VOLUME CHANGE OF SAND DEPOSITS SUBJECTED TO CYCLIC SHEAR

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SUMMARY

Resonant column test data are presented which establish a correlation between excess porewater pressures induced by cyclic strain and volume change. The data are in good agreement with previous work. A method is proposed by which the cyclic strain approach could be used to predict seismically-induced settlements.

INTRODUCTION

When loose to medium sands are subjected to cyclic shear stresses of sufficient magnitude, they will experience a compressive volumetric strain. When these sands are saturated, this volumetric strain will cause the development of excess porewater pressures which may lead to liquefaction or cyclic mobility. In undrained laboratory tests of saturated samples, this excess porewater pressure is a sensitive measure by which minute volume changes can be detected. These volume changes can be measured by releasing the excess porewater pressure (reconsolidating) and measuring the volume of porewater displaced. This measurement provides an accurate indication of volume change and does not need to be corrected for membrane penetration effects (Ref. 1).

Dobry et al., 1982, (Ref. 2), observed in cyclic triaxial shear tests, using up to 300 loading cycles, that there is a threshold cyclic shear strain amplitude of approximately $1.2 \times 10^{-2}\%$ below which no excess porewater pressure develops, and thus no volume change occurs. The authors (Ref. 3) conducted resonant column tests on saturated sand samples in the compressive and torsional mode and observed that for test samples which have not been previously shaken the threshold cyclic shear strain amplitude is approximately $1.5 \times 10^{-3}\%$, and that between the shear strain amplitudes of $1.5 \times 10^{-3}\%$ and $1.2 \times 10^{-2}\%$ cyclic strain hardening occurs when the specimen is pre-shaken. The latter tests used many strain cycles (approximately 10^4) at frequencies of approximately 100 Hz. For pre-shaken specimens, the threshold strain observed generally tended to increase to the level of the pre-shaking strain; however, in no instance did the threshold strain for fully saturated samples exceed the strain of $1.2 \times 10^{-2}\%$, which in Ref. 2 was identified as the

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strain below which gross displacement between particles is frictionally blocked.

The implication of the above discussed findings is that in pre-shaken deposits no volume change is likely to occur at cyclic strain amplitudes below $1.2 \times 10^{-2}\%$. However, in virgin deposits which were not pre-shaken, settlements could conceivably occur at lower cyclic shear strains. Most soils in earthquake areas experienced pre-shaking during their geologic history. However, recent alluvial deposits and uncompacted fill may not have experienced pre-shaking, and some deposits may be subject to cyclic strains which exceed their previous pre-shaking level, and thus experience some porewater pressure buildup below the threshold strain amplitude of $1.2 \times 10^{-2}\%$. The objective of this paper is to present data on the volume change associated with the porewater pressure buildup observed in resonant column tests conducted by the authors, and to show how the cyclic strain approach could be used to predict seismically-induced settlements.

CORRELATION BETWEEN VOLUME CHANGE AND EXCESS POREWATER PRESSURE

In the test series presented in Ref. 3, excess porewater pressure buildup was observed for different cyclic shear strain amplitudes, and the samples were only reconsolidated after completion of the test, which frequently resulted in initial liquefaction. The procedure did not produce much data on volume change associated with cyclic shear stresses which do not induce liquefaction. To produce such data, the authors conducted three torsional resonant column tests on hollow cylindrical specimens (refer to Ref. 2 for procedures and material used). The specimens were prepared to 60% relative density and tested under a 96 kPa confining pressure. As noted in Ref. 3, full saturation is difficult to achieve in the resonant column test. The degree of saturation achieved, as measured by the B parameter, is tabulated hereafter.

Specimen M-4	$B = 0.93$
Specimen M-5	$B = 0.90$
Specimen M-8	$B = 0.98$

The correlation between the volumetric strain, as measured by porewater displacement, and the excess porewater pressure developed is shown in Fig. 1, where:

Δu = excess porewater pressure;

σ_3' = initial confining pressure;

ϵ_v = volumetric strain;

ΔV = volume change; and

V_C = initial volume of sample after confining pressure is applied.

Note that the data vary within a narrow range. In the same figure, data from Lee and Albaisa (Ref. 1) are plotted, which are for the same type of sand (Monterey No. 0) prepared to 50% relative density and subjected to 104 kPa confining pressure. The Lee and Albaisa data were normalized to the relative density of 60% and the confining pressure of 96 kPa using the data in Ref. 1, which presents test results on the effect of confining pressure and density on volume change. Good agreement can be seen between the data in this paper and the data in Ref. 1, even though the data in Ref. 1 show a slightly smaller volumetric strain.

While the degree of saturation (within the range of the data) did not substantially affect the measured volume change, it did have a considerable effect on the cyclic strain amplitude at which the excess porewater pressure could be "stablized" (did not increase with additional strain cycles) for a certain excess porewater pressure ratio. This is shown in the following table for the case of $\Delta u/\sigma'_3 = 0.2$. (This pore pressure ratio was chosen because at higher ratios $\Delta u/\sigma'_2$ was difficult to stabilize with the test method used.)

Specimen	B	Shear Strain Amplitude
M-5	0.90	$1.9 \times 10^{-2}\%$
M-4	0.93	$1.5 \times 10^{-2}\%$
M-8	0.98	$8.8 \times 10^{-3}\%$

The reason specimens M-4 and M-5 did not liquefy, even though they were excited with a large number of cycles above the threshold strain of $1.2 \times 10^{-2}\%$, is that part of the volume change could occur without increasing the excess porewater pressure. It has been shown in Ref. 3 that saturated specimens ($B \geq 0.97$) could not be subjected to a very large number of cycles of shear strain above $1.2 \times 10^{-2}\%$ without inducing initial liquefaction.

PREDICTION OF SETTLEMENT INDUCED BY CYCLIC STRAIN

It has been shown by the data presented in Fig. 1 and in Ref. 1, that the volume change associated with a given excess porewater pressure level can be reasonably predicted. It has also been shown (Ref. 2 and Ref 3) that a unique correlation can be established between cyclic strain and excess porewater pressure which applies to a wide range of sands. As an alternate to the approach presented in Ref. 1, it will be possible to combine these two elements of information to predict seismically-induced settlements below the level of initial liquefaction [it has been shown by Lee and Albaisa (Ref. 1) that if initial liquefaction occurs, the volume change is much larger than that shown in Fig. 1]. First, the correlation between cyclic strain and excess porewater pressure, as established by strain-controlled cyclic triaxial tests (Ref. 2), must be corrected for membrane penetration effects. This could be accomplished by measuring the cyclic component of $\Delta u/\sigma'_3$ and calculating the ratio between the measured and the theoretical cyclic component which should be 1/3 $(\sigma_1' - \sigma_3')$, and correcting accordingly (in Ref. 2, it is shown that this correlation is consistent up to $\Delta u/\sigma_3' = 0.2$) or by methods discussed in Ref. 4. Second, an equivalency will have to be established between cyclic strain and earthquakes of given magnitudes (similar to that established for cyclic stress). The cyclic strain at any given depth can then be calculated from information on the peak surface acceleration and G_{max} as shown in equation 3.5, Ref. 2, pg. 117, and the excess porewater pressure, and thus the incremented settlement for the given depth can be predicted on the basis of the estimated Δu which corresponds to the calculated cyclic strain. The advantage of using this procedure would be that G_{max}, which is a soil property measurable in the field, is used as a key parameter.

CONCLUSION

Data are presented on the correlation between excess porewater pressure buildup, volume change, and cyclic strain. The data are in good agreement with data presented in Ref. 1, which were obtained by different methods. It can be shown that the volume change can be reasonably predicted. An approach is recommended by which the correlations between cyclic strain and excess porewater pressure, and between excess porewater pressure and volume change, could be used to predict seismically-induced settlement. The approach has the advantage of using G_{max}, which can be measured in-situ, as a key parameter. Further studies will be needed to correct the data presented in Ref. 2 for membrane penetration effects and to establish a correlation between seismic events and numbers of equal cycles of shear strain.

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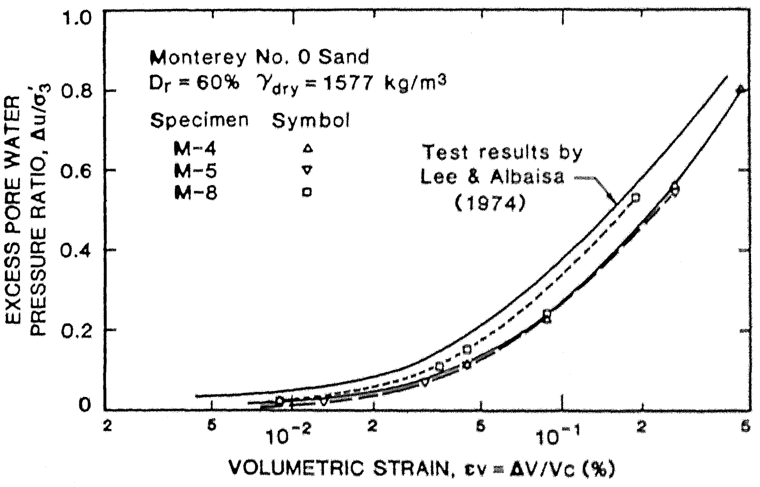

FIG. 1: Excess porewater pressure ratio vs. volumetric strain