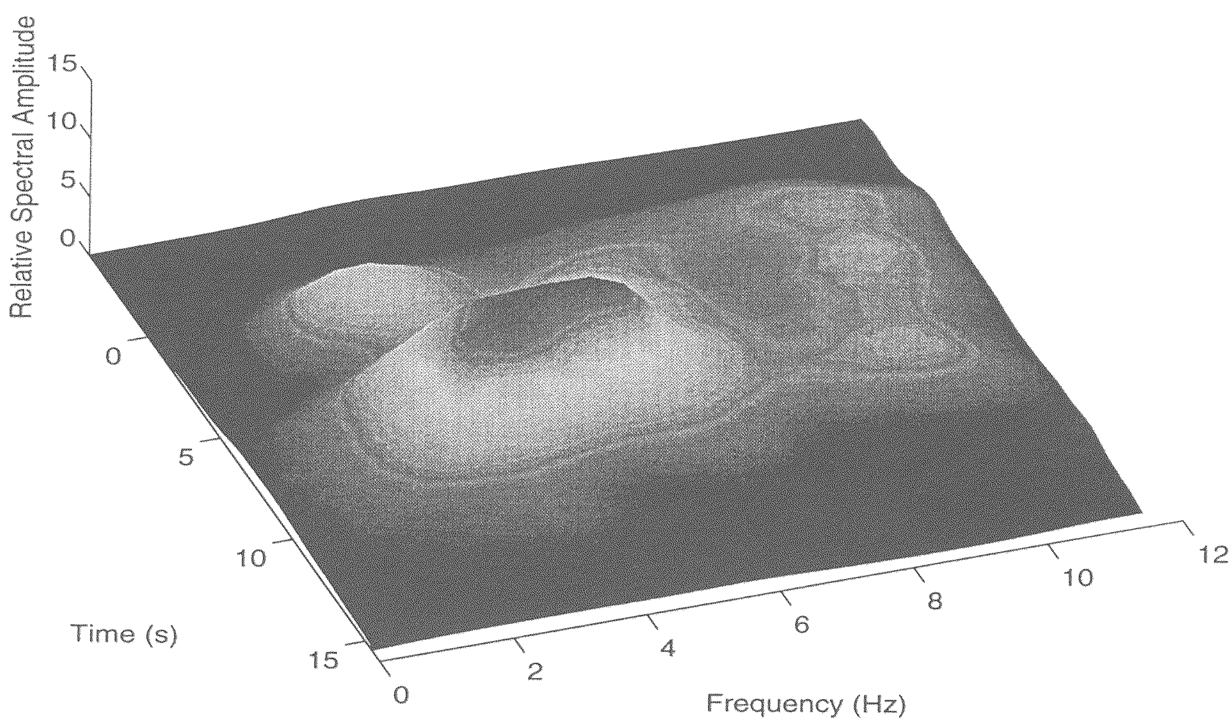

Figure 7 Soil system evolutionary time history for the initial 20 s of the Superstition Hills earthquake. The changing system is shown in spectral representation.

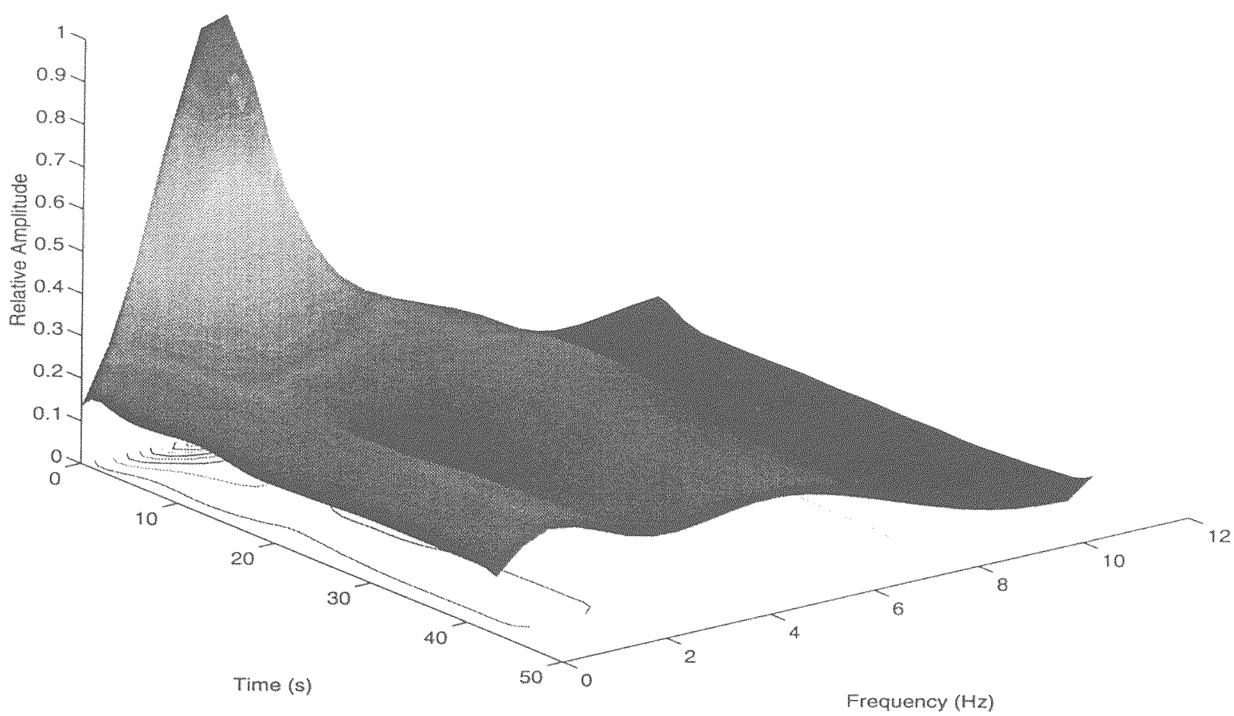

Figure 8 Soil system evolutionary time history for the coda of the Superstition Hills earthquake. The changing system is shown in spectral representation.

Recent Research on Liquefaction of Silts and Silty Sands at Santa Clara University

Sukhmander Singh*

Abstract

The paper presents a summary of the results of cyclic triaxial load testing of samples of silt, and silty sands. The paper emphasizes differences in behavior observed between reconstituted triaxial samples of clean sand, of sand containing 10, 20, 30 and 60 percent silt, pure silt, and undisturbed samples of silt and silty sand. An important observation is that the mechanisms of deformation for silt are different for reconstituted and undisturbed samples, the undisturbed sample having a specific "geologic" structure which seems to slow down the excess pore water pressure accumulation, but which still results in cyclic deformations regularly increasing from the very beginning of the test and rapidly reaching high levels. The other important observation is that fine grained non-cohesive soils such as silts and silty sands can be as or even more susceptible to liquefaction as clean sands. Test results on samples of sands containing 10, 20 or 30 percent of silt indicate lesser resistance to liquefaction than that of pure sand samples. The paper shows the difficulty in identifying a representative parameter to compare the behavior of silts and silty sands with pure sand, and it seems that more research will be needed in this area.

Introduction

Liquefaction behavior of silts and silty sands is routinely evaluated or studied in terms of the parameters used for sands. However, testing of undisturbed samples of silts (Singh and Chew, 1988) indicated that the pore pressure generation and deformation characteristics of silty samples were quite different than that of sand samples In order to resolve this a systematic study of the cyclic strength behavior of laboratory prepared samples of sand containing different percentages of silt and pure silt were undertaken to compare with test results from undisturbed samples, and to re-examine the influence of non-cohesive fines (silts) on the liquefaction behavior of sands.

Test Results on Undisturbed Samples

A wide range of undisturbed samples of silts, silty sands, and claying silt were tested and results were discussed by Singh and Chew (1988) With the exception of very loose silts, large strains occurred more quickly in the silts as opposed to the sands, while pore pressure buildup was slower in the silts (**Figure 1**)

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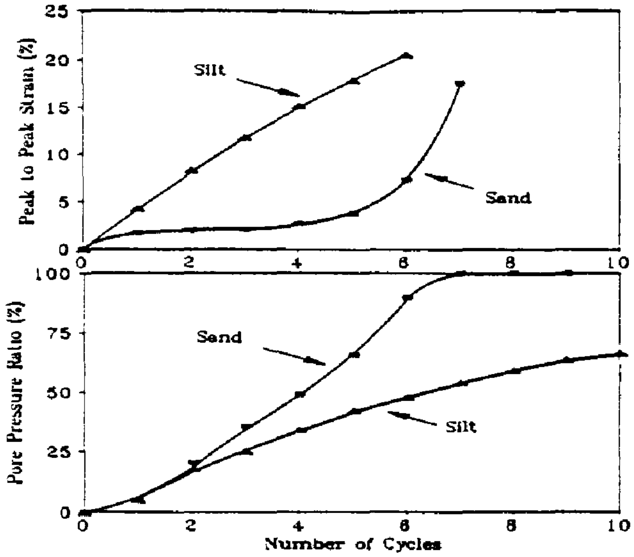

Fig. 1. Strain and pore pressure development in a typical silt and loose sand (from Singh and Chew, 1988)

The behavior of silty sands with less than 20 percent silt was dominated by the sands, while sandy silts with more than 60 percent silt would be controlled by the silt. On the basis of these observations, it appears that the pore pressure buildup was not a good criteria for undisturbed but large straining silts during cyclic loading because the large strains are observed before significant pore pressure buildup occurs.. For more detailed discussions, the reader is referred to a more recent work by Singh (1994).

Test Results on Reconstituted Samples

Flint shot #4 sand, a uniform sand, was used for testing. Uniform non-cohesive silt was obtained by sieving fine sand from Pasadena, California, through a #200 sieve. Moist tamping method was used for sample preparation. Preparation of silt samples was a challenge. In all of the test series involving silt, it was found that the results were very sensitive to the mixing moisture and tamping procedure for sample preparation. Consistencies in all aspects such as mixing, tamping and handling were very important to achieve consistent results. The presence of a somewhat weaker layer was readily evident from the manner in which the sample would fail. Further details of sample preparation are given in Singh (1994). Figure 2 shows the relationship between cyclic stress ratio and number of cycles to initial liquefaction for reconstituted samples of pure sand, pure silt and silty sand.

It may be noted from **Figure 2** that sands containing 10, 20, or 30 percent of silt have lesser cyclic strength than that of 100 percent sands These samples were prepared to approximately the same relative density of 50%. Maximum and minimum densities were determined separately for each case. and 50% relative density estimated from the maximum and minimum densities. It has been suggested that relative density is not a suitable index for characterizing behavior of silty sands (Ishihara et al., 1980). Laboratory controlled studies on the effect of silt content on cyclic strengths of clean sands have been reported by Chang et al. (1982) and Kuerbis et al., 1988).

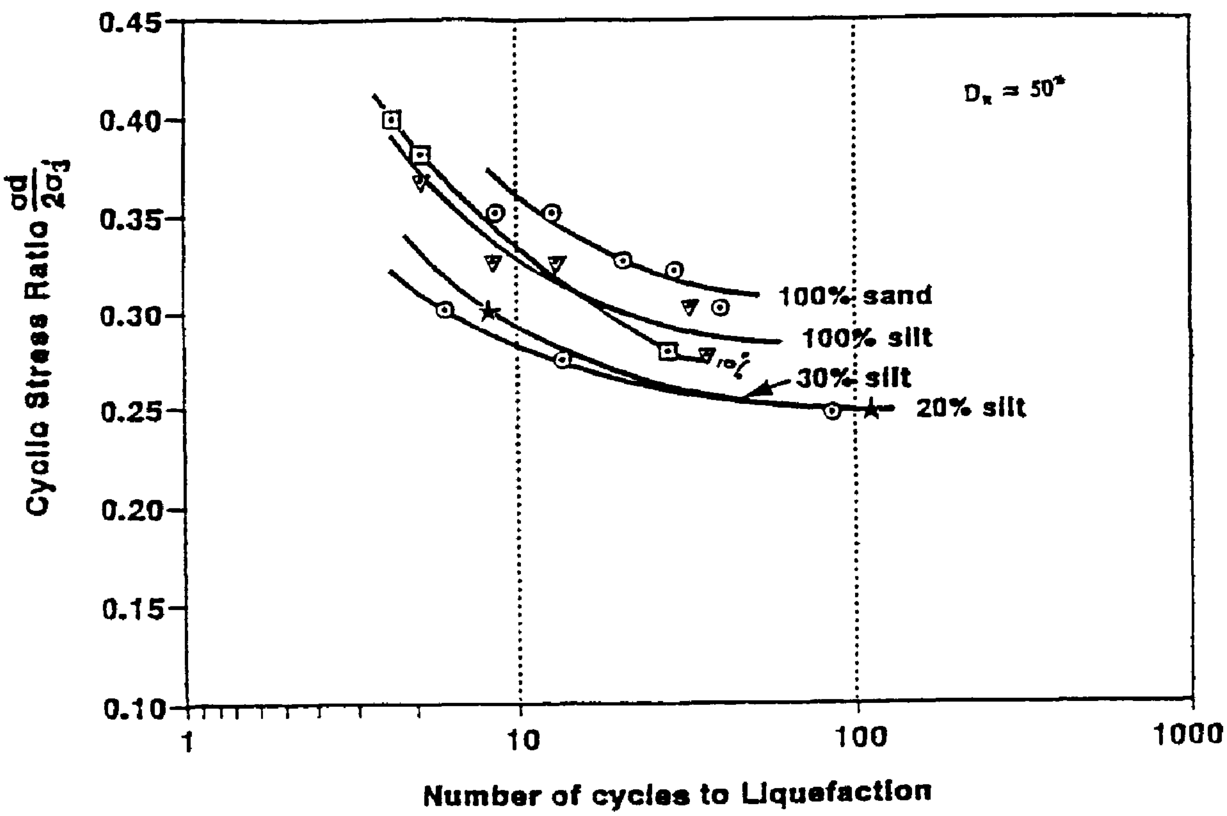

Fig. 2. Relationship Between Cyclic Stress Ratio and Number of Cycles to Initial Liquefaction for Reconstituted Samples of Sand, Silty Sand and Silt (from Singh, 1994)

Chang et al. used void ratio as the basis for comparison and tested silty sand samples at the same void ratio as the 100 percent sand samples, and concluded that the cyclic resistance increases as the silt content increases; that the increase is slight, up to 10% silt content, and begins to develop more as the silt content increases to 30 % silt. Chang et al. explains this behavior in terms of sand grain to sand grain contact in the soil structure. But it appears to be due to the increase in relative density as the more silt is added and the samples are prepared at the same void ratio

Studies by Kuerbis et al. (1988) suggest that the higher the silt content, the lower the cyclic resistance for given relative density. Studies reported herein indicate similar results (Figure 2). Kuerbis et al. also reported that over the range of overlapping void ratios of various silty sands, the cyclic resistance at a given void ratio decreases with increase in silt content. Kuerbis et al. used the concept of sand-skeleton void ratio to explain the results and concluded that the rather small change in behavior with increasing silt can be explained by the fact that the sand skeleton void ratio remains virtually unaltered with the addition of silt. Silt merely acts as a filler of sand skeleton voids and hence behaves as an inert component (up to about 20% of silt). Tokimatsu and Yoshimi (1984) and Seed et al. (1985) suggested on the basis of field performance of sandy soils with fines that soils containing more than 20% clay (finer than 5μm) would hardly liquefy unless their plasticity indexes are low.

From the foregoing, it appears that it is not easy to clarify the influence of fines on the behavior of sands under cyclic loading, and that the liquefaction characteristics of silts may not be estimated on the basis of criteria currently used for sands. In an attempt to explain the behavior in terms of void ratio, **Figure 3** was prepared; and it appears that whereas, void ratio may be the

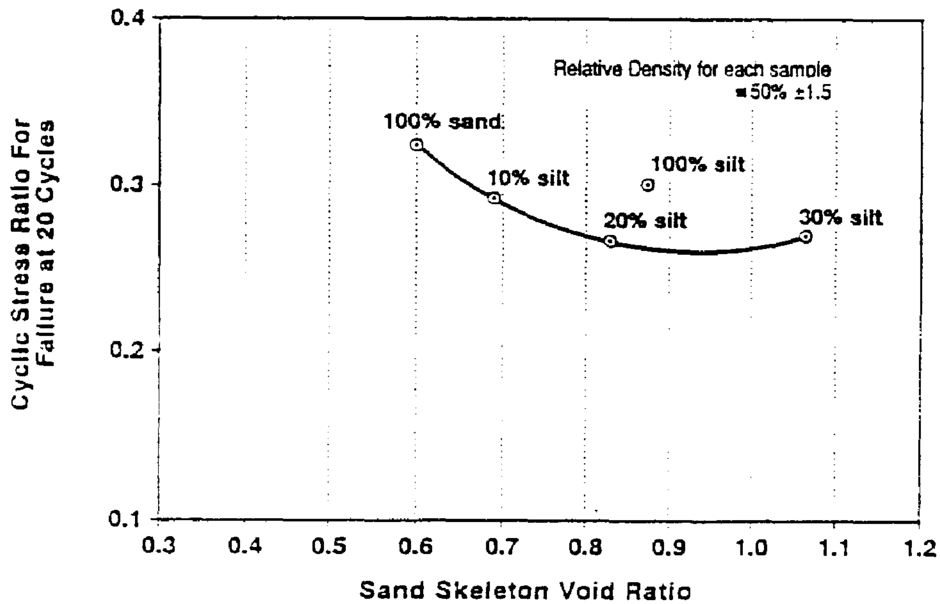

Fig. 3. Relationship between Cyclic Stress Ratio and Sand Skelton Void Ratio (from Singh, 1994)

better index than relative density, to explain the influence of fines on sand behavior, the interpretation in terms of void ratio alone beyond a percentage of fines of 60% (**Figure 4**) need further studies and should be made with caution. As also pointed out by Chang, et al. (1982), it appears that when the silt content reaches 60 percent or more, the soil fabric becomes one of sand grains embedded in silt with practically no sand grain to sand grain contact, so the specimen behavior is totally determined by the silty fines. conversely, it may be suggested that a silt sample containing about 30 percent or more of sand content will have its pore pressure generation characteristics approaching that of sand. However, additional data is needed to draw definitive conclusions on this aspect.

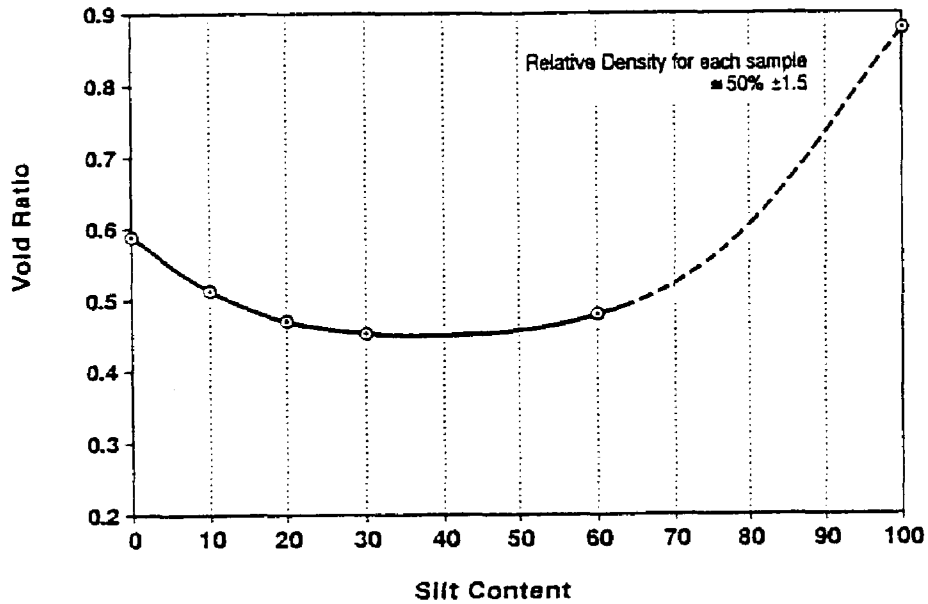

Fig. 4. Effect of Silt Content on the Void Ratios of Samples Prepared at 50% Relative Density (from Singh, 1994)

Conclusions

On the basis of the studies reported herein, the following conclusions may be drawn:

1. There is a difference in the strain developments and the pore pressure generation characteristics of undisturbed and laboratory prepared samples of silts tested under cyclic triaxial loading conditions.

2. There is a problem in establishing criteria for liquefaction of undisturbed silts in terms of joint consideration of pore pressure and deformation.

3. For a given relative density, sands containing 10, 20 or 30% of silt by weight have lesser resistance to liquefaction than pure sands. The loss of resistance appears to be consistent when results are compared in terms of void ratio, thus implying that void ratio may be a better index to use for silty fine sands and silts.

4. One hundred percent silt samples tested at the same relative density as the 10, 20, and 30% silt in sand showed higher strengths, but not higher than pure sands.

Acknowledgements

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