress of 100 kPa. The specimens were prepared by mixing Ottawa sand with a non-plastic silt at different silt contents (0 to 100% by weight) (Thevanayagm et al. 2002). OS-15 in this figure refers to sand-silt mix at 15% silt content. At the same e, liquefaction resistance of silty sand decreases with an increase in silt content. Beyond a transition silt content of about 20 to 30%, the trend reverses and liquefaction resistance increases with further increase in silt content. Similar observations have been widely reported in the literature (e.g. Zlatovic and Ishihara 1997, Koester 1994, Vaid 2004, Polito and Martin 2002, Carraro et al. 2003, Cubrinovski and Rees 2008).



(a) e versus N_L (b) $(e_c)_{eq}$ versus N_L

Figure 3. Effect of silt content on liquefaction resistance



$(CRR)_{tx}$ at 15 cycles versus $(D_{rc})_{eq}$

Figure 4. Effect of silt content on CRR vs $(D_{rc})_{eq}$

To examine the utility of the intergranular void ratio concept, the data set shown in Fig.3a was reorganized into two groups, one for silt content (FC) less than a threshold value (FC_{th}) and the other for silt content exceeding FC_{th}, and replotted against $(e_c)_{eq}$ and $(e_f)_{eq}$, instead of e in the x-axis. Fig.3b shows the data for FC<FC_{th} showing a narrow band for the cyclic strength versus $(e_c)_{eq}$ compared to the data set in Fig.3a. This idea was tested for more than 30 silty sands and found to hold well (Veluchamy 2012). Fig.4 shows a relationship between CRR (at 15 cycles to liquefaction, obtained from cyclic triaxial tests) versus $(D_{rc})_{eq}$, for many different sands and sand-silt mixes. The data points for all soil mixes fall in a narrow band, further illustrating that the effects of silt content on CRR can also be characterized using the inter-grain contact density $(D_{rc})_{eq}$ of the soil.

2.3 Effect of silt content on c_v

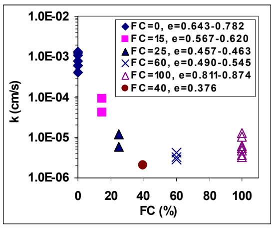


Figure 5. k vs silt content

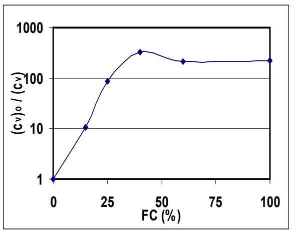


Figure 6. c_{vo}/c_v vs silt content

Fig.5 shows the variation of k against silt content for the same Ottawa sand-silt mixture reported in Fig.3 (Thevanayagam et al. 2001). k decreases steadily with an increase in silt content up to a threshold value of FC of about 25 to 30%. Fig.6 shows the normalized (c_{vo}/c_v) values at nearly the same $(e)_{eq}$ versus silt content, where c_v and c_{vo} are the coefficient of consolidation of Ottawa sand-silt mix and clean Ottawa sand, respectively. The direct and significant influence of silt content on k is reflected on c_v. (c_{vo}/c_v) increases (viz. c_v decreases) steadily with an increase in silt content up to a threshold value of silt content (FC_{th}) and it is little affected with further increase in silt content.

2.4 Effect of $(D_{rc})_{eq}$ and c_v on q_{c1N}

Penetration of a CPT probe into a saturated soil causes highly non-uniform stresses, shear strains, and excess pore pressures in the soil around the probe. The rate of penetration, geometry of the penetrating probe, stress-strain characteristics of the soil, and its consolidation characteristics are expected to influence the rate of dissipation of the excess pore pressures and therefore the effective stress regime around the cone.

If the stress-strain characteristics of a sand and silty sand are the same, and the probe geometry is the same, one could expect the same penetration resistance if the penetration rate is so slow that it is essentially a drained penetration with no excess pore pressures. Likewise, if the penetration is extremely fast, essentially making it a full undrained penetration, one could expect the same penetration resistance for both soils. At any other rates of penetration, one would expect different pore pressure responses for sand and silty sand due to differences in consolidation characteristics. Therefore, different penetration resistances would be expected in sand and silty sand, even if they have the same stress-strain characteristics.

2.4.1 Model Cone Test Results

A series of exploratory model cone tests were performed on clean Ottawa sand and silty sand mix at 25% silt content. Cone penetration tests were done on each soil mix while they were dry and again while they were fully saturated (Sivaratnarajah 2016). The test hypotheses were that: (a) in the absence of excess pore pressures, cone resistance is affected by primarily intergranular contact density. Therefore, the cone resistances must be very similar for both soils at the same $(D_{rc})_{eq}$, when they are dry, and (b) when the soil is saturated, cone resistance is influenced by intergranular contact density and k and c_v. Therefore, cone resistance of saturated sand and saturated silty sand must be different even when the intergranular contact density $(D_{rc})_{eq}$ is the same.

Fig. 7 shows measured q_{c1N} versus $(D_{rc})_{eq}$ data from the above tests. OS-00 refers to Ottawa sand without any silt content. OS-25 refers to Ottawa sand with 25% silt content. The soil mix is the same Ottawa sand –silt soil mix indicated in data sets shown in Fig.3. The following observations can be made.

- When the sand (open triangle) and silty sand (solid blue triangle) were dry, the q_{c1N} versus $(D_{rc})_{eq}$ data for sand and silty sand follow a similar trend, not indicating any significant effect of silt content on q_{c1N}. This is because the cone resistance in dry soils is influenced by the intergranular contact density, and not (air) permeability or (air) coefficient of consolidation. The tests were fully drained for both soils. The measured q_{c1N} is a predominantly mechanical response of the soil without any influence by permeability k, coefficient of consolidation c_v or pore pressures around the cone.
- When the q_{c1N} versus $(D_{rc})_{eq}$ data for dry sand (open triangle) is compared with saturated sand (open red square), again, no difference is observed in the q_{c1N} versus $(D_{rc})_{eq}$ trend. This q_{c1N} versus $(D_{rc})_{eq}$ trend is because, for all practical purposes, the cone penetration is almost fully drained response in saturated sand, and hence does not noticeably differ from q_{c1N} for dry sand at the same $(D_{rc})_{eq}$.
- Saturated silty sand (solid red square) shows significantly low q_{c1N} compared to q_{c1N} for saturated sand (open square) at the same $(D_{rc})_{eq}$. This reduction in q_{c1N} for saturated silty sand is because, the presence of silt reduces the k and c_v in saturated silty sand, and therefore induces noticeable pore pressures, and makes the penetration process in saturated silty sand partially or fully undrained response, whereas the penetration in sand is fully or nearly fully drained response. Therefore, they have different q_{c1N} response at the same $(D_{rc})_{eq}$.
- Likewise, saturated silty sand (solid red squares) exhibits a low q_{c1N} compared to dry silty sand (solid triangle), at the same $(D_{rc})_{eq}$, for the same reasons as above.

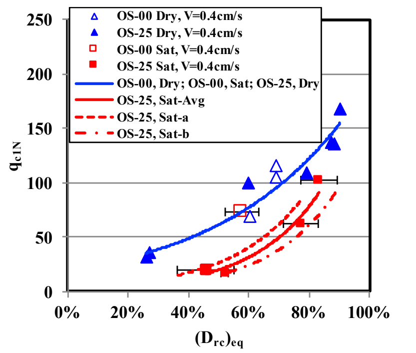
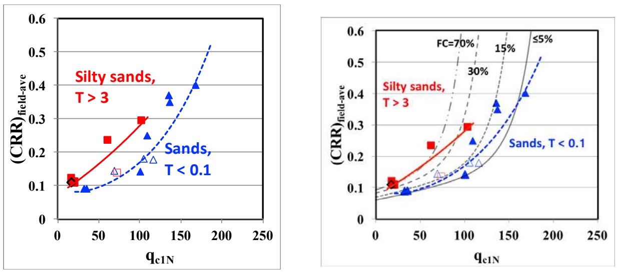


Figure 7. Effect of silt (k and c_v) on q_{c1N} vs $(D_{rc})_{eq}$

3 CRR-q_{c1N}-T FOR LIQUEFACTION SCREENING

Despite the preliminary nature of the data sets involved, when compared at the same $(D_{rc})_{eq}$, it is noted that the presence of silt, which influences c_v, the q_{c1N} of saturated silty sand is lower than that of clean sand, whereas the cyclic resistances are nearly the same (Fig.4) for saturated sand and silty sand. CRR is related to $(D_{rc})_{eq}$. whereas q_{c1N} is related to $(D_{rc})_{eq}$ and c_v. This points to a three-way CRR-q_{c1N}-T relationship. This indicates the fines-content-dependent liquefaction screening chart shown in Fig.1 could be further refined to develop a more rational T-dependent CRR-q_{c1N}-T relationship.

In an attempt to develop such a relationship, first the measured $(CRR)_{tx}$ vs $(D_{rc})_{eq}$ relationship, obtained from triaxial tests, shown in Fig. 3, was corrected for multi-shaking effects (Seed et. al 1978) to obtain an equivalent $(CRR)_{field}$ versus $(D_{rc})_{eq}$. Secondly, the model cone data shown in Fig.7 and additional model cone data collected at different penetration rates were organized into a q_{c1N}-$(D_{rc})_{eq}$-T relationship. Based on these two sets of relationships, by matching the data for the same $(D_{rc})_{eq}$, a CRR- q_{c1N} -T relationship was obtained as shown in Fig. 8a.



(a) CRR-q_{c1N}-T (b) CRR-q_{c1N}-T vs current screening charts

Fig. 8. Liquefaction screening: CRR - q_{c1N}-T

The dashed blue line (T<0.1) in Fig.8a shows the relationship for saturated sand. The red line (T>3) shows the relationship for saturated silty sand at 25% silt content. The T values for saturated sand (blue dash line) are less than 0.1 whereas the T values for the saturated silty sand (red line) are greater than 3. As T increases the CRR-q_{c1N} curve shifts to the left, for the same CRR, due to excess pore pressures developed around the cone in silty sands. For the same CRR, saturated silty sand (red line) shows a smaller q_{c1N} than saturated sand.

Fig.8b shows the CRR-q_{c1N}-T relationship (in Fig.8a) superimposed on the current CRR-q_{c1N}-FC liquefaction screening chart from Boulanger-Idriss-2014 (black lines for FC of 5, 15, 30 and 70%). The dash-blue line (T<0.1) which corresponds to saturated sand follows the of B-I-2014 curve trend for sand. The red line (T>3) that corresponds to saturated sand-silt mix (prepared at FC=25%) follows the B-I-2014 trend for high silt content. This indicates that the different screening curves for different silt contents in screening charts (Fig.1) are indeed manifestations of the effect of k and c_v (reflected in T), not just the gross amount of silt content. As the silt content increases, typically k and c_v decreases and T increases and hence q_{c1N} decreases for the same CRR. The reduction in q_{c1N} for silty sand is due to lack of rapid pore pressure dissipation around the cone in silty sand compared to the case for a clean sand at the same CRR.

4 CONCLUSIONS

Non-plastic silt content in silty sands affects intergrain contact density, liquefaction resistance CRR, permeability k, coefficient of consolidation c_v, and normalized cone penetration resistance q_{c1N}. When the effect of silt content on intergrain contact density is (approximately) accounted for, a sand and silty sand show similar CRR at the same equivalent void ratio $(D_{rc})_{eq}$. q_{c1N} is sensitive to $(D_{rc})_{eq}$ as well as c_v, cone diameter d and penetration velocity v. q_{c1N} of a silty sand is smaller than that of a sand at the same $(D_{rc})_{eq}$ when v and d are the same. This difference is apparently caused by different rates of drainage conditions that prevail around a cone tip in silty sand compared to that of sand. When velocity v, cone diameter d, and c_v are taken into account, there appears to exist a relationship between q_{c1N}, $(D_{rc})_{eq}$, and T.

Combining the CRR vs $(D_{rc})_{eq}$ and q_{c1N}-$(D_{rc})_{eq}$-T relationships, there exists a relationship between CRR-q_{c1N}-T. What separates the CRR-q_{c1N} relationship (Fig.1) for silty sands from sand are the effects of silt content on CRR, and the additional effects k and c_v on q_{c1N}. A rational liquefaction screening relationship between CRR-q_{c1N}-T is likely. Such a screening method could be implemented in the field measurements q_{c1N} and c_v. Such a rational CRR-q_{c1N}-T liquefaction screening method could help reduce the level of uncertainty in the current screening methods and advance the state of practice in liquefaction triggering analysis.

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