4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1226

LIQUEFACTION TESTING OF FINE-GRAINED SOIL PREPARED USING SLURRY DEPOSITION

Jennifer DONAHUE[1], Jon BRAY[2], and Michael RIEMER[3]

ABSTRACT

An experimental research program has been undertaken to assess the cyclic response of soils with significant fines (both plastic and non-plastic). Advanced cyclic testing of low plasticity silty and clayey soils is required to characterize the liquefaction susceptibility of fine-grained soils, to evaluate their liquefaction resistance, and to gain insight regarding their post-liquefaction response (i.e., volumetric strain and residual strength). Fine-grained soils from Adapazari, Turkey are being reconstituted and systemically tested so that the significant characteristics, or combination of characteristics, that primarily control their liquefaction susceptibility and cyclic response can be identified. Replicate testing required development of a modified version of the slurry deposition method for specimen preparation. The proposed method is presented and preliminary results from cyclic simple shear testing on reconstituted test specimens of Adapazari silts and clays of low plasticity are presented. Some results from comparable cyclic triaxial testing are also presented. This is part of an ongoing study to develop a database of experimental results upon which to characterize silty soils and to build robust soil constitutive models for advanced dynamic analysis.

Keywords: Liquefaction, Silts, Slurry Deposition, Reconstitution, Fine-grained soils

INTRODUCTION

The strong shaking produced by the 1999 Kocaeli earthquake (M_w = 7.4) caused widespread damage throughout the northwest region of Turkey. Hundreds of structures in Adapazari were severely damaged as evidenced by building settlement, sliding, and tilting. The materials underlying the buildings that experienced ground failure were found to be primarily fine-grained soils (Bray et a1. 2004b). The use of state-of-the-art methods for screening and identification of potentially liquefiable soils (as defined by the recent consensus paper by Youd et al. 2001) in Adapazari did not commonly identify the problematic soils because of deficiencies in the widely used "Chinese criteria" for fine-grained soils (Bray et al. 2004a).

Recent studies by Bray and Sancio (2006) and Boulanger and Idriss (2006) have developed alternative criteria for identifying soils susceptible to liquefaction. Based primarily on cyclic testing of "undisturbed" specimens of Adapazari silts and clays, Bray and Sancio (2006) found that soils with Plasticity Index (PI) < 12 and with water content to liquid limit ratios (w_c/LL) > 0.85 were susceptible to liquefaction as evidenced by a dramatic loss of strength resulting from increased pore-water pressure and reduced effective stress. Liquefaction of fine-grained soils is typically manifested as cyclic mobility with limited flow deformation resulting from a transient loss of shear resistance due to the development of excess water pressures. Boulanger and Idriss (2006) use PI < 7 to identify soils exhibiting "sand-like" behavior that are susceptible to liquefaction and PI ≥ 7 to identify soils exhibiting "clay-like" behavior that are judged to not be susceptible to liquefaction. Clay-like soils

[1] Ph.D. Candidate, Dept. of Civil and Environ. Engineering, Univ. of California, Berkeley, CA, jdonahue@ce.berkeley.edu
[2] Professor, Dept. of Civil and Environ. Engineering, Univ. of California, Berkeley, CA, bray@ce.berkeley.edu
[3] Associate Adjunct Professor, Dept. of Civil and Environ. Engineering, Univ. of California, Berkeley, CA, riemer@ce.berkeley.edu

may soften due to the loss of effective stress resulting from the build-up of positive excess pore pressures, but the term liquefaction is reserved for sand-like soils. Thus, different definitions of liquefaction are, in part, leading to slightly different liquefaction susceptibility criteria. However, both research groups make it clear that fine-grained soils can undergo severe strength loss due to increased pore-water pressures that reduce the effective stress in the soil temporarily.

In this study, a reliable specimen preparation method is required for replicate testing of silty soil specimens of varying characteristics (e.g., different PI, void ratio (e), and overconsolidation ratio (OCR), among other factors). After presenting a modified version of the Slurry Deposition Method (SDM), preliminary results from a series of cyclic simple shear (CSS) and cyclic triaxial (CTX) tests are presented and discussed.

MATERIAL TESTED

Over 402 individual samples were returned from Adapazari, Turkey following comprehensive site investigations by Bray et al. (2004a). Using information such as the plasticity index (PI), water content (w_c), liquid limit (LL), fines content (FC, i.e., amount by weight smaller than 75 μm), amount finer than 5 μm, and amount finer than 2 μm, the soils were combined into seven batches. It was decided that the baseline material for the research, or soil "G", would have a fines content (amount finer than 75 μm) of 80% and a PI of 10, which is representative of many of the fine-grained soils that exhibited liquefaction in Adapazari during the 1999 Kocaeli earthquake. The gradation of the seven soils used is shown in Figure 1, and the corresponding parameters derived from index testing are summarized in Table 1.

To better understand the Adapazari soils, representative soils were analyzed by X-Ray Diffraction and examined using a scanning electron microscope (Willamette Report, 2005). The soil samples were taken from different locations and different depths. The parent material appears to have moderate amounts of plagioclase, hornblende or amphibole, K-feldspar, quartz, calcite, and a mix of dolomite and ferroan dolomite (possibly as ferroan or as ankerite). The representative soils appear to be genetically related, stemming from similar parent materials. The clay mineral assemblage includes smectite (or highly expandable, randomly interstratified illite/smectite, 80-90% expandable layers), chlorite (intermediate Fe-Mg composition), illite (muscovite in the coarser fractions), and kaolinite (increasing disorder with decreasing particle size). Smectite is the dominant component of the finest clay fraction, but illite is the most abundant clay in the coarser clays. Materials analyzed in the 2 to 15 µm range are primarily composed of illite, calcite, and quartz, in order of decreasing proportion. This combination accounts for 65 to 70% of the total composition in each specimen. Magnesium-rich chlorite, plagioclase, and a smectite/illite combination round out the remaining significant minerals. Figure 2 provides representative Scan Electron Microscope photographs of the material used in this study. These photos illustrate the diverse nature of the materials present in these fine-grained soils.

Table 1. Index Parameters for Soils A through G

Soil Nomenclature	Plasticity Index	Liquid Limit	Plastic Limit	% of Particles < 0.075 mm	% of Particles < 0.002 mm	Unified Soil Classification
A	2	31	29	72%	5%	ML
B	5	32	27	77%	10%	ML
C	5	32	27	88%	14%	ML
D	11	38	27	94%	12%	ML
E	14	39	25	95%	16%	CL
F	7	28	21	57%	8%	CL-ML
G	10	31	21	77%	15%	CL

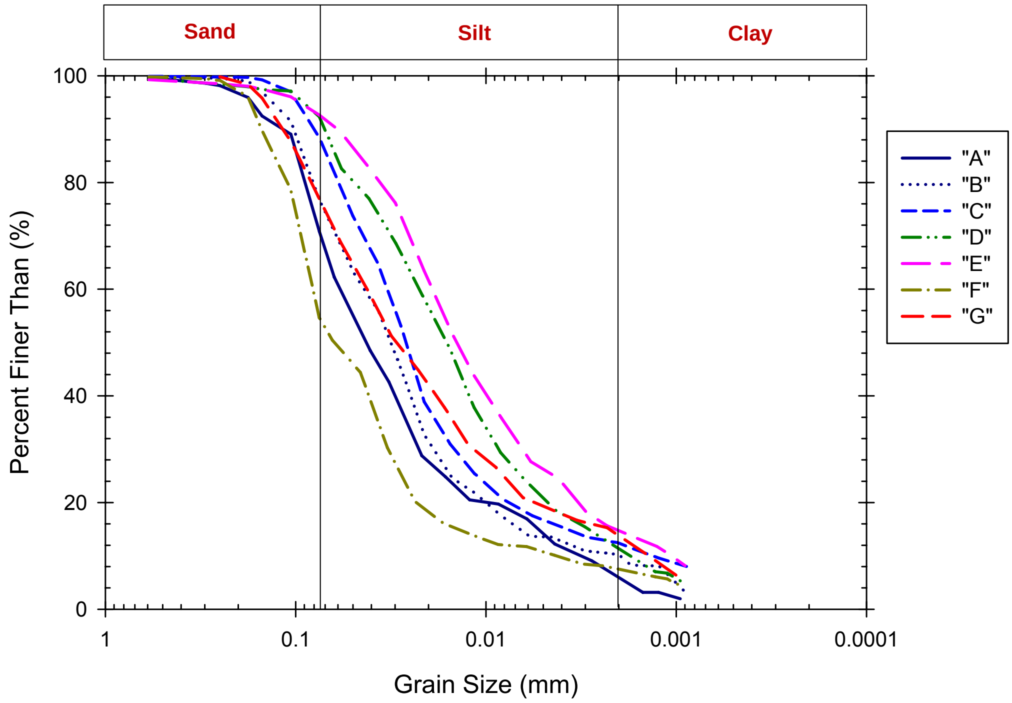

Figure 1. Gradation Information for Seven Soils used in Liquefaction Analysis.

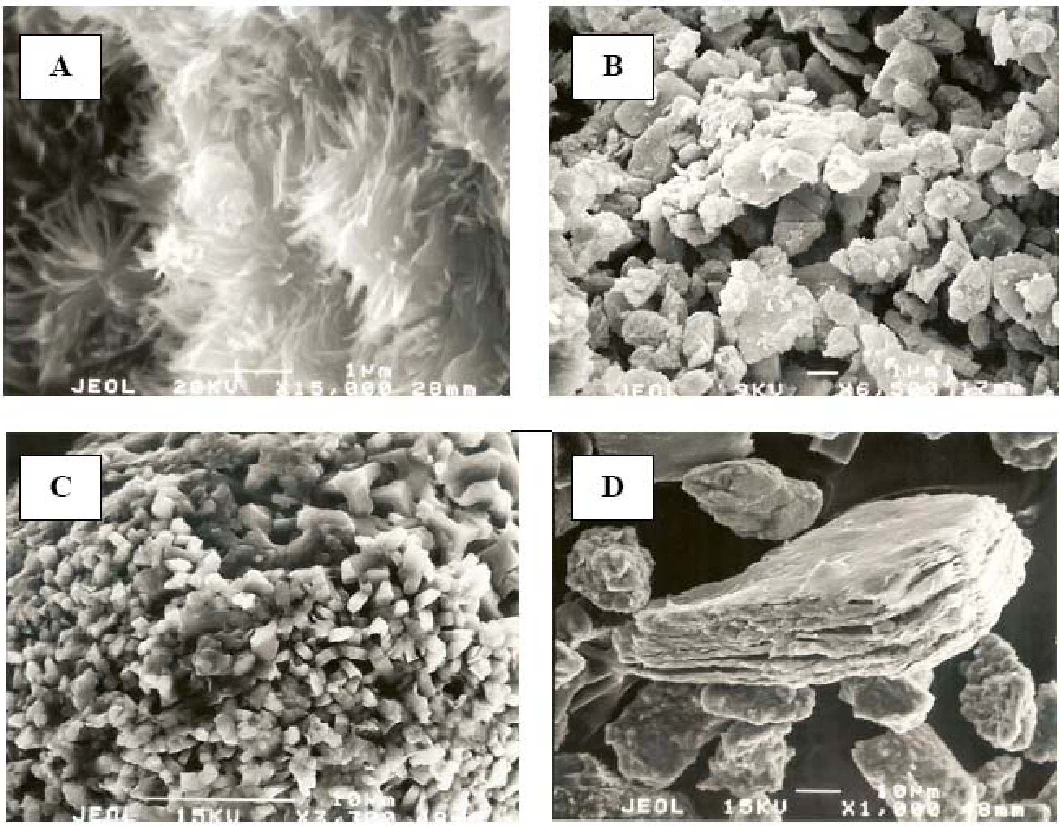

Figure 2. Representative Photos. a) 1(minus) micron: illite at 15,000x zoom from 28 mm, b) 2(minus) micron: landscape of silt structure at 6,500x zoom from 17 mm, c) 20 (minus) micron: close-up of colony element at 3,300x zoom from 48 mm, c) 20 (minus) micron: platy material at 1,000x zoom from 48 mm

SPECIMEN PREPARATION

Methods of Soil Reconstitution

The primary purpose of this testing program is to use uniformly reconstituted specimens that may be tested in a systematic and controlled manner to minimize the significant inherent variability of naturally deposited soils, so that specific factors can be isolated and evaluated.

Soils "A" through "G" are currently being tested at different void ratios, cyclic stress ratios (CSRs), water content to liquid limit ratios, and effective confining pressures. Comparison of these different soils, which are all tested in the same manner, will provide critical insight into the factors that primarily affect the cyclic resistance of silty soils.

As such, the decision on the type of specimen preparation method was one of the major challenges to this program of research. Several methods of reconstitution were considered:

- Moist Tamping
- Wet Pluviation
- Dry Pluviation
- Slurry Deposition Method
- In-Place Wet Pluviation

Moist tamping was discarded, because it does not produce specimens that are representative of a natural deposition process. It is also known that specimens prepared in this method can exhibit sharply defined boundaries between layers. Traditional Wet Pluviation consists of pouring a thin slurry of material into a large tub of water in order to allow a natural sedimentation from the suspension. The material is then consolidated, cored and tested. However, this method was ruled out due to the lack of large quantities of the available silt and the long time required to prepare specimens. However, it should be noted that the Wet Pluviation method forms the soil fabric most like that formed in situ by natural fluvial depositional processes. Dry Pluviation was likewise ruled out because the soils of Adapazari are deposited in a fluvial environment.

Of the methods listed above, only the latter two proved to be useful in this testing program. The Slurry Deposition (SD) method will be explained in detail in the following sections. Because large quantities of Soil "G" and other representative batches are not available, an In-Place Wet Pluviation (IPWP) method was also developed. Here, the silt slurry is poured through a column of water directly into the simple shear mold, and allowed to settle naturally, in a sequence of multiple layers, or lifts. This second method is similar to wet pluviation and is intended to produce higher void ratio's, lower densities, and a higher water content to liquid limit ratio (wc/LL), which would better represent the in situ state of the soils of Adapazari.

Each method has its own advantages and disadvantages. Although SD is a viable method that will produce repeatable, uniform reconstituted specimens designed to isolate specific factors that influence liquefaction, it is not representative of a natural process. Conversely, the IPWP method produces specimens that are no longer homogeneous, and it can be argued that the weakest elements within the specimen may control the response. However, the soil fabric of the specimen is more realistic and representative. Results of cyclic tests using the IPWP specimen preparation method will be published in the future as this procedure was just recently developed.

Testing Criteria

Almost as important as clarifying which characteristics control liquefaction is the actual definition of what liquefaction is, and when it occurs. A clear definition is required to compare results across different studies. Historically, varying levels of both stress and strain have been used as part of the definition.

Traditionally, in the laboratory, liquefaction has been defined as the point at which the pore-water pressure has increased to a level that (nearly) equals the initial total confining stress (i.e., the pore pressure ratio, $r_u = \Delta u/\sigma_{co} \approx 1.0$, which means there is zero effective stress). Alternatively, because the point of $r_u \approx 1.0$ is often difficult to discern precisely and may not be reached in all cases, 3% single amplitude strain (typically in extension), or 5% double amplitude (DA) axial strain is commonly used for cyclic triaxial testing. For cyclic simple shear testing, Wijewickreme and Sanin (2004) define liquefaction as the occurrence of single-amplitude horizontal shear strain of 3.75%. Others researchers (e.g., Bray and Sancio 2006, Kammerer 2002, and Wu 2002) use 5% horizontal shear strain for interpreting cyclic simple shear tests. Previous research has also indicated that effective stress = 20% or r_u=80% is sufficient to cause significant shear strains leading to deformation (e.g., Boulanger 1998).

For the following experiments, the traditional 3% single amplitude axial strain, or 5% double amplitude strain will be used as the initiation of liquefaction for CTX testing. For CSS testing, 5% single amplitude shear strain will be used as the definition of the onset of liquefaction. Though not a proxy for liquefaction, the less traditional r_u=80% was also used only for a stress-based comparison between the different specimens in cyclic simple shear. When tested, the soils rarely reached an effective stress of zero, but rather stabilized at effective stresses that were approximately 20% of their original levels.

Slurry Deposition Method

To date, most specimen reconstitution for liquefaction has been performed on sands and silty sands. The specimen preparation method described by Kuerbis and Vaid (1988) has been the primary means for silty sands. Their method uses a thick slurry and has been proven to produce uniform, non-segregated specimens of silty-sand soils. One of the features of the method entails mixing the material with de-aired water directly within the mold. With a sandy material, the mold is vigorously rotated until the slurry is thoroughly mixed, thereby ensuring a homogenous material.

When this method is applied to a silty material, the formation of a homogeneous specimen is unattainable. The problem becomes apparent during the mixing phase. As a thick slurry, the silt does not blend properly because water and fine particles are prohibited from movement due to the reduced hydraulic conductivity. In order to achieve a homogenous specimen during the mixing phase of this method, the slurry would need to include substantially more water. This goes against the concept of the method since the thinner slurry would begin to settle out of suspension due to gravitational processes as soon as the mixing is completed.

Zdravkovic (1996) developed a method of reconstituting silts in the form of a thick slurry for use in a cyclic torsional shear device. The basic premise of this method was adopted and modified for the development of specimens for the cyclic triaxial and cyclic simple shear devices. The proposed method is not described in its entirety, but the highlights for the development of cyclic triaxial specimens are described below.

The material begins at a state of 12% water content. This water content is sufficient to hold fines in place and decrease segregation through gravitational processes. De-aired water is added to bring the material up to a water content of approximately 45%. At this water content, the material has become a slurry for optimum mixing and workability. The vacuum triaxial mold is assembled and the material placed inside the mold. A vacuum of approximately 13 kPa is applied through a vacuum chamber attached to the top and bottom of the specimen. An additional 6 kg of load, equivalent to 10 kPa of deviatoric stress, is applied vertically to the top of the specimen.

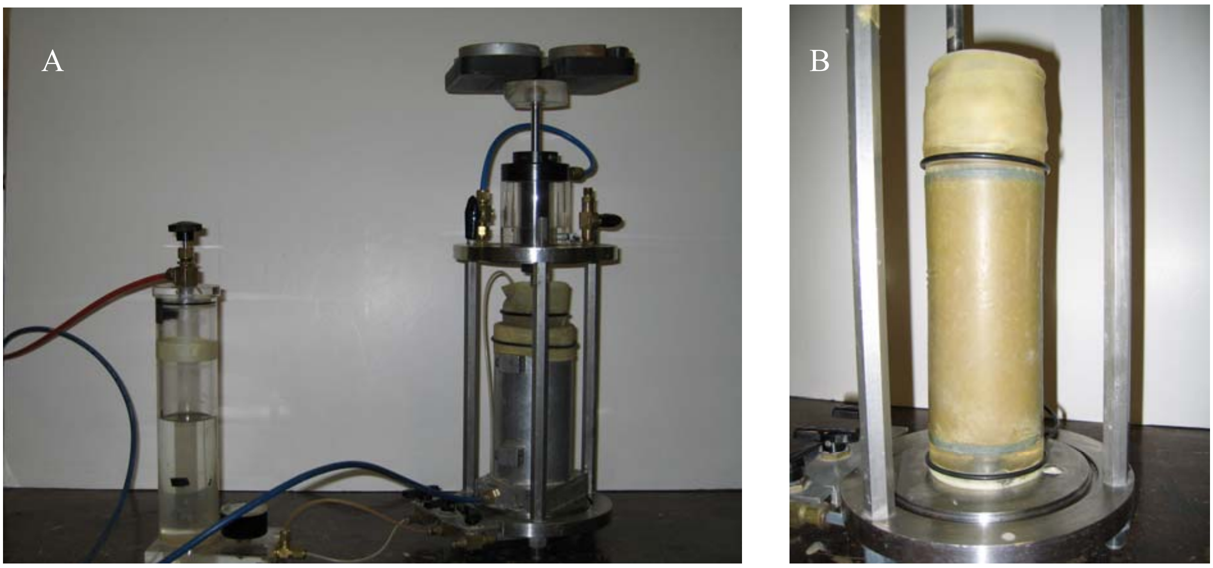

Figure 3. Photo of Specimen Preparation. A) Specimen inside vacuum mold consolidating from a slurry. Specimen is also attached to vacuum chamber delivering 0.13 atm vacuum at top and bottom with 6 kg load. B) Specimen once vacuum mold has been removed.

Using this load combination and letting the specimen consolidate for two days yields a specimen able to stand freely under its own weight (Figure 3B). The specimen may then be transferred to the cyclic triaxial device for saturation and consolidation to either a K_o or isotropic stress state for testing. The low stresses applied by the vacuum chamber and vertical load are subsequently superseded during consolidation.

To ensure that this method was viable, it was important to confirm that it could create repeatable, homogenous specimens. For this evaluation, a specimen was prepared, consolidated, and subjected to water content and gradation analysis. Additional soil still in slurry form was used as a control batch. Gradation results from hydrometer and sieve analysis for the specimen, which was divided into a top, middle, and bottom portions are given in Figure 4. Water contents from six places within the specimen yielded an average of 28.1 with a standard deviation of only 0.11. Given these results, it is evident that the 7.1 cm diameter, 13 cm height specimen is relatively homogenous throughout.

Because void ratio is often a critical criterion in liquefaction assessment, specimens were prepared using the SD method and subjected to Constant Rate of Strain Consolidation. Representative results are shown in Figure 5. Interestingly, Soil "A" has a higher initial void ratio in comparison to Soil "G". The soil particles of Soil "A" could form into a looser state initially due to particle gradation and shape, and this requires additional investigation.

One of the strengths of the SD method is the reproducibility of specimen characteristics. To test this concept, multiple Constant Rate of Strain Consolidation tests were performed on the Soil "G". Results showed the same void ratio at a given level of stress for each test. This "intrinsic" void ratio curve is unique for each of the soils tested prepared using the SD method. One drawback is that the void ratios at a given stress level are lower than in naturally occurring Adapazari silts.

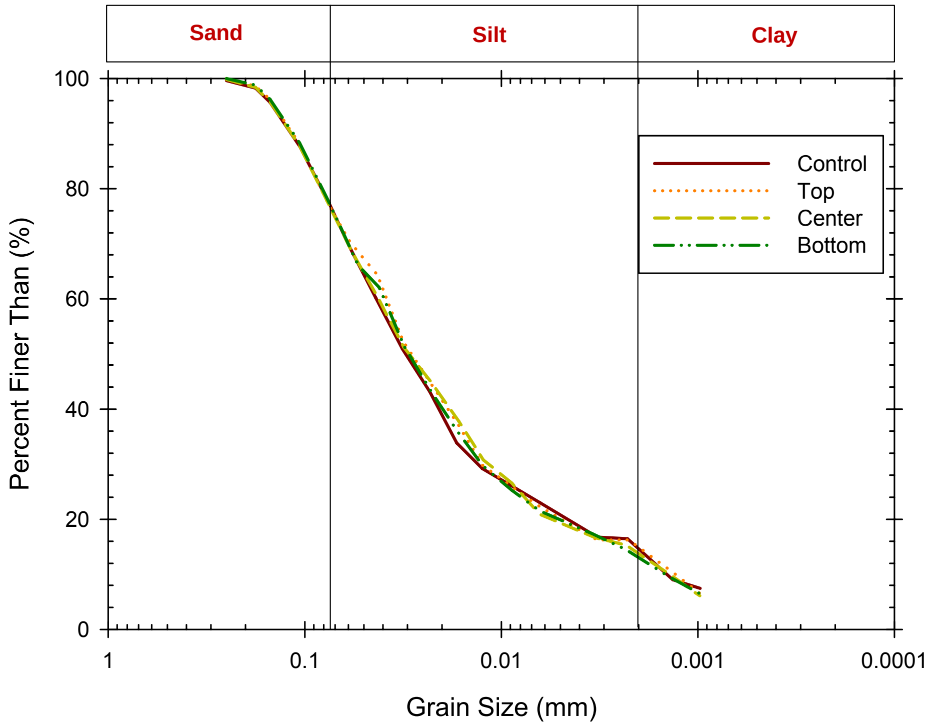

Figure 4. Gradation and Sieve Analysis on Control Portion and Three Regions within an Initially Consolidated Specimen of Soil "G"

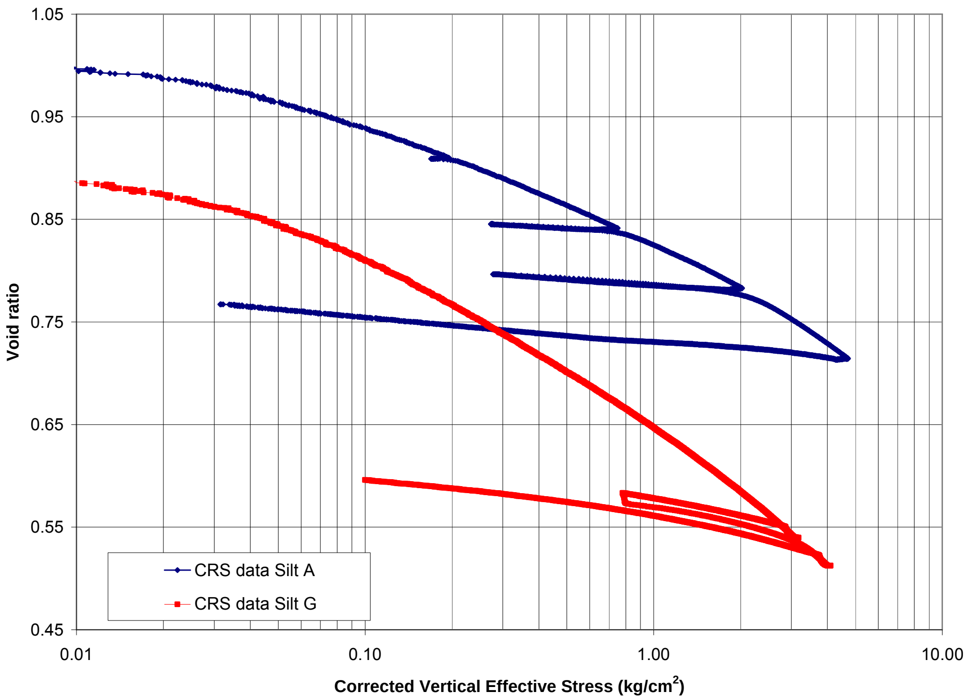

Figure 5. Representative Results from Constant Rate of Strain Consolidation. Soil "A" and Soil "G" are compared, e_o for "A" Soil is 1.01, e_o for "G" is 0.92

CYCLIC SIMPLE SHEAR TESTING

All cyclic simple shear test specimens were prepared using the modified Slurry Deposition method described previously, but adapted to a simple shear mold. Each specimen was encased in a 10 cm diameter wire reinforced membrane with moderate wire stiffness, c=1.0. Using differential vacuum and backpressure saturation, all specimens achieved a B-Value of at least 0.97. The testing system used for this study is the upgraded U.C. Berkeley Bi-directional cyclic simple shear apparatus (Kammerer 2002).

All specimens were initially consolidated to a vertical effective stress (σ'_v) of 137 kPa with no applied static shear stress (i.e., τ = 0, level-ground) prior to commencement of constant load cyclic shear loading. A vertical effective stress of 137 kPa was used in order to approximate a mean effective stress (σ'_m) of 100 kPa. In "constant load" testing, the vertical load is kept constant while a saturated sample is sheared undrained. This use of undrained testing with a wire-reinforced membrane and constant vertical load provides reasonably good compliance with the desired boundary conditions, i.e. maintaining zero radial strain, constant volume, and constant overburden stress.

One of the recognized shortcomings of simple shear testing relates to the lack of imposed complementary shear stresses. Previous research by Frank et. al. (1979) tested samples with diameter to height (D/H) ratios between 3.75 and 7.5 and found no difference in the resulting loading resistance. Numerical studies also suggest that in samples with D/H rations greater than 4, the lack of complementary shear stresses influenced a relatively small portion of the sample. The D/H for the specimens used in this study was approximately 5.

Stress-Strain Response

Testing was performed on all seven batches of the soils at a constant Cyclic Stress Ratio (CSR) of 0.21 and at a frequency of 0.005 Hz. Tests were performed at this low frequency in order to more accurately measure pore pressures. In each case, the first cycle and cycle to reach 5% shear strain for Soils "A" through "F" were compared to Soil "G". Results of these tests are shown in Figure 6. Though each is tested at different void ratios, each of the initial void ratios are intrinsic to that material given the level of stress and the selected specimen preparation method.

It can be noted from Figure 6 that no clear trend can be drawn from comparing only the PI of the material. Soil "B" and Soil "G" exhibit similar "banana" loops upon failure and both fail at 6 or 7 cycles, yet Soil "B" has a PI of 5 and Soil "G" has a PI of 10. The failure cyclic loops of Soil "G" (PI=10) and Soil "D" (PI=11) exhibit very similar banana loops at failure. However, Soil "G" fails at 7 cycles versus 3 cycles to failure for Soil "D". Soils "B" and "C" both have PI = 5, yet the specimens have very different banana loops at failure, and "B" fails at 6 cycles and "C" fails at 3 cycles. Figure 7 demonstrates the distinctive response of each of these soils subjected to cyclic loading. Notice that the responses of the soils within the initial cycles of loading are different. Though the soils exhibit a similar response by the sixth cycle, Soil "B" reaches r_u=80% at a slower rate than Soil "C".

Despite their lower void ratios, specimens reconstituted by the SD method develop large strains relatively quickly. Compared to natural samples of Adapazari silts tested by Sancio (2003) with the same PI and LL, strains in the reconstituted soils developed approximately twice as fast. For instance, one specimen from Sancio's work developed 16% DA strain in 19 cycles. Soil "D", which has the same PI and LL, developed 20% DA strain in only 7 cycles. Time under confinement effects are likely one of the reasons for the observed differences in the response of reconstituted and natural soil specimens, and this is currently being investigated. Also, the large strains that develop at relatively low formation void ratios in the reconstituted soils prepared by SD motivated us to investigate the In-Place Wet Pluviation method. However, the results from the Slurry Deposition method are useful in that they allow for a systematic investigation of the key factors because of their uniformity and lack of segregation.

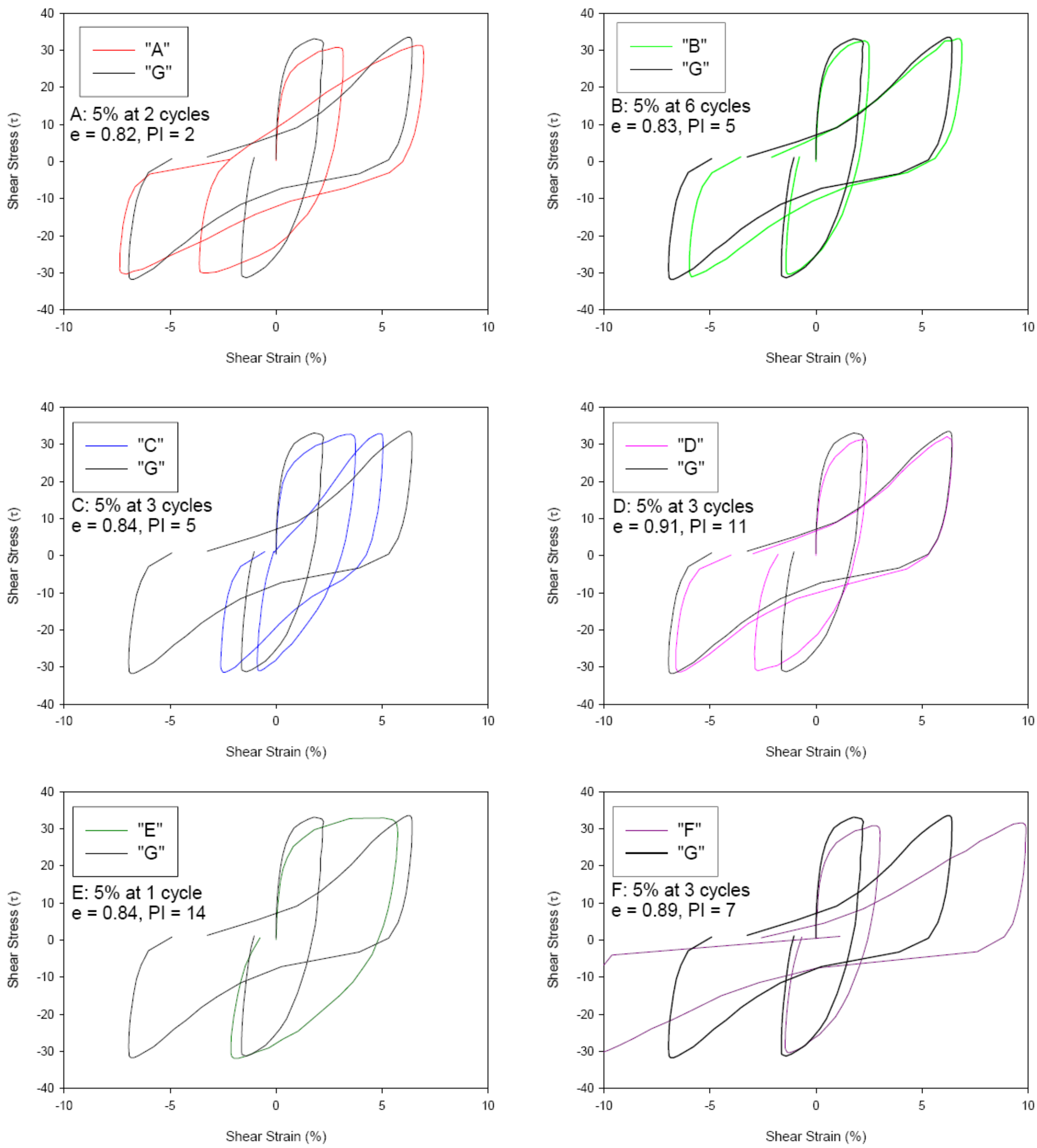

Figure 6. Cyclic Simple Shear Results. First Cycle and Cycle to reach 5% Shear Strain are compared to Soil "G". Soil "G" reaches 5% Shear Strain at 7 cycles, e = 0.68, PI = 10 $\sigma'_v \approx 137$ kPa, CSR = 0.21

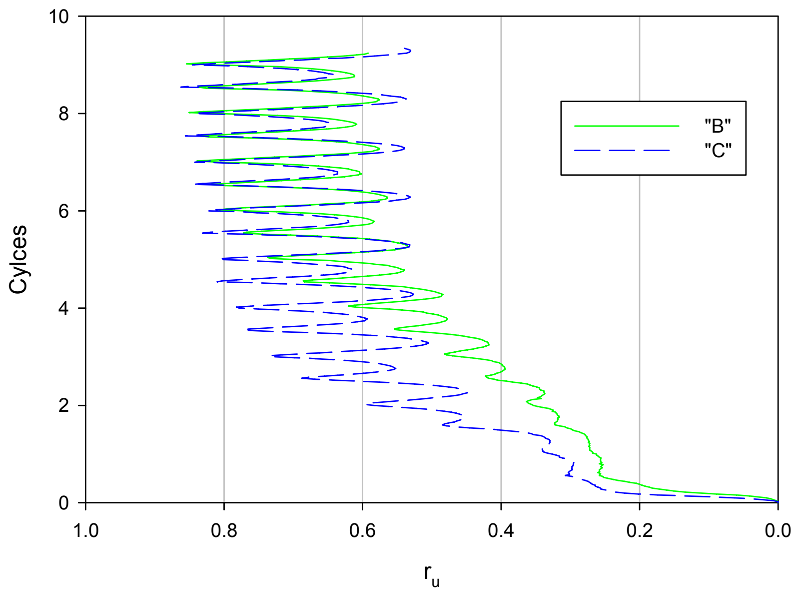

Figure 7. Cyclic Simple Shear Results. Comparison of Soils "B" and "C" during cyclic loading. $\sigma'_m \approx 100$ kPa, CSR = 0.21

As mentioned previously, the onset of liquefaction is defined here based on the shear strain developed during cyclic loading. Figure 8 presents shear strains which develop during the first four cycles of loading for the tests shown previously in Figure 6. The cyclic mobility of each of the soils is clearly shown. By the fourth cycle, most of the soils have already developed substantial pore pressures (r_u>70%), and all have reached or are nearing the 5% single amplitude strain level.

Also of interest is the comparison between Soils “B” and “D” (see Figure 9). Although Soil “D” develops large strains early during the cyclic loading, the rate of growth from cycle to cycle is relatively small. In contrast, Soil “B” exhibits more of a flared shape. By the seventh cycle, Soil “B” mimics the behavior of Soil “D”.

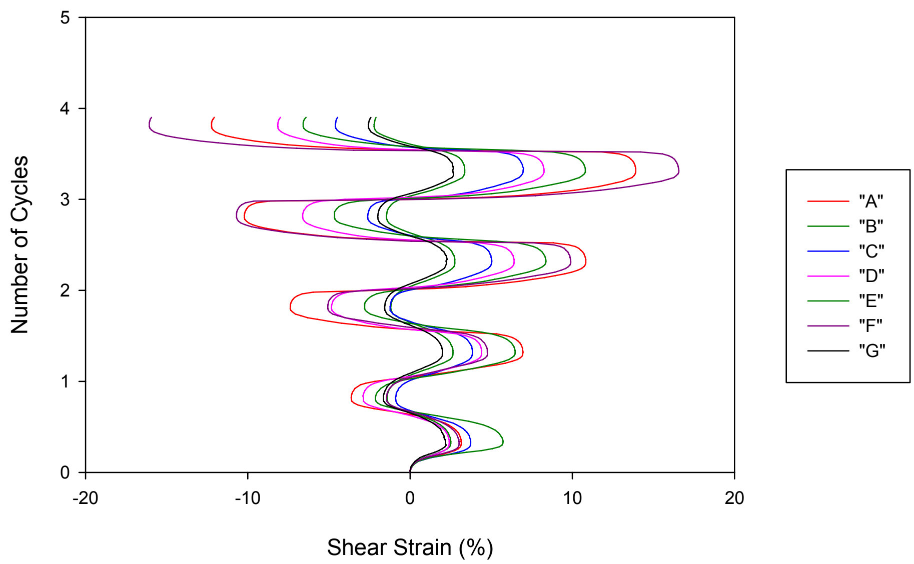

Figure 8. Cyclic Simple Shear Results. Shear Strain for Soils "A" through "G"

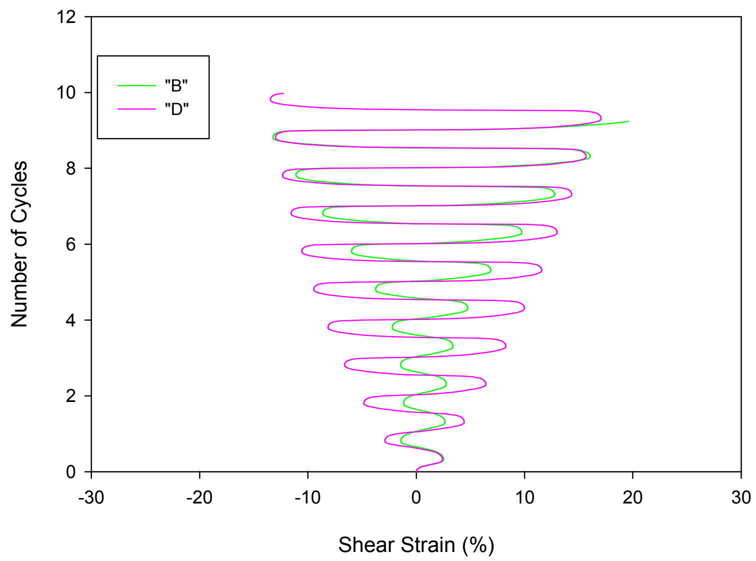

Figure 9. Cyclic Simple Shear Results. Comparison of Soil "B" and "D"

CYCLIC TRIAXIAL TESTING

Four representative tests were performed using the Cyclic Triaxial (CTX) testing device. Samples were prepared using the Slurry Deposition method. After achieving satisfactory B-values of at least 0.97, the specimens were consolidated isotropically to an effective confining stress (σ'_c) of 50 kPa. The four tests used two CSR levels: 0.22 and 0.44, in combination with frequencies of 0.005 and 1 Hz.

At a CSR of 0.22, it was found that the specimens failed at 68 cycles for 1 Hz, but only 5 cycles for 0.005 Hz. This order of magnitude difference between nearly identical specimens with similar void ratios and densities is consistent with the findings of Zergoun and Vaid (1994) and Boulanger et. al. (1998). These researchers also found orders of magnitude of difference between testing at low and high frequencies during CTX testing. An example of the stress-strain curves for high frequency and low frequency testing is shown in Figure 10.

The material exhibits significantly different responses at these two loading frequencies. Notice in Figure 10(B) that relatively little shear strain develops in the early cycles. It is possible that the manner of reconstituting creates a sensitive material which is relatively brittle under sustained loads. During the faster loading, the material is more compliant and able to develop strains up to 10% DA.

At a CSR of 0.44, the specimens failed quickly, reaching 5% double amplitude axial strain at 2 cycles for 1 Hz and 1 cycle for 0.005 Hz. This trend is consistent, but less dramatic, than the previous tests results at CSR = 0.22.

CONCLUSIONS

Specimen preparation is a critical element of liquefaction testing of fine-grained soils. For example, silty soils are typically not of uniform particle size, and silts commonly have soil particles that range from clay-size to sand-size. It is difficult to achieve uniform test specimens when soil particles range in size from less than 1 micron to over 100 microns. Yet, specimen consistency is required if soil characteristics that affect liquefaction are to be examined systematically in an experimental testing program.

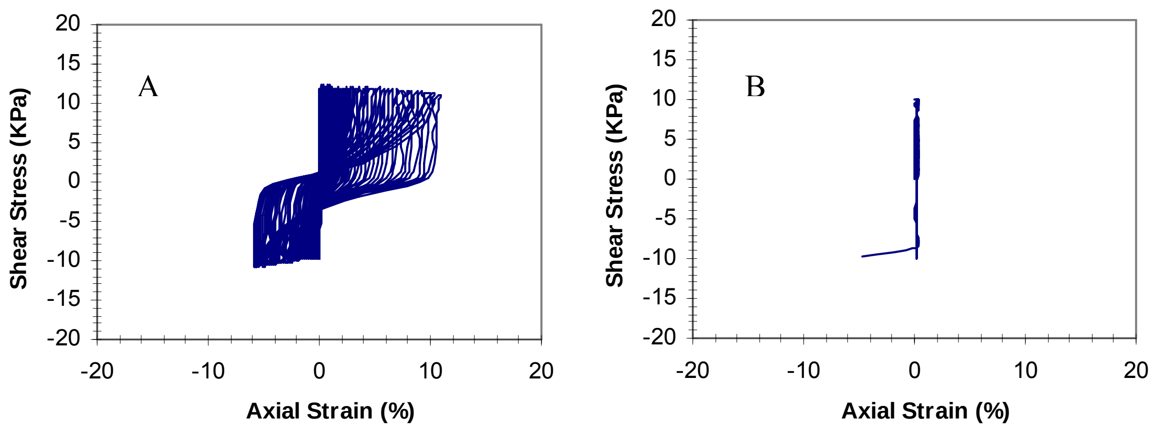

Figure 10. Cyclic Triaxial Results. A) CSR=0.225, Frequency = 1 Hz, Cycles to 5% DAε_a = 68, wc/LL=0.84, e_o=0.71 B) CSR = 0.20, Frequency = 0.005 Hz, Cycles to 5% DAε_a = 5, wc/LL=0.88, e_o=0.74

Several specimen preparation methods were explored, and a modified version of the Slurry Deposition method has been utilized because it produced repeatable and uniform soil specimens. Ongoing work has found that a slightly modified Wet Pluviation method, termed the In-Place Wet Pluviation method, is also promising in that it produces soil fabrics that are more representative of that found in nature due to fluvial deposition. However, this method does produce specimens that can be layered and are clearly less uniform than those prepared using the Slurry Deposition method.

Preliminary cyclic simple shear and cyclic triaxial test results were presented. At this early stage of testing over the relatively small range of plasticity indexes explored, the cyclic tests performed on silts and clays with PIs from 2 to 14 showed no clear trend that plasticity index is a discriminating factor to be used to evaluate liquefaction susceptibility and resistance. As has been shown in previous studies, loading rate effects are clearly a factor in cyclic testing. The number of cycles to reach liquefaction decreases significantly as the loading frequency decreases several order of magnitude. For these fine-grained soils, low loading frequencies are required if reliable porewater pressure measurements are to be made. Ongoing studies will closely examine other factors including additional combinations of PI, w_c/LL, stress history, fines content, clay content, and void ratio.

The stress-strain response of silty soils is best described as cyclic mobility with limited shear strain potential. Cyclic loading clearly leads to a significant development of positive excess pore-water pressures, which leads to a reduction in effective stress and a softening of the soil response. However, the dilative nature of the Adapazari silty soils, for the given confining pressure, produce only a transient loss of shear strength that is quickly regained with increasing deformation. Hence, the consequences of liquefaction of these loose silts will likely not be as severe as that of loose, saturated sands.

ACKNOWLEDGEMENTS

The experimental research program presented herein was made possible by funding from the National Science Foundation under award number CMS-0408760 and the United States Geological Survey under award number 05HQGR0009. The financial support of the NSF and USGS is gratefully acknowledged. The views expressed in this paper are not endorsed by the sponsors. The authors would also like to gratefully acknowledge Willamette Geological Service in Philomath, Oregon for the X-Ray Diffraction analysis.

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