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RECENT ADVANCES IN LIQUEFACTION OF FINE GRAINED SOILS

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ABSTRACT

Paper reviews present literature recommendations on liquefaction of soils with fines starting with the experimental evidence previously published by the authors. The liquefaction behavior of silts and silt clay mixers was investigated over a range of plasticity index values of interest by conducting cyclic triaxial tests on reconstituted samples and their behavior was compared with that of sand. It was found that saturated silts with plastic fines behave differently from sands both with respect to rate of development of pore water pressure and axial deformations with number of load cycles. The results also showed that liquefaction susceptibility of silts shows a marked change with change in the values of plasticity index. For a PI range of 2-4%, the liquefaction resistance of silt was found to decrease with an increase in plasticity. Some recent criteria may be helpful in deciding the liquefaction susceptibility of a fine grained soil. However, there is still considerable confusion in ascertaining their liquefaction susceptibility, based on simple field, and/or lab. tests.

INTRODUCTION

Extensive effort has been devoted to the study of liquefaction of sands in the last 50 years and research has progressed to the stage that liquefaction behavior of saturated cohesionless soils can be predicted from laboratory investigations or from simple in-situ test data such as standard penetration values [N1 or (N1)60] or Cone Penetration Test (CPT) data, and the experience during the past earthquakes, (Youd and Idriss 2001 and Youd et. al, 2001). Until recently, fine grained soils such as silts, clayey silts and sands with fines and silty soils were generally considered nonliquefiable. However, observations following several recent earthquakes indicate that many cohesive soils liquefied. These cohesive soils had clay fraction less than 20%, liquid limit between 21-35%, plasticity index between 4% and 14% and water content more than 90% of their liquid limit. Kishida (1969) reported liquefaction of soils with up to 70% fines and 10% clay fraction during Mino-Owar, Tohankai and Fukui earthquakes. Observations during several other earthquakes show evidence of liquefaction in silty and clayey soils (Turkey earthquakes, etc.). This led to study of liquefaction and cyclic mobility of fine grained soils. It is has now been established that practically all soils including sands, silts, clays, and gravels and their mixtures can liquefy depending upon the seismic and environmental factors.

Fine grained soils that may be susceptible to liquefaction (based on Chinese criteria) appear to have the following characteristics (Seed and Idriss, 1983).

Percent finer than 0.005 mm (5 microns) < 15%

Liquid limit < 35 %

Water content > 90% of LL

The Chinese criteria have been considered inadequate as discussed later in the paper. Seed et al. (1985) suggested that if the fines in sand are less than 5%, their effect on liquefaction susceptibility may be neglected and suggested use of charts in Fig. 1 for sands as well for soils with fines. It may be worthwhile to elaborate on the 'Chinese criteria' for liquefaction of fine grained soils here. According to Wang (1979), the following criteria are recommended by the Chinese Code for Aseismic Design of Hydraulic Structures. According to these criteria, any silty soil which contains less than 15 % to 20% clay particles (smaller than 5 μ m size) and has plasticity index of more than 3, can liquefy during a strong seismic motion if its water content is greater than 90 % of its liquid limit.

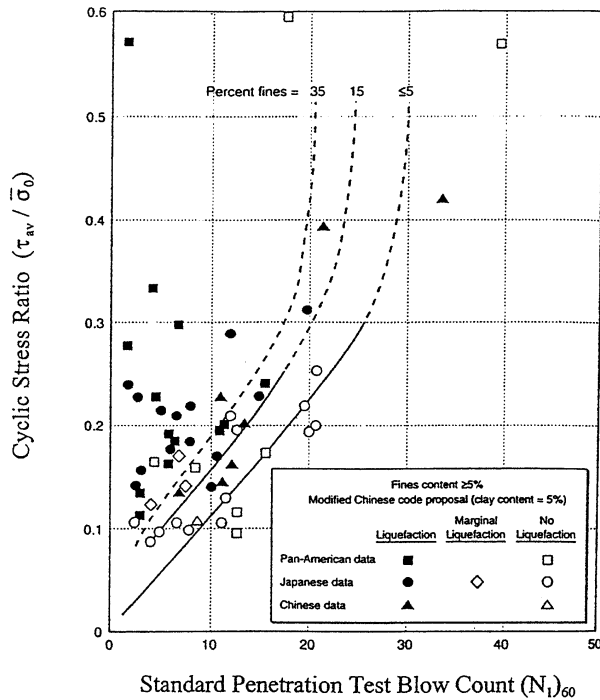


Fig.1. Relationship between Stress Ratio Causing Liquefaction and $(N_1)_{60}$ values for Silty Sand for $M = 7.5$ (after Seed et al. 1985)

The Chinese practice of determining the liquid and plastic limits, water content and clay fraction differs somewhat from the ASTM procedures followed in USA and some other countries. Finn (1991, and Finn et al (1993) and Perlea et al (1999) suggested the following adjustments of the index properties as determined using the US standards, prior to applying the Chinese criteria:

1. Decrease the fines content by 5%
2. Increase the liquid limit by 1%
3. Increase the water content by 2

Fig. 2, further illustrates the Chinese criteria modified as discussed above and applied to the index properties determined following the US or similar standards. The soils that fall below the line defined by $w = 0.87 LL$ and $LL = 33.5$ in Fig. 2 will be considered as susceptible to liquefaction.

EARLIER WORK BY AUTHORS

Studies undertaken at UMR (now M ST) in the early 1980's also identified the effect of plasticity of soil on the liquefaction of silts. Dynamic triaxial tests were conducted on 73.65 mm (diameter) and 147.3 mm (high) samples of two different silts (A and B) to determine the effect of plasticity index on susceptibility to liquefaction. The index properties of these silts are as follows:

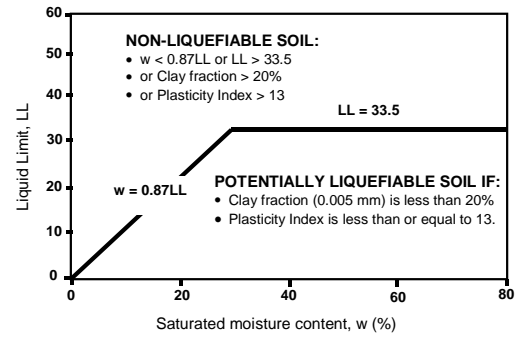


Fig. 2. Chinese Criteria Adapted to ASTM Definitions of Soil Properties (Perlea, Koester and Prakash, 1999)

	Soil A	Soil B
Percent finer than 75 μ (0.075 mm)	93-98	96-98
Natural water content %	18-26	----
Liquid limit	32.0-36.0	24.2-26.6
Plasticity index	9-14 (mostly~10)	1.6-1.8
Clay content (<2 μ m)	2.0-7.2%	
Specific gravity of soil particles	2.71	2.725
Particle size D_{50} mm	0.06	0.022

Soil A is a naturally occurring silt. The PI of this silt was altered by adding the clay fraction obtained from this soil itself (Puri, 1984). The tests on silt A were conducted at PI = 10, 15 and 20. The PI of silt B was varied in the low plasticity range by adding kaolinite. The tests on silt B were conducted at PI = 1.7, 2.6 and 3.4 (Sandoval 1989).

A typical data for the tests on silt A is shown in Fig. 3. It is seen from this figure that for the case of silt samples tested the failure defined by 5% or 10% double amplitude (DA) axial strains occurs before the condition of initial liquefaction defined by $u = \bar{\sigma}_3$ occurs.

Fig. 4. shows the effect of plasticity index (PI) on cyclic stress ratio inducing 5% DA strain in a given number of load cycles. Increase in PI value is seen to increase the cyclic stress ratio.

The trend of the data from other tests was similar with the exception that for the case of $PI=20$, the condition $u=\bar{\sigma}_3$ did not develop within the range of cyclic load applications used in this study.

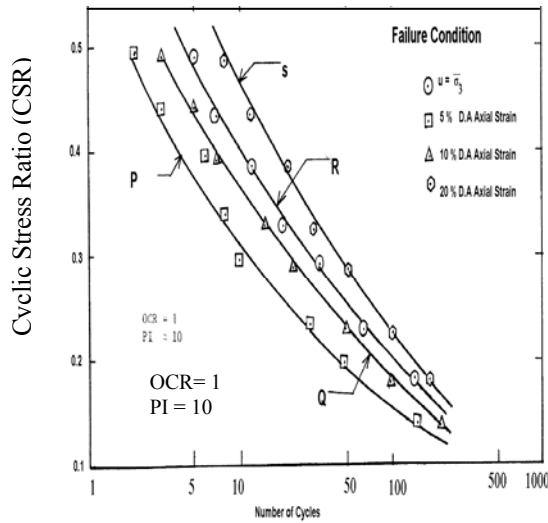


Fig. 3. Cyclic Stress Ratio versus Number of Cycles for Reconstituted Saturated Samples, silt A, For $\bar{\sigma}_3 = 15$ psi, (Puri, 1984)

confining pressure resulting in development of the initial liquefaction. This is just opposite the case when PI of 10% or greater for Soil A.

Combining results for Soils A and B with CSR normalized at void ratio of 0.74, (Prakash and Guo, 1998) leads to results as shown in Fig. 6. It is observed from this figure that for PI values of less than about 4% the cyclic stress ratio causing liquefaction in any given number of cycles decreases with an increase in PI values. For PI values beyond about 4%, the cyclic stress ratio causing initial liquefaction in any given number of cycles increases with an increase in the PI values.

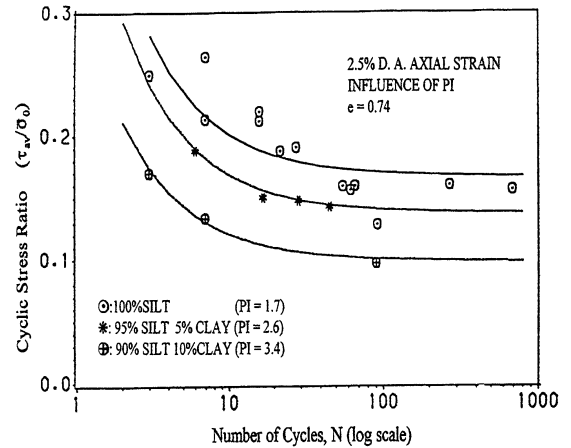


Fig. 5. Cyclic Stress Ratio versus Number of Cycles for Low Plasticity Silts for Inducing Initial Liquefaction Condition at 15 psi Effective Confining Pressure; $PI = 1.7, 2.6,$ and 3.4 , for Density 97.2-99.8 pcf, and $w = 8\%$ (Sandoval 1989; Prakash and Sandoval 1992)

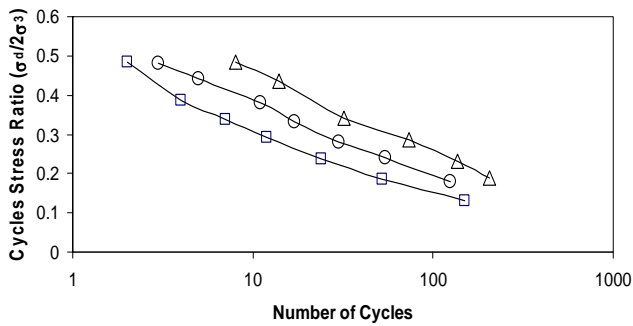


Fig. 4. Cyclic Stress Ratio versus number of Cycles for Reconstituted Saturated Samples, Silt A, $\bar{\sigma}_3 = 10$ psi, (□ $PI=10$, ○ $PI=15$ and △ $PI=20$) (Puri,1984)

Typical results of the investigation on samples of silt B showing the effect of plasticity index ($PI = 1.7\%, 2.6\%$ and 3.4%) on the cyclic stress ratio causing initial liquefaction in any given number of cycles are shown in Fig. 5.

It is clear from this figure that the cyclic stress ratio causing liquefaction in a given number of cycles decreases with the increase in plasticity index. It was observed during the testing phase that cyclic loading of plastic silts results in pore pressure build up which becomes equal to the initial effective

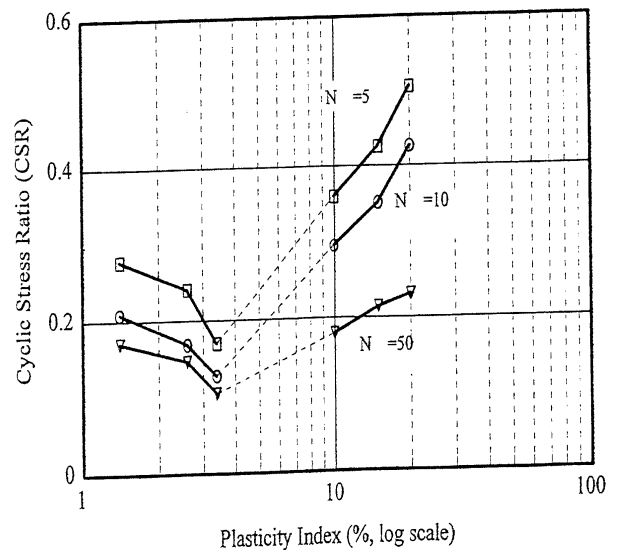


Fig. 6. Cyclic Stress Ratio versus Plasticity Index for Silt-clay Mixtures (CSR Normalized to initial Void Ratio $e_0 = 0.74$) (Sandoval, 1989, Prakash and Guo 1998)

Based on these results, it may be inferred that there is a critical value of PI at which saturated samples of silt–clay mixtures have a minimum resistance to cyclic loading or highest susceptibility to liquefaction. It is worth mentioning here that the data of El Hosri et. al., (1984) on undisturbed sample Fig.7 also suggests a similar effect of PI on cyclic stress ratio causing liquefaction as observed during the present investigation.

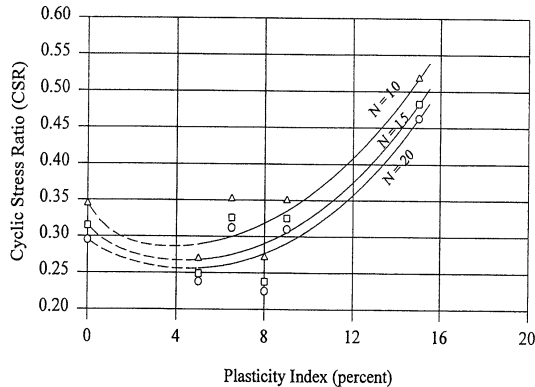


Fig. 7. Normalized cyclic Stress Ratio versus plasticity Index on Undisturbed samples (After El Hosri et al 1984 and Prakash and Guo 1998)

SOME CONFLICTING OPINIONS ABOUT EFFECT OF FINES ON LIQEFACATION AND RECENT DEVELOPMENTS

There are several research findings worth mentioning on the effect of fines on liquefaction potential of soils. Some of these opinions are conflicting and some time may be confusing. Specifically:

1. Seed et al (1985) have recommended that for sands containing less than 5% fines, the effect of fines may be neglected. For sands containing more than 5% fines, the liquefaction potential decreases as shown in Fig. 1. Neglecting the effect of fines should therefore be expected to lead to conservative estimates of liquefaction potential. However this suggestion is not based on experimental or field data.
2. Zhou (1981) made an interesting observation based on CPT tests on silty sands at one site and clean sands at another site that an increase in the fines content in sand decreases the CPT resistance but increases the cyclic resistance of the soil. No explanation is given for this peculiar behavior.
3. Zhou (1987) observed that if the clay content P_c in a soil is more than the critical percentage P_c^* , the soil will not liquefy.

The value of P_c^* are related to the intensity of earthquake I as follows:

Intensity (I)	7	8	9
P_c^* (%)	10	13	16

4. Ishihara and Koseki (1989) had suggested that low plasticity fines ($PI < 4$) do not influence the liquefaction potential. However, they did not consider the effect of the void ratio in their analysis.
5. Finn (1991) made an observation about the effect of fines in sand in developing equivalent clean sand behavior. If the void ratio of silty sand and clean sand is the same the liquefaction resistance decreases. If the comparison is made at the same $(N_1)_{60}$, the effect of fines is to increase the liquefaction resistance. If comparison is made using the “the same void ratio in sand skeleton” as the criteria, then there is no effect on the cyclic strength provided the fines can be accommodated in the sand voids.
6. Ishihara (1993) mentioned that in soils in which the fines content is sufficient to separate the coarser particles, the nature of the fines controls the behavior. Low plasticity or non-plastic silts and silty sands may be highly susceptible to liquefaction. This will be the case when PI is less than about 10. For soils with moderately plastic fines (fines content more than about 15 % and $8 \leq PI \leq 15$), the liquefaction behavior may be uncertain and may need further investigation. It is obvious that it is still not possible to evaluate the likelihood of liquefaction of silts or silty clays with the same confidence as for clean sands without additional investigations.

It is thus seen that there are different conclusions about the effect of fines on liquefaction resistance.

7. Seed et al., (2001) observed that there is significant controversy and confusion regarding the liquefaction potential of silty soils (and silty /clayey soils), and also coarser, gravelly soils and rockfills.
8. Finn et al., (1994), Perlea et al., (1999) and Andrews and Martin (2000) have provided general criteria about liquefaction susceptibility of soils with fines. The findings of Andrews and Martin (2000) are summarized in Table 1. For use of Table 1 clay refers to fraction finer than 0.002 mm and liquid limit should be determined using Casagrande type equipment.
9. Bray et al (2004) and Boulanger and Idriss (2005) and Idriss and Boulanger (2008) have investigated the liquefaction of soils with fines and shown that fine grained soils with more than 50 % passing US sieve # 200 can be reasonably grouped either into soils that exhibit sand-like stress-strain behavior or soils that exhibit clay like stress-strain behavior during monotonic and cyclic undrained shear loading. They observed that clay like behavior should be expected for silts (ML and MH) that have $PI \geq 7$ and for clays (CL and CH) . Sand like behavior should be expected if their PI is < 7 . For sand like materials, field test data such as N-values or CPT data

may be used for determination of liquefaction potential. For clay like materials, laboratory testing may be necessary for ascertaining their behavior during cyclic loading. They also suggested that both sand-like and clay-like soils can develop excess pore water pressures and significant strains during undrained cyclic loading.

Table1. Liquefaction susceptibility of silty and clayey sands (Andrew and Martins, 2000)

	Liquid limit < 32	Liquid limit ≥ 32
Clay content <10%	Susceptible	Further studies required (Considering plastic non-clay sized grains such as Mica)
Clay content >10%	Further studies required (Considering non-plastic clay sized grains such as mine and quarry tailings)	Not susceptible

10. Bray et al. (2004) and Plito (2001) have suggested that the plasticity index rather than percent of clay size particles as a criterion for assessing the susceptibility of fine grained soils to liquefaction.
11. Bray et al. (2004) found that soils that were observed to have liquefied in Aadapazari during the Koceli (1999) earthquake did not typically meet the Chinese criteria for liquefaction susceptible fine grained soils. During their investigation they found that soils with $PI < 12$ underwent liquefaction, soils between 12 and 18 were moderately prone to liquefaction and soils with $PI > 18$ were not prone to liquefaction at the effective confining pressures used in the experiments.
12. The authors in their earlier investigation (Puri, 1984) had also observed that Soil A had developed pore water pressure equal to the initial effective confining pressure and the peak to peak axial strain at this stage was in excess of 5 %.
13. Wang, Yuan and LI (2007) investigated the liquefaction susceptibility of saturated loess (silty soil) and fine sand obtained from an airport site near Lanzhou, China. This loess had PI varying from 7.2 to 9. Their studies indicated that this loess was more susceptible to liquefaction than fine sand.
14. Ghalandarzadeh, Ghahremani and Konagai (2007) Investigated liquefaction behavior of clayey sand from a site where large sand boiling, softening and large deformations had been observed in Iran due to an earthquake of magnitude 6.4. The soil had a liquid limit of 38 %, $PI=18$ %, and fine fraction (finer than 75 microns) of 44%. They performed cyclic triaxial tests. The analysis of data indicated that the clayey sand deposit likely developed high residual excess pore water pressures and

significant shear strains during the earthquake.

15. Towhata (2008) has mentioned that it was previously thought that soils with fines are more resistant to liquefaction. However, he has also mentioned that the fines employed in those studies meant silts and clays that were cohesive in nature and fine materials without cohesion may still be vulnerable. It is the opinion of the authors based on the data presented here that the soils with low plasticity ($PI < \text{about } 7$) may liquefy or develop large deformations under cyclic loading.

CONCLUSIONS

It may be concluded that:

- (1) The silts and silt-clay mixtures behave differently from sands, both with respect to development and build up of pore water pressures, and deformations under cyclic loading.
- (2) The silts and clays can be prone to liquefaction under certain conditions.
- (3) The plasticity index and not the percentage of fines can serve as better criteria for liquefaction susceptibility of silts and clays.
- (4) There are several gaps in the existing literature and no definite guidelines are available to ascertain liquefaction susceptibility of fine soils based on a simple test, as for sands. This is not surprising since it took more than 4 -5 decades to have acceptable criteria for liquefaction of sands as we see today (2010).. So more work is needed and probably in few decades we will have a good understanding of the liquefaction behavior of fine grained soils.

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