SOIL LIQUEFACTION – INFLUENCE OF NON-PLASTIC FINES IN LIQUEFACTION RESISTANCE

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Abstract: It has been understood since the 1960’s that the presence of silt and clay particles will in some manner affect the resistance of a sand to liquefaction. However, a review of studies published in the late literature shows that no clear conclusions can be drawn as to in what manner altering the fines content affects the liquefaction resistance of a sand under cyclic loading. This is particularly true for soils containing non-plastic, i.e. silty fines.

An attempt of clarification of the effects of non-plastic fines on the liquefaction susceptibility of sandy soils is presented here in light of a recent study conducted by Martin and Polito (2001), and a recent conceptual framework proposed by Thevanayagam (2000).

The assessment of triggering potential is also focused in this document with a review of the latest updates of in situ liquefaction hazard evaluation methods. Since the influence of non-plastic fines on liquefaction susceptibility is the main subject of this work, a detailed presentation of the corrections factors, often used in simplified liquefaction evaluation methods to take into account the affect of fines content on the soil, is made for each in situ test presented.

Finally, the influence of the presence of nonplastic fines might have on the methods for liquefaction analysis for sands currently used in engineering practice is analyzed and some suggestions will be made on how to evaluate liquefaction potential in these cases, based on the latest studies on the matter.

Keywords: Liquefaction, Silt, Non-Plastic Fines, Fines Correction, Simplified Procedure

1. Soil Liquefaction Phenomena

The term liquefaction has historically been used in conjunction with a variety of phenomena that involve soil deformations caused by monotonic, transient, or repeated disturbance of saturated cohesionless soils under undrained conditions.

There is a known tendency for dry cohesionless soils to densify under loading. However, if the soil is saturated, rapid loading (such as earthquakes) occurs under undrained conditions and this tendency will cause excess pore pressure to increase and, consequently, effective stresses to decrease. Excess pore pressure results from the impeded drainage caused by plastic volumetric strain that arises quickly enough so that the pore fluid cannot escape as fast as the plastic strain accumulates. Liquefaction phenomena that result from this process can be divided into two main groups: Flow Liquefaction and Cyclic Mobility. Flow liquefaction occurs much less frequently than cyclic mobility but its effects are usually far more severe. Cyclic mobility, on the other hand, can occur under a much broader range of soil and site conditions than flow liquefaction.
The liquefaction of sands during earthquakes has occurred throughout recorded history, and certainly before that, however it was not until the early 1960’s that scientific research into the subject began in earnest. Since the 1964 Anchorage, Alaska, and Nigata, Japan earthquakes, great strides have been made in understanding the mechanisms behind liquefaction and the conditions that make soils susceptible to it.

Even if a soil deposit is susceptible to liquefaction it does not mean, however, that liquefaction will be triggered if an earthquake or any other disturbances occurs. Cyclic mobility is an earthquake related phenomena, but flow liquefaction can be triggered in a variety of ways (pile driving, geophysical exploration, blasting and vibrations from a passing train, for example).

For liquefaction to be triggered it requires a strong enough disturbance and it is the evaluation of the nature of that disturbance that is one of the most critical parts of liquefaction hazard evaluation. It is generally considered that the flow liquefaction surface, FLS represents the stress conditions at the initiation of liquefaction both for cyclic mobility and flow liquefaction.

2. Assessment of Triggering Potential

There are two general types of approaches available for the assessment of liquefaction triggering potential which are laboratory testing of "undisturbed" samples and the use of empirical relationships based on correlations of observed field behaviour.

The use of laboratory testing is complicated by difficulties associated with sample disturbance during both sampling and reconsolidation. It is also difficult and expensive to perform high-quality cyclic shear testing and also the fact that cyclic triaxial testing poorly represents the loading conditions of principal interest for most seismic problems. Accordingly, the use of in situ “index” testing is the dominant approach in common engineering practice. The three in situ test methods that have now reached a level of sufficient maturity as to represent viable tools for this purpose are the Standard Penetration Test (SPT), the Cone Penetration Test (CPT) and the measurement of in-situ shear wave velocity ($V_s$).

Most available correlations for liquefaction potential assessment are based on field observations and SPT or CPT data for liquefied and nonliquefied sites. Liquefaction occurrence may not be easily detected on the ground surface and penetration resistance data are usually obtained from sites that have undergone considerable shaking.

Estimating soil state from penetration tests is the backbone of liquefaction assessments. Since it is extremely difficult to obtain samples of cohesionless soils in anything like an undisturbed condition, engineering of sands and silts is highly dependent on penetration tests.

The correlations for the SPT and CPT tests in the document were presented by Seed et al. (2003) in a recent state-of-the-art paper regarding the assessment of triggering potential. This correlation has contours of probability of liquefaction plotted for $P_L=5, 20, 50, 80$ and 95%. This correlation provides greatly reduced overall uncertainty being the principal uncertainty in the engineer’s ability to assess a suitable CSR and representative $N_{1,60}$ values for design cases. The development of this correlation is founded in an expanded database of field performance.
case histories, improved knowledge of factors affecting the SPT, improved methods for accessing site-specific ground motions, screening of field data case histories for quality data only and the use of powerful probabilistic tools.

The resulting relationships provided greatly reduced uncertainty as well as help to deal with corollary issues that have long been difficult and controversial such as magnitude-correlated duration weighting factors, adjustments for fines content and corrections for effective overburden stress. When considering the SPT, the new correlation is a significant improvement, since all prior correlations had been based on the use of the simplified $r_d$ of Seed and Idriss (1971) for back analysis of field performance case histories and were, as a result of that, unconservatively biased relative to actual case-specific seismic response analysis. The new correlations, on the other hand, can be safely used in conjunction with project-specific dynamic response analyses without introducing bias.

The CPT as also been quite improved mainly on the adjustment for fines content where the new contours provide for much smaller adjustments of $q_{c,1}$ for fines content and character than did the curves from Robertson and Wride which have been deemed unconservative for some time.

A comparison between these two tests is mandatory to know how to perform the best liquefaction triggering potential analysis of the soil possible at this time.

The SPT is the most commonly used in situ test. It has been used for more than 75 years and has the largest database of penetration data worldwide. Its obvious advantages are the very simple procedure, almost all soil types can be tested and rugged equipment. What is usually neglected by engineers is the lack of repeatability of the test even when considering the same equipment and adjacent borings. Even after improvements to the SPT by mechanizing the hammer system to control the energy delivered, the repeatability of the test can only be considered of 60% which is considerably low for engineering purposes.

The CPT has been around nearly as long as the SPT. The main difference is that the CPT evolved considerably since its original form with the growth of the offshore industry making the CPT the reference test for geotechnical engineering offshore. There were numerous improvements but the most important in engineering purposes is the interesting combination of a continuous data record with excellent repeatability and accuracy, all at relatively low cost. The standard deviation is about 2% of full-scale output. The fact that CPT is fully continuous means it “misses” almost nothing. Even for strata too thin to characterize, the CPT provides some indicators of potentially problematic materials if one examines $q_c$ and $f_s$ traces carefully. CPT also offers advantages with regard to cost and efficiency since no borehole is required.

The two main reasons why CPT has not been used extensively for liquefaction assessment are that the test does not provide a sample for soil classification and grain size analyses, and the limited amount of CPT-based field data pertaining to liquefaction potential was available. However, the number of field case histories with CPT data has increased significantly in recent years.
In round numbers, the SPT, even with energy measurements and subsequent
correction, is four to five times less repeatable than the CPT. An argument sometimes put
forward in favour of the SPT is the possibility of obtaining a geological sample of the stratum
which the CPT is unable. However, for engineering purposes, it’s not that important to have
geological information of the stratum if its mechanical properties are known, which is what the
CPT is able to do and with much more accuracy than the SPT although, sometimes, a good
compositional knowledge of the soil is required and so a geological sample is needed.

To sum up, there’s no contest; choose either the CPT or both tests. Note, however, that
this does not mean that the SPT database is useless since it is possible to use SPT-based
experience when only CPT soundings have been carried out by means of correlations between
the two tests.

3. Soils with Non-Plastic Fines

Since the 1960’s it is known that the presence of silt and clay particles will in some
manner affect the resistance of a sand to liquefaction. However, when reviewing the studies
published in the literature they show that no clear conclusions can be drawn as to in what
manner altering the fines content affects the liquefaction resistance of a sand under cyclic
loading. This is particularly true for soils containing non-plastic fines (silts). The plasticity index
of the fines fraction has been recognized as an important factor in the liquefaction susceptibility

Both clean sands and sands containing fines have been shown to liquefy in the field
(Mogami and Kubo (1953); Robertson and Campenella (1985); and Holzer et al. (1989)) and in
the laboratory (Lee and Seed (1967a); Chang et al. (1982); and Koester (1994)). Also, non-
plastic silts, most notably mine tailings, have also been found to be susceptible to liquefaction
(Dobry and Alvarez (1967); Okusa et al. (1980); and Garga and McKay (1984)).

There is no clear consensus in the literature as to the effect which increasing non-
plastic fines content has upon the liquefaction resistance of a sand. Both field and laboratory
studies have been performed and some of the results of these studies are conflicting.

Field studies following major earthquakes have produced conflicting evidence as to the
effects of silt on the liquefaction resistance of sands. Based upon case histories of actual soil
behaviour during earthquakes, there is evidence that soils with greater fines contents are less
likely to liquefy in a seismic event. Okashi (1970) observed that during the 1964 Nigata
earthquake in Japan, sands were more likely to liquefy if they had fines content of less than 10
percent. Fei (1991) reports that for the 1976 Tangshan earthquake in China the liquefaction
resistance of silty soils increased with increasing fines content. Also, Tokimatsu and Yoshimi
(1983) found in a study of 17 worldwide earthquakes that 50 percent of the liquefied soil had
fines contents of less than 5 percent. They also found that sands with fines content greater that
10 percent had a greater liquefaction resistance than clean sand at the same blowcount.
Other filed reports show the opposite results. Tronsco and Verdugo (1985) report that mine tailings dams constructed of soils with higher silt contents are more likely to liquefy than similar dams constructed of sands with lower silt contents. Chang, Yeh, and Kaufman (1982) note that case studies reveal that most liquefaction resulting from earthquakes has occurred in silty sands and sandy silts.

When considering laboratory testing there continues to be conflicting evidence about the effect of non-plastic fines in the cyclic resistance of sands. Several investigators have found that the cyclic resistance of a sandy soil increases with increasing silt content. For specimens prepared to a constant gross void ratio, Chang et al. (1982) found that after a small initial drop, cyclic resistance increased dramatically with increasing silt content. The cyclic resistance increased nearly linearly with silt content until a silt content of 60 percent was reached, increasing to a cyclic resistance between 50 and 60 percent greater than that of the clean sand. Similarly, Dezfulian (1982) reported a trend of increasing cyclic resistance with increasing silt content.

Based on the framework proposed by Martin and Polito (2001) in conjunction with the conceptual framework by Thevanayagam (2000), it is possible to isolate two factors, which govern the liquefaction behaviour of silty sands and sandy silts. These factors are soil specific relative density and limiting silt content with which most behaviour reported in the literature can be explained. Three distinct behavioural patterns were found for the cyclic resistance of soils composed of sand and non-plastic silt. The type of behaviour is determined by whether there is sufficient room in the voids created by the sand skeleton to contain the silt present without disturbing the sand structure. This silt content has been called the limiting content.

When the silt content of a soil is below its limiting silt content, there is sufficient room in the voids created by the sand skeleton to contain the silt and the soil can be described as having silt contained in a sand matrix. The cyclic resistance of the soil is then controlled by the soil specific relative density of the specimen, where the soil specific relative density is calculated using the gross void ratio of the specimen and the maximum and minimum index void ratio for the particular mixture of sand and silt. Increasing the soil specific relative density increases the soil’s cyclic resistance.

If the silt content is greater than the limiting silt content, the specimen’s structure consists predominately of sand grains suspended within silt matrix with little sand grain to sand grain contact. Above the limiting silt content, the amounts of sand present in the soil and its soil specific relative density have little effect on its cyclic resistance. The cyclic resistance for these soils is then controlled by the silt fraction void ratio of the soil. Decreasing the silt fraction void ratio increases the soil’s cyclic resistance.

There is a transition zone consisting of soils with silt contents at or slightly above the limiting silt content. This zone occurs as a result of the structure of the soil changing from a predominately sand controlled fabric to a predominately silt controlled fabric as silt content increases.
4. Assessment of Triggering Potential of For Soils with Non-Plastic Fines

The first step in engineering assessment of the potential for “triggering” or initiation of soil liquefaction is the determination of whether or not soils are susceptible to liquefaction. The “Modified Chinese Criteria” (Wang (1979), and Seed and Idriss (1982)) represent the most widely used criteria for defining potentially liquefiable soils over the last two decades. However, in recent earthquakes there was significant liquefaction-type damage where the soils responsible appeared to be more “cohesive” than would be expected based on the Chinese Criteria. It is therefore recommended that the Modified Chinese Criteria be relegated to history and that we move forward to broader consideration of potentially liquefiable soil types. This approach is described in the document based on Andrews and Martin (2000).

Andrews and Martin (2000) re-evaluated the liquefaction field case histories from the database of Wang (1979), as well as a number of subsequent earthquakes, and have transposed the “Modified Chinese Criteria” to U.S. conventions (with clay sizes defined as those less than about 0.002mm). Their findings are largely summarized in Table 1.

<table>
<thead>
<tr>
<th>Clay Content</th>
<th>Liquid Limit $^1 &lt; 32$</th>
<th>Liquid Limit $^1 \geq 32$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2 &lt; 10%$</td>
<td>Susceptible</td>
<td>Further Studies Required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Considering plastic non-clay sized grains – such as Mica)</td>
</tr>
<tr>
<td>$\geq 10%$</td>
<td>Further Studies Required</td>
<td>Not Susceptible</td>
</tr>
<tr>
<td></td>
<td>(Considering non-plastic clay sized grains – such as mine and quarry tailings))</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Liquid Limit determined by Casagrande-type percussion apparatus
2. Clay defined as grains finer than 0.002mm

Table 1 - Liquefaction susceptibility of silty and clayey sands (After Andrews and Martin, 2000)
As was described before, for the soils with sufficient “fines” to separate the coarser particles, it is the fines that control the potential for cyclically induced liquefaction. In those cases, cyclically-induced liquefaction appears to occur primarily in soils where these fines are either nonplastic or are low plasticity silts and/or silty clays \((PI \leq 12\% \text{ and } LL \leq 37\%)\) and with high water content relative to their Liquid Limit \((w_c > 0.85LL)\). In fact, low plasticity or non-plastic silts and silty sands can be among the most dangerous of liquefiable soils, as they not only can cyclic liquefy but they also “hold their water” well and dissipate excess pore pressures slowly due to their low permeabilities.

Finally, two additional conditions necessary for potential liquefiability are saturation (or at least near-saturation) and “rapid” (largely undrained) loading.

The cyclic resistance of the soil is determined as function of either SPT blowcount or CPT tip resistance and fines content. These parameters are plotted together in the form of the familiar charts that divide in liquefiable and non-liquefiable zones. The cyclic resistance of the soil is then determined by entering the chart at the corrected penetration resistance, going to the appropriate curve based on the fines content of the soil and then reading the corresponding cyclic resistance off the vertical axis. Some charts do not have multiple curves for the various fines contents but employ correction factors for fines content.

In order to take into account the effect of nonplastic fines in the cyclic resistance of sand, specific correlations are proposed for the SPT and CPT. However, these correlations are only for fines content below the limiting silt content for no correlations specific for sands above the limiting silt content but, according to a recent paper of Boulanger and Idriss (2006), a nonplastic silt exhibits a very similar behaviour to that of a clean sand when subject to cyclic loading. This similarity in behaviours might indicate that the clean sands curve can be used to assess the liquefaction potential for sands with silt above the limiting silt content but the corrections for fines content must be investigated before being used. The reason for this need for investigation is due to the fact that it is the silt fraction void of the soil that controls behaviour so it would be the sand to fill the voids. However, the behaviour of silt with sand in the voids may not the similar to that of sand with silt in the voids. Also, according to Martin and Polito (2001), the amount of sand present has little effect in the soil’s cyclic resistance.
4.1 Soils Below the Limiting Silt Content – SPT and CPT based Correlations

The correction that was proposed in the study by Martin and Polito (2001), considering the behaviour of soils with non-plastic fines below the limiting silt content, is to adjust the NCEER curves so that they become coincidental with the clean sands curve when the fines corrections are applied. The new term $\gamma$ is to be used in conjunction with the NCEER $\alpha$ and $\beta$ factors. It is both a function of fines content and the corrected SPT blow count, $N_{1,60}$.

\[
(N_{1})_{60CS} = \alpha + \beta(N_{1})_{60} + \gamma
\]  

(Eq. 1)

Where:

$\alpha$ and $\beta$ as for NCEER

\[
\gamma = 0.1 + 0.008((N_{1})_{60} - 4)(FC - 5)
\]

(Eq. 2)

NCEER
Youd and Idriss (1997)

$\alpha = 0$ For FC < 5\%
$\alpha = \exp[1.76 - (190/FC^2)]$ For 5\% < FC < 35\%
$\alpha = 5.0$ For FC > 35\%

$\beta = 1.0$ For FC < 5\%
$\beta = \left[0.99 + (FC^{1.5} / 1000)\right]$ For 5\% < FC < 35\%
$\beta = 1.2$ For FC > 35\%
The correlation here presented was proposed by Carraro, Bandini and Salgado (2003) in a recent paper on the effects of nonplastic fines in liquefaction initiation. This correlation was developed following an approach targeted at avoiding the subjectivity inherent in the observation of liquefaction in the field and the effects of prior shaking. A $(\text{CRR})_{7.5\%}\text{q}_{c1}$ correlation is obtained by combining the results from the penetration resistance analysis of Salgado et al. (1997) using CONPOINT and a considerably large set of laboratory test results.

It was found in this study that, for a given relative density, sand with nonplastic silt up to 10 percent has a slightly higher cyclic resistance than clean sand. However, cone resistance increases at a faster rate with fines content than cyclic resistance, and the proposed liquefaction resistance curves for 5 and 10 percent silt content are located to the right of the clean sand curve when they are usually to the left (Fig. 1). This gradual shift to the right of the CRR-qc1 curves may be explained by observations made by Salgado et al. (2000). These authors found, for the same materials used in the present study, that sands with low silt content and a fabric in which the sand particles are mostly or completely in contact are more dilative than clean sand. For a given relative density, dilative silty sands subjected to cyclic loading show higher resistance to liquefaction than clean sand. Cone resistance is increased not only by dilatancy, but also by the critical-state friction angle, which consistently increases with the addition of fines.

![Fig. 1 – Proposed correlations between cyclic resistance ratio $(\text{CRR})_{7.5\%}$ and normalized cone resistance $q_{c1}$ for sand with 0, 5 and 10% nonplastic silt](image.png)
The liquefaction potential assessment in situ has been greatly developed in the last years for clean sands. The most common tests for evaluation liquefaction triggering potential in situ are the SPT and the CPT, both penetration tests since they describe cyclic resistance more accurately than other tests. The charts developed for these tests in order to evaluate the cyclic resistance of the soil are essentially based on historical data and are being constantly updated with new data from recent earthquakes. Among other factors, these charts have different correlations between penetration resistance and cyclic resistance for different fines content. These correlations are also based on historical data but most lack the plasticity of the fines with which the different correlations of the chart were developed. This lack of distinction for different plasticity of the fines can render the correlations unconservative when considering nonplastic fines in the sand voids considering the influence of nonplastic fines in the cyclic resistance of sand here presented.

After reviewing the literature for correlations specific for sand with nonplastic fines, and conducting a small parametric analysis for sand with different amounts of fines content, based in values from Olsen and Mitchell (1995) approximate soil characterization framework based on normalized cone penetration resistance and friction ratio, some conclusions can be made.

### 4.2 Parametric Analysis

In order to test the correlations presented before in this work a parametric analysis was performed. This analysis was based in values from Olsen and Mitchell (1995) approximate soil characterization framework based on normalized cone penetration resistance and friction ratio.

<table>
<thead>
<tr>
<th>Soil Characteristics</th>
<th>FC [%]</th>
<th>Rf [%]</th>
<th>qc [atm]</th>
<th>qc,1 [MPa]</th>
<th>∆qc [MPa]</th>
<th>qc,1,mod [MPa]</th>
<th>Current (5% Liquefaction Probability)</th>
<th>Recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose Clean Sand</td>
<td>5</td>
<td>0.28</td>
<td>65</td>
<td>6.5</td>
<td>0.0</td>
<td>6.5</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Loose Silty Sand</td>
<td>15</td>
<td>0.50</td>
<td>45</td>
<td>4.5</td>
<td>0.0</td>
<td>4.5</td>
<td>0.06</td>
<td>Out of Chart</td>
</tr>
<tr>
<td>Loose Sandy Silt</td>
<td>50</td>
<td>0.55</td>
<td>15</td>
<td>1.5</td>
<td>0.0</td>
<td>1.5</td>
<td>0.05</td>
<td>Non-Applicable</td>
</tr>
<tr>
<td>Medium-Dense Clean Sand</td>
<td>5</td>
<td>0.45</td>
<td>90</td>
<td>9.0</td>
<td>0.0</td>
<td>9.0</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Medium-Dense Silty Sand</td>
<td>15</td>
<td>0.85</td>
<td>60</td>
<td>6.0</td>
<td>1.0</td>
<td>7.0</td>
<td>0.08</td>
<td>Out of Chart</td>
</tr>
<tr>
<td>Medium-Dense Sandy Silt</td>
<td>50</td>
<td>1.50</td>
<td>25</td>
<td>2.5</td>
<td>1.7</td>
<td>4.2</td>
<td>0.07</td>
<td>Non-Applicable</td>
</tr>
</tbody>
</table>

Table 2 – Parametric Analysis Results for the CPT correlations
For this analysis it was considered that when the fines content were varying from 40 to 60 percent that it was above the limiting silt content for that soil, the fines varying from 10 to 15 percent to be below the limiting silt content and when the fines were below 5 percent it was considered to be clean sand. The values for the analysis were chosen in order to try to obtain cone resistance values for soils with varying silt content but with the same soil specific relative density.

The “Clean Sand” and “Silty Sand” are considered to have silt content below the limiting silt content, while the “Sandy Silt” is considered to have silt content above the limiting silt content of the sand. Starting with the CPT correlations, it can be seen that both for the “Loose” and “Medium-Dense” sand with silt below the limiting silt content, the recommended and the current correlations have a nearly perfect correspondence. However, the proposed correlation for the CPT by Carraro, Bandini and Salgado (2003) is based on an increase in cone resistance with increasing silt content. Since this parametric analysis was based on the approximate soil characterization framework by Olsen and Mitchell (1995), so that type of behaviour could not be analysed. This means that the CRR determined by the proposed correlation is conservative in this analysis since it considers a decrease in cone resistance with increasing fines content. This can be observed from the results of the analysis were the CRR for the proposed approach are either equal to that of the current approach (“Clean sand”), or so low that can not even be observed in the chart of the proposed correlation. However, the current correlations used will be unconservative when considering a soil for which the cone resistance increases with increasing silt content.

The SPT correlations are in very good agreement although it must be pointed out that, conceptually, the current approach is still wrong. Increasing cyclic resistance with increasing silt content without taking plasticity into consideration is erroneous as was shown by Martin and Polito (2001). Also, if the framework by Salgado et al. (2000) can be transposed to the SPT, since both the CPT and SPT measured penetration resistance, the current approach will be unconservative if increasing fines content increases SPT blowcount.

<table>
<thead>
<tr>
<th>Soil Characteristics</th>
<th>(N_{1,50})</th>
<th>(C_{\text{FINES}})</th>
<th>(N_{1,50,CS})</th>
<th>Current (5% Liquefaction Probability)</th>
<th>Recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose Clean Sand</td>
<td>13</td>
<td>1.021</td>
<td>13</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Loose Silty Sand</td>
<td>9</td>
<td>1.089</td>
<td>10</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>Loose Sandy Silt</td>
<td>5</td>
<td>1.520</td>
<td>8</td>
<td>0.05</td>
<td>Non-Applicable</td>
</tr>
<tr>
<td>Medium-Dense Clean Sand</td>
<td>18</td>
<td>1.016</td>
<td>18</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Medium-Dense Silty Sand</td>
<td>12</td>
<td>1.069</td>
<td>13</td>
<td>0.08</td>
<td>0.10</td>
</tr>
<tr>
<td>Medium-Dense Sandy Silt</td>
<td>8</td>
<td>1.320</td>
<td>11</td>
<td>0.08</td>
<td>Non-Applicable</td>
</tr>
</tbody>
</table>

Table 3 - Parametric Analysis Results for the SPT correlations (converted from the CPT)
Now discussing the “Sandy Silt” results from the parametric analysis one can clearly observe that the great decrease in cyclic resistance predicted by Martin and Polito (2001), when above the limiting silt content, does not occur when considering the current approach. This occurs because the current approach considers an increase in cyclic resistance with increasing silt content without considering plasticity. However, the current approach cannot be deemed unconservative since there is no data about how great is the difference between cyclic resistance between sand and silt.

Since a similarity in behaviours between nonplastic silt and sand is known and, according to Martin and Polito (2001), when a sand has a silt content greater than the limiting silt content, it is the silt fraction void of the soil that controls behaviour, the “clean sand curves” might be considered adequate for liquefaction assessment. However, this hypothesis must be investigated as well as the correction factors to apply when the silt content reaches the limiting silt content. Again, this analysis was made considering a decrease in cone resistance with increasing silt content. If that does not occur, for soils with silt content above the limiting silt content, the current approach would be deemed unconservative.

5. Conclusions

When the silt content of a soil is below its limiting silt content, the current correlations provide a good approach to the cyclic resistance that is expected of the soil since it does not differ much from the clean sand cyclic resistance. The decrease observed in the parametric analysis is due to the fact that the analysis is based a decrease in penetration resistance with increasing silt content.

If the silt content is greater than the limiting silt content, no definitive conclusions can be made for further investigation on this topic is required. The great loss of cyclic resistance predicted by Polito could not be observed in the analysis made and, since currently there are no correlations specific for sands with silt above the limiting silt content, the accuracy of the current approach could not be evaluated. However, the similarity in behaviour between sand and silt, shown by a recent study presented before, might indicate that the clean sands curve might be adequate for the evaluation of liquefaction resistance for sands with silt greater than the limiting silt content. This correlation might be possible since Martin and Polito (2001) showed that it is the silt controlling the behaviour of the soils when considering silt contents of that magnitude.

The findings in the study conducted by Salgado et al. (2000) should be investigated further. This need for investigation is due to fact that the findings of that study suggest that increasing silt content of a soil increases its penetration resistance. This finding would render all current correlations unconservative when considering silt that present this behaviour. This trend as been shown to be present in the CPT and should also be verified for SPT. The proposed correlation presented by Carraro, Bandini and Salgado (2003) for the CPT was chosen based on its conservative nature on a topic which clearly needs further investigation.
References


