Plasticity Based Liquefaction Criteria

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Abstract

Since their introduction into Chinese building codes in the 1970's, plasticity-based liquefaction criteria have provided a means for evaluating the liquefaction susceptibility of sands with clayey fines. These criteria are used to separate soils that may be considered non-liquefiable from those susceptible to liquefaction. The majority of the proposed criteria contain some minimum requirement regarding clay content and soil plasticity. The results of a parametric study into the effects of plastic fines content and plasticity on the liquefaction susceptibility of sandy soils were used to evaluate the accuracy of several of the more commonly used plasticity-based liquefaction criteria.

Most of the proposed criteria were found to have conservative requirements in terms of soil plasticity. Soils meeting the plasticity criteria were found to have very different deformation characteristics under cyclic loading than those soils not meeting the criteria. However, all the criteria reviewed were also found to include other requirements which were not accurate predictors of liquefaction susceptibility. In light of these findings, recommendations are provided for a simplified plasticity-based liquefaction criteria.

INTRODUCTION

Since their introduction into Chinese building codes in the 1970's, plasticity-based liquefaction criteria have provided a means for evaluating the liquefaction susceptibility of sands with clayey fines. These criteria are used to separate soils that may be considered non-liquefiable from those susceptible to liquefaction. The majority of the proposed criteria contain some minimum requirement regarding clay content and soil plasticity, which is typically quantified either in terms of the liquid limit or plasticity index of the soil.

The results of a parametric study into the effects of plastic fines content and plasticity on the liquefaction susceptibility of sandy soils (Polito, 1999; Polito and Martin, 2000) were used to evaluate the accuracy of several of the more commonly used plasticity based liquefaction criteria. A major finding of the study was that soils with higher levels of plasticity were found to have very different deformation characteristics under cyclic loading than those soils with lower levels of plasticity. Soils with higher levels of plasticity were found to undergo a cyclic mobility form of failure characterized by small post-loading strains, despite developing effective confining stresses equal to zero. Soils with lower levels of plasticity were found to be subject to the sudden loss of strength and large strains which are commonly associated with flow liquefaction.

Based upon these findings and an assessment of the various parameters found in the more commonly used plasticity based liquefaction criteria, recommendations are provided for a simplified plasticity based liquefaction criteria.

TESTING PROGRAM

A series of cyclic triaxial tests were performed in order to determine the effects which an increase in the amount plastic fines and the plasticity of those fines have upon the liquefaction resistance of sandy soils. The details of the testing program have been given elsewhere (Polito, 1999). Sixteen combinations of kaolinite, bentonite, and non-plastic silt were mixed with a medium to fine sand, with fines contents varying from 4 to 37 percent, and clay contents varying from 2 to 37 percent. All soils were tested at a relative density of approximately 25 percent.

PLASTICITY BASED LIQUEFACTION CRITERIA

Since the early 1970's, building codes in the People's Republic of China have included a listing of "thresholds to liquefaction" used to separate soils which are to be considered liquefiable from those considered non-liquefiable (Jennings, 1980). These criteria, presented in Table 1, are commonly referred to as the Chinese criteria, and are based on the observed behavior of soils during several major earthquakes in the Peoples Republic of China. The key focuses of the criteria are the percentage of "clay" (smaller than 0.005 mm) present, the plasticity index of the soil, and its density.

Table 1:Thresholds to Liquefaction (After Jennings, 1980)

Condition	**Threshold**
Mean grain size (mm)	$0.02 < D_{50} < 1.0$
Clay particle content (percent)	10 <
Uniformity coefficient	10 <
Relative density (percent)	75 <
Void Ratio	> 0.80
Plasticity index (percent)	< 10
Depth to water table (m)	< 5
Depth to sand layer (m)	< 20

Based upon further field experiences and differences in testing methodologies, several modifications have been proposed to the Chinese criteria (Seed et al., 1983; Finn et al., 1994; and Koester, 1994). A summary of these modifications is presented in Table 2.

Table 2: Modifications to Plasticity Based Liquefaction Criteria

Author	**Proposed Criteria/Modifications**
Seed et al. (1983)	Percent finer than 0.005 mm < 15% Liquid Limit, LL < 35% Water content at least 90% of LL
Finn et al. (1994) modifying Seed et al. (1983)	Decrease fines content by 5% Decrease liquid limit by 2% Increase water content by 2%
Koester (1994) modifying Seed et al. (1983)	Decrease fines content by 5% Increase liquid limit by 1% Decrease water content by 2%

In order to examine the applicability of these criteria the results of the tests performed were evaluated in terms of each of these criteria. The applicable factors in each criteria were compared to the factors for the specimens tested.

In the laboratory, all of the specimens tested were found to be liquefiable (i.e. reached a condition of zero effective confining stress) in a number of cycles and cyclic stress ratio likely to occur during a moderately large earthquake in the field. As all of the specimens liquefied in terms of their effective stresses in the lab, the type of liquefaction induced deformation that occurred, whether flow liquefaction or cyclic mobility, was considered. Although a detailed discussion of flow liquefaction and cyclic mobility is beyond the scope of this paper, these behaviors are briefly summarized herein.

While soils susceptible to flow liquefaction and cyclic mobility both achieve a condition of zero effective confining stress, their behaviors are quite different. Soils susceptible to flow liquefaction, such as loose sands and silts, exhibit large, sudden strength loss and often undergo large displacements. Soils susceptible to cyclic mobility, such as dense sands, generally exhibit only temporary strength losses and small deformations.

It is assumed that if cyclic mobility does develop in the field, the limited strains produced would do little damage and produce little evidence of occurrence. In contrast to flow liquefaction, the consequences of cyclic mobility may be considered minor enough to treat it as a non-liquefaction scenario for most design cases.

The main soil dependent factors of the Chinese criteria and the major proposed modifications were evaluated. These factors include soil plasticity, clay content, water content, mean grain size, relative density, and void ratio.

Soil Plasticity. Soil plasticity is one of the primary criteria used by all four systems to separate liquefiable and non-liquefiable soils. Whether the soil plasticity is quantified using the plasticity index or the liquid limit of the soil, it was found to be the single best indicator of whether a soil with clayey fines will undergo a cyclic mobility or a flow liquefaction failure.

The requirement in the Chinese criteria calling for soils with plasticity indexes greater than ten percent to be considered non-liquefiable appears reasonable. For the two soils tested which met this requirement, both underwent cyclic mobility failures. In fact, all of the soils tested which had plasticity indexes of seven or greater were found to be susceptible to cyclic mobility rather than flow liquefaction failures.

The modifications proposed by Seed et al. (1983), Finn et al. (1994) and Koester (1994) all call for a liquid limit of between 34 and 36 percent as the threshold between liquefiable and non-liquefiable soils. This requirement appears conservative. While the two soils which had liquid limits greater than 36 percent both underwent cyclic mobility failures, all of the soils with liquid limits of 20 or greater were also found to undergo cyclic mobility, rather than flow liquefaction, failures.

Clay Content. The criterion proposed in the Chinese criteria that sands with clay contents greater than 10 percent be considered non-liquefiable does not appear to be an accurate means of dividing between soils susceptible to flow liquefaction and those susceptible to cyclic mobility. Of the sixteen soils tested, ten would be declared non-liquefiable based upon this requirement. Of these ten, five were found to be susceptible to flow liquefaction.

Similarly, the requirement proposed by Seed et al. (1983) that soils with clay contents greater than 15 percent be considered non-liquefiable under this criteria, does not appear infallible. Of the sixteen soils tested, five would be considered non-liquefiable based upon this requirement. Of these five, one was found to be susceptible to flow liquefaction, while another was a borderline case.

Water Content. The criterion proposed by Seed et al. (1983) that soils with water contents less than 90 percent of their liquid limits may be considered non-liquefiable, appears to be valid. Of the sixteen soils tested, three would be considered non-liquefiable based upon this requirement. All three of these soils were found to be susceptible to cyclic mobility. This finding also applies to the criterion proposed by Finn, et al. (1994) which sets the dividing line at a water content of 88 percent of the liquid limit.

Mean Grain Size. The requirement in the Chinese criteria that the mean grain size of a soil be between 0.2 and 1 millimeters in order to be liquefiable does not appear to be an accurate means of dividing between soils susceptible to flow liquefaction and those susceptible to cyclic mobility. All sixteen of the soils tested met this requirement, and thus would be considered liquefiable under the Chinese criteria. Of these, however, only nine were found to be susceptible to flow liquefaction.

Relative Density. The Chinese criteria indicates that soils with a relative densities less than 75 percent are susceptible to flow liquefaction. While soils with relative densities above 75 percent are almost certainly susceptible to cyclic mobility, regardless of fines content or composition, soils with relative densities below this level do not appear to be inherently susceptible to flow liquefaction. Of the sixteen soils tested, all would be considered liquefiable based on their relative densities, yet five, all of which had relative densities of 25 percent, were found to be susceptible to cyclic mobility.

Void Ratio. The requirement that soils with void ratios smaller than 0.8 may be considered non-liquefiable under the Chinese criteria does not appear valid. Of the sixteen soils tested, twelve had void ratios smaller than 0.8 and thereby would be considered non-liquefiable based upon this requirement. Of these twelve, seven, all of which had void ratios between 0.75 and 0.58, were found to be susceptible to flow liquefaction.

IMPLICATIONS

The major implication which may be made from this study is that the one parameter which consistently separates soils susceptible to flow liquefaction and those susceptible to cyclic mobility is the plasticity of the soil. Whether that plasticity is quantified in terms of plasticity index or liquid limit, soils that meet some threshold level of plasticity tend to be safe from flow liquefaction failures.

While a threshold plasticity index of 10 seems to be appropriately conservative for separating soils susceptible to flow liquefaction from soils which tend to undergo cyclic mobility, the proposed threshold value of 35 for liquid limit may be overly conservative. Although more study is clearly necessary due to the limited size of the database, this investigation found that soils with liquid limits above 20 were not susceptible to flow liquefaction. This may be seen in Fig. 1, which shows the separation that occurs between soils susceptible to flow liquefaction and soils susceptible to cyclic mobility when they are plotted in terms of their Atterberg limits.

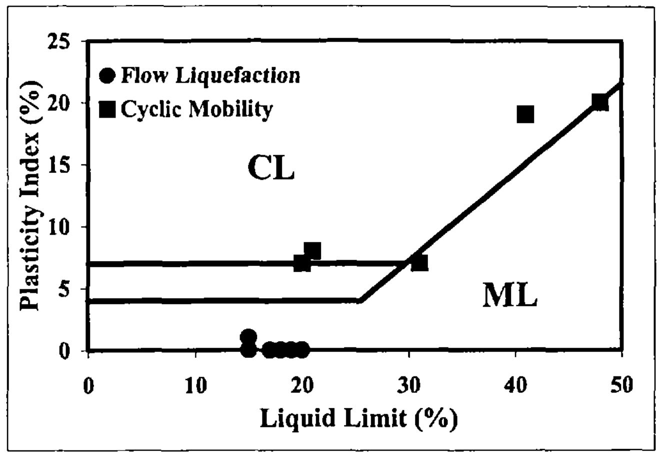

Fig. 1: Liquefaction behavior as a function of Atterberg limits

Based upon Fig. 1, a proposed zone of liquefiable soils (i.e. those susceptible to flow liquefaction and large and sudden strength loss) is indicated on the plasticity chart shown in Fig. 2, and includes soils with plasticity indexes less than 7 and liquid limits less than 25. Although the findings of this study would appear to indicate that soils with liquid limits between 25 and 35 percent, and plasticity indexes between 7 and 10 percent are safe from flow liquefaction, a second zone of potentially liquefiable soils was established as shown in Fig. 2. Soils that plot in this region should be tested in the laboratory to determine their susceptibility to flow liquefaction. Soils with plasticity indexes greater than 10 and liquid limits greater than 35 seem almost certainly to undergo cyclic mobility failures.

LIMITATIONS

As with any laboratory study, the results can only be rigorously applied to the soils tested in that study. Extrapolation of the observed trends to other soils is of course possible, but should always be done using proper engineering judgement. For example, all specimens in this study were tested at 25 percent relative density, which is near the lower bound for soils found in natural deposits. Soil deposits with a given level of plasticity may be less susceptible to flow liquefaction at higher relative densities.

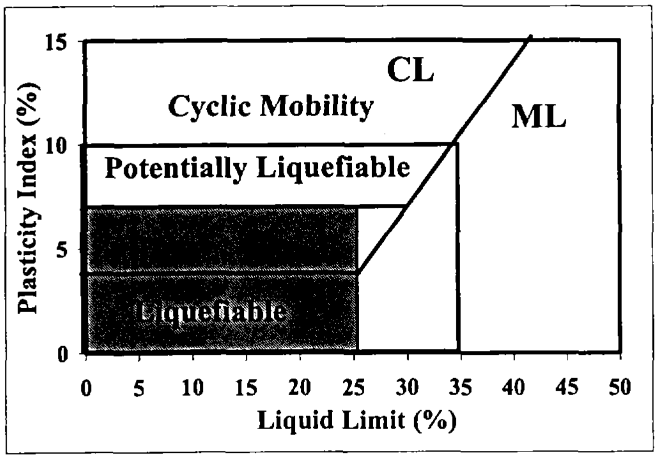

Fig. 2: Proposed plasticity based liquefaction criteria

As the sands tested in this study were fine to medium grained, care should be used in applying these findings and recommendations to soils which contain large percentages of coarse sands and gravels. The plasticity of the soils were determined by performing Atterberg limit tests on the material passing the Number 40 sieve (smaller than 0.43 mm.) As the majority of the soil passed the number 40 sieve, the Atterberg limits determined for the soil where based on a large fraction of the soil mass, and thus the activity (the ratio of the plasticity index to the percentage of clay in the soil) of the soil passing the # 40 sieve is similar to the activity of the soil for which the cyclic behavior was determined. For soils where a large portion of the of the sand fraction is larger than the # 40 sieve and is therefore not involved in the determination of the Atterberg limits, the chart may not be applicable as the overall activity of the soil mass may be lower.

CONCLUSIONS

Several sets of criteria have been proposed for separating liquefiable from non-liquefiable sands based upon the clay content, plasticity, and density of the soil. A review of these criteria has shown that the one parameter which consistently separates soils susceptible to flow liquefaction from soils which tend to undergo cyclic mobility is the soil plasticity. Whether measured in terms of plasticity index or liquid limit, soils that meet some threshold level of plasticity tend to be safe from flow liquefaction failures and the large strength loss and deformations associated with this form of failure.

By plotting the data on a plasticity chart, it is possible to identify zones where soils are either susceptible or potentially susceptible to flow liquefaction or susceptible to cyclic mobility. A soil's behavior during cyclic loading can then be predicted based upon its Atterberg limits.

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