LIQUEFACTION OF SILT-CLAY MIXTURES

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SUMMARY

No guidelines are available for evaluating the liquefaction potential of silt-clay mixtures during an earthquake, based on their simple property i.e. density, void ratio, plasticity index, and standard penetration values. The liquefaction behavior of these soils is not properly understood at present (2000) and is often confused with that of sand-silt mixtures. Pore water pressure generation mechanism of silt and silt-clay mixtures is discussed based on the published information. Through statistical analysis, an approximate correlation between cyclic stress ratio (CSR) for initial liquefaction and plasticity index (PI), initial void ratio (e_0) and number of cycles (N) has been established. It is shown that an increase in plasticity index lowers the cyclic stress ratio for liquefaction in low plasticity range. There appears to be a critical value of plasticity index at which the resistance to liquefaction of silty soil is at a minimum. The liquefaction resistance of silt-clay mixtures increases with the increase of plasticity index beyond this critical point. A physical explanation for this behavior is presented.

INTRODUCTION

Silts and silt-clay mixtures are found in several parts of the world. Their liquefaction behavior during earthquakes has not been critically examined as compared with the liquefaction behavior of clean sands. However it has been observed that, if a sand-fines mixture has the *same standard penetration value* $(N_1)_{60}$ as the clean sands, the addition of fines increases its liquefaction resistance (Seed et al. 1985). This has led to an *erroneous* belief that the addition of fines to sands increases their liquefaction resistanceand therefore, addition of clays to silts will also increase their liquefaction resistance. However, Troncoso (1990) established that if fines are added to sands, their resistance to liquefaction decreases if the soils are tested at the *same void ratio*. Neither Troncoso (1990) nor Seed et al. (1985) describe the plasticity characerisitics of fines in the sand.

It is generaly believed that addition of clay or introduction of plasticity to the silt increases the resistance of silts against liquefaction (Puri 1984). It was demonstrated by Sandoval (1989), and Prakash and Sandoval (1992), that for plasticity index (PI) in the range of 2-4%, the liquefaction resistance of silt decreases with increasing plasticity. In this paper it is shown that an increase of plasticity in silts does not necessarily mean increased resistance to liquefaction both in undisturbed and remolded state. Also, other relevant data from literature which substantiates the above hypothesis has been critically examined. There appears to be a critical PI value at which the liquefaction resistance is minimal. Specific values for critical PI are not known at present (2000).

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SILT CLAY MIXTURES

In nonplastic silts, the nature of pore pressure generation is about the same as that for sands. If a small percentage of highly plastic material is added to nonplastic silt one of the following two phenomena may happen:

1) The rate of buildup of pore water pressure increases due to the fact that the clay content will reduce the hydraulic conductivity of the soil, leading to higher pore pressures; and

2) Plasticity may impart cohesive character to this mixture. This will therefore, increase the resistance to liquefaction of the mixture.

It is the interplay of these factors which will determine whether the liquefaction resistance of silt-clay mixtures increases or decreases compared to that of the pure silts.

Typical test data on liquefaction of silts and silt-clay mixtures has been critically evaluated.

ANALYSIS OF DATA

Typical test results from the published literature on liquefaction of silts and silt-clay mixtures, obtained from both undisturbed specimens and reconstituted samples, are criticlly evaluated and analyzed to establish their liquefaction behavior and to study their dependence on Plasticity Index.

Undisturbed Samples

El Hosri *et al* (1984) performed tests on six silt specimens in undisturbed state obtained from depths of 20 and 40 m at two sites. The soils tested were mainly silts with traces of clay or clayey silt (ML-CL or ML-MH) with PI between 5-15% except one sample which consisted of silty sand. Table 1 lists cyclic stress ratios (CSR) for liquefaction in 20 cycles and the corresponding void ratios.

The following observations are made:

1) Sample B with e_0 of 0.478 and PI of 5%, failed at CSR of 0.32. CSR Sample A (PI of 0) with e_0 of 0.644 is 0.295. Although Sample B is much denser than Sample A, CSR for Sample B is only slightly higher than that of Sample A. Therefore, it can be inferred that if the void ratio of Sample B were close to that of Sample A, CSR at failure for Sample B is likely to be much less than the CSR for Sample A. This shows that introduction of a small amount of plasticity lowers the CSR at liquefaction.
2) Sample C with e_0 of 0.548 and PI of 8%, failed at CSR of 0.265. Again, even though Sample C is denser than Sample A, the resistance to liquefaction of this sample is smaller than that of Sample A. Also, the PI of Sample C is more than the PI of Sample B, but CSR at liquefaction of Sample C is less than that of Sample B. However, this comparison is not sufficient because the void ratio of Sample C is greater than that of Sample B.

Table 1. Characteristics of the Specimens and Test Results of El Hosri *et al*., 1984 (Guo 1999)

Sample No.		Gradation <2μm%	PI	e_0 of Sample	Soil Type	Number of Cycles	CSR
Site (I)	A	0	-	0.644	SM	20	0.295
	B	19	5	0.478	ML-CL	20	0.32
	C	21	8	0.548	ML	20	0.265
Site (II)	D	17	9	0.654	ML	20	0.305
	E	28	15	0.914	ML-MH	20	0.326*
	F	15	6.5	0.600	ML-CL	20	0.335

- extrapolated value

It is seen that there are two variables, e_0 and PI, which control the CSR for initial liquefaction. Therefore, in order to study the effect of one variable, PI, it was decided to normalize the CSR for all samples for a common void ratio of 0.644. It was *assumed* that the CSR for initial liquefaction is inversely proportional to the void ratio (Guo, 1999; Guo and Prakash 1999).

In Table 2, cyclic stress ratios of all the samples are normalized to the initial void ratio of 0.644 for liquefaction in 20 cycles. The listing was rearranged according to the values of plasticity index of the samples. In Figure 1, this normalized CSR is plotted against PI. It is seen from the plot that the cyclic stress ratio of undisturbed samples decreases first with an increasing plasticity index up to a PI of about 5 and then increases with increasing PI. For Sample E with PI = 15, the cyclic stress ratio is even higher than that for Sample A, with no plasticity. The test results presented above clearly show that plasticity index has a definite influence on liquefaction resistance of silt-clay mixtures.

Table 2. Normalized test results for various number of cycles (CSR normalized to initial void ratio e_0 = 0.644)

Sample No.	PI	Number of Cycles	CSR	Number of Cycles	CSR	Number of Cycles	CSR
A	-	20	0.295	15	0.315	10	0.345
B	5	20	0.238	15	0.249	10	0.269
F	6.5	20	0.312	15	0.326	10	0.352
C	8	20	0.225	15	0.238	10	0.271
D	9	20	0.310	15	0.325	10	0.350
E	15	20	0.463	15	0.483	10	0.518

In Table 2, the normalized CSR for liquefaction with number of cycles N=10, N=15 are also listed and plotted in Figure 1. It is clear that the increase of plasticity index decreases the liquefaction resistance of silty clay mixtures in the low plasticity index range. In the middle and/or high plasticity index range, an increase of plasticity index increases the liquefaction resistance for undisturbed silt-clay mixtures.

Figure 2 shows the relationship between excess pore pressure ratio $\Delta u/\underline{-}_0$ and cycle ratio N/N_L for five undisturbed silt samples (Samples B-F in Table 1 and 2) and Sacramento sand (Sample A), where N_L is the number of cycles required to cause initial liquefaction and N is the number of cycles required to develop excess pore water pressure Δu. This figure shows that the excess pore pressure ratio increases rapidly at the beginning of cyclic load application on the clayey silt specimens. This increase in pore pressure is at a much faster rate than that observed for the Sacramento Sand (Sample A). The above test results of El Hosri *et al.* (1984) show that silty soils are vulnerable to pore water pressure buildup which is substantially different from that for sands. The pore pressure buildup is much faster at the beginning of loading in silt-clay mixture than in sand. Similar pore pressure build up in silty soils has been observed by Wang *et al*. (1996).

On the basis of studies on undisturbed samples, the following is concluded:

1. Tests indicated that the pore water pressure buildup in silt-clay mixture is remarkably different from that for sands.

2. The increase of PI decreases the liquefaction resistance of silt-clay mixtures in the low range of plasticity. In the high plasticity range, the liquefaction resistance increases with increasing PI.

3. For silt-clay mixtures, the criteria used to define the liquefaction of sand may no longer be applicable because of the difference in pore pressure buildup and deformation relationship as compared to those of sand.

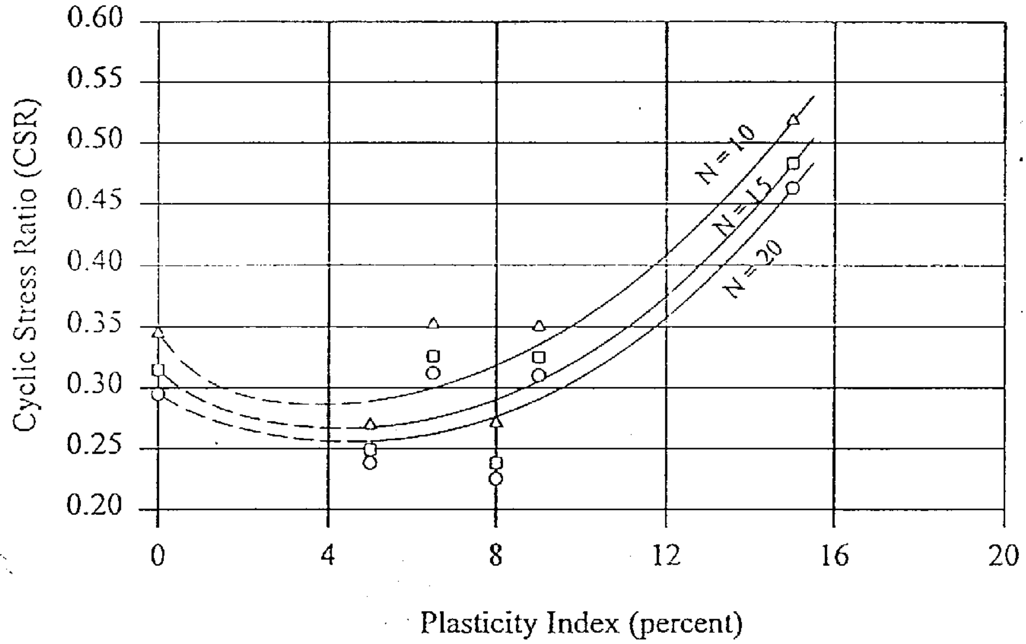

Figure 1 Normalized cyclic stress ratio vs. plasticity index on undisturbed samples; data of El Hosri *et al.*, 1984 (Guo 1999)

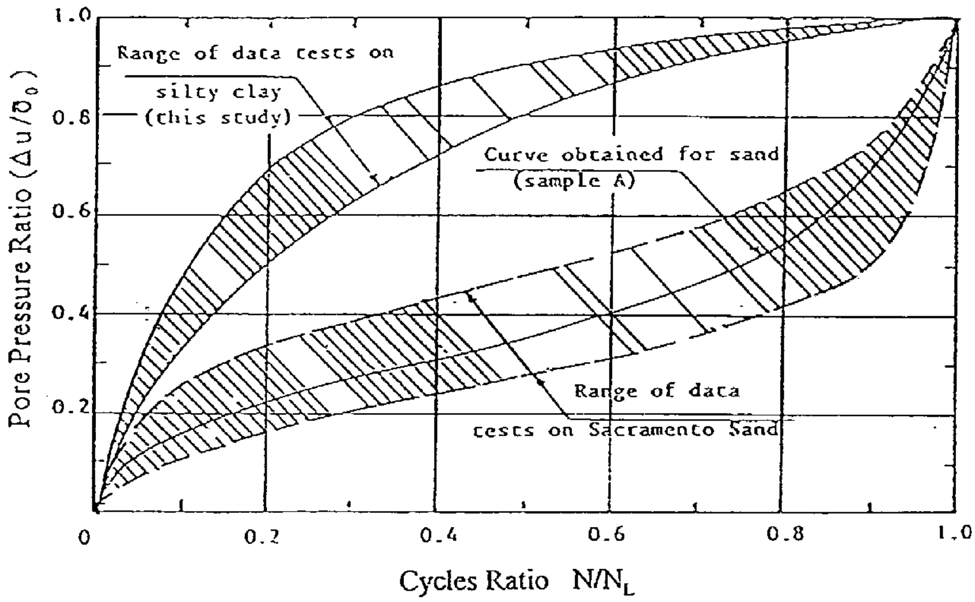

Figure 2 Rate of pore pressure buildup in cyclic triaxial tests on undisturbed samples (after El Hosri *et al.*, 1984)

Reconstituted Samples

Sandoval(1989) and Prakash and Sandoval(1992) performed liquefaction tests on silt (96 percent passing #200 sieve and PI = 1.7%). A commercially available kaolinite was added to increase the PI of this silt to 2.6 and 3.4. In these tests cyclic stress ratio(CSR) to cause liquefaction for a particular number of cycles decrease when plasticity index increases. For example, for 10 cycles, the cyclic stress ratios for initial liquefaction are 0.21, 0.17 and 0.128 for PI = 1.7, 2.6 and 3.4 respectively (Guo and Prakash 1999). Test results indicated that in the low plasticity range, the effect of increase in PI is to lower the cyclic stress ratio to cause initial liquefaction. Puri (1984, 1990) performed tests on reconstituted samples of similar silt and silt clay mixtures with PI of 10% to 20%. The main conclusion of this study is that the liquefaction resistance of silts and silt-clay mixtures in the PI range 10% - 20% increases with increasing PI.

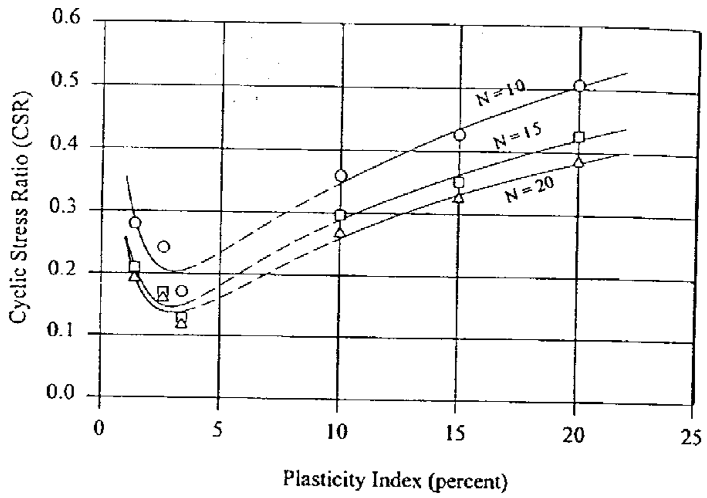

Figure 3 Cyclic stress ratio vs. plasticity index for reconstituted samples of silt-clay mixtures; tests by Puri (1984) and Sandoval (1989) (CSR normalized to initial void ratio e_0 =0.74)

Test results of the two studies above are shown in Figure 3 which shows the changes of cyclic stress ratio with plasticity index as well as number of cycles. The plasticity index range for the lowest value of CSR is between PI values of 4 and 10. The two studies, validate the hypothesis stated previously which may be rewritten as:

4. The pore pressure buildup increases because the fine particles of clay reduces the hydraulic conductivity of the mixture, leading to higher pore pressures in the low plasticity range.

5. Plasticity imparts some cohesive character to this mixture and therefore increased resistance to liquefaction in the high plasticity range

Also, on undisturbed samples, structure, aging and cementation have not been investigated. Therefore, there is a need of further systematic study of liquefaction behavior of these soils.

NONLINEAR STATISTICAL FORMULATIONS

Fifty-two results of triaxial test on reconstituted samples of silt with PI ranging from 0 to 20% were selected to develop a correlation between the cyclic strength of silty soil and the factors affecting its cyclic stress ratio (Guo, 1999). The test results selected for this study were taken from Ishihara et al. (1978), Puri (1984), Zhu and Law (1988), Sandoval (1989), and Chang (1990). Several nonlinear models were studied so that a better model could be selected to represent the cyclic strength of the soil using the program SYSTAT. The statistical results showed that the cyclic stress ratio of silt-clay mixtures strongly related to plasticity index, PI, and initial void ratio, e_0, as well as the number of stress cycles, N. The selected relationship which gave the best fit is:

$$CSR = 0.065 - 0.234\, PI^{0.5} + 0.057\, PI + 0.34\left(e_0/N\right)^{-0.028} \qquad \textbf{(1)}$$

Where CSR = cyclic stress ratios required to trigger liquefaction;

PI = plastic index of the fines;

e_0 = initial void ratio;

N = number of cycles for triggering liquefaction;

The value of relative coefficient, R^2, is 0.920. In the above formulation, the CSR is observed to be sensitive to the plasticity index. Figure 4 shows a plot of CSR versus plasticity index calculated using Eq. (1) for initial void ratios equal 0.7 and number of cycles equal 20. All the available 14 sets of data with the same test conditions are shown in the plot.

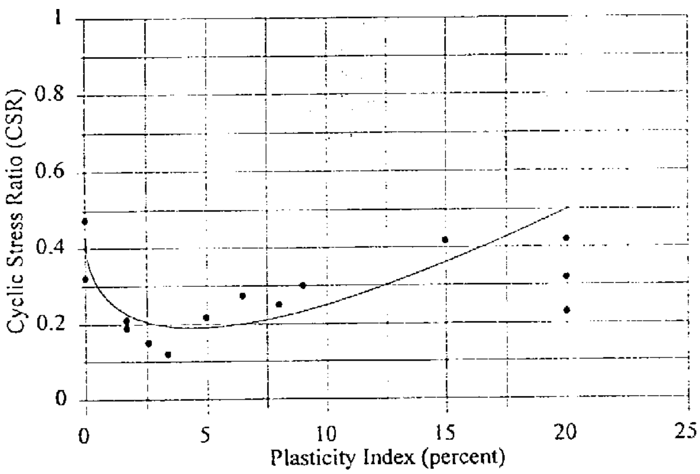

Figure 4 Cyclic stress ratio versus plasticity index on reconstituted samples of silty soils according to Eq. 1 for N=20 and $e_o = 0.7$

This curve is similar in shape with the curves in Figure 1 and 3 developed using the results of El Hosri (1984), Puri (1984), and Sandoval (1989), respectively. However, the relationship in Figure 1 needs to be further refined when more test data becomes available.

CONCLUSION

Based on the analysis of the published test data on liquefaction resistance of silty-clay performed on both undisturbed and reconstituted specimens, the following conclusions are drawn:

For silty clay mixtures, their liquefaction resistance is sensitive to the plasticity index of the soil.

- There appears to be a critical value of PI below which the increase of plasticity index lowers the Cyclic Stress Ratio for liquefaction and beyond this critical value, the increase of plasticity index increases the value of cyclic stress ratio for initial liquefaction. For the limited data analyzed, the critical value of plasticity index is most probably between 4% and 5%.
- The cyclic behavior of silt-clay mixtures is not very clear at the present stage. There is no definite criterion for evaluating the liquefaction protential of such soils. There is confusion on the influence of clay content and plasticity index. A relationship between CSR and e_0 is not available. For proper understanding the seismic behavior of silt and silt clay mixtures, those factors need further study.
- The effects of fabric, aging, and cementation are also not quantitatively known. Clearly the importance of fabric in fine grained soils, such as silts, needs to be recognized when evaluating the pore pressure generation.

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