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ABSTRACT

In recent years, a significant research effort has been focused on assessing the performance of structures founded on potentially liquefiable materials. While significant progress has been made on predictive tools for cases in which large deformations are likely, the ability to accurately and reliably predict small to moderate lateral deformations (<1m) has proven more elusive. As a result, there is a universal need for high quality, element-level laboratory test data to calibrate and validate constitutive laws and numerical models for predicting the deformation of soil with limited liquefaction potential. To address this increasingly urgent need, a comprehensive cyclic simple shear testing program on liquefiable sands has been undertaken using the UC Berkeley Bi-directional Simple Shear Device. Many of the tests performed have new and innovative aspects that can provide information and insight into the behavior of soils showing limited deformation potential. Described in this paper are results from a K_α test series, which replicates sloping ground conditions, and a newly developed and innovative "fabric" test series, which examines the influence of previous loading history on soil fabric and behavior.

INTRODUCTION

Liquefaction is one of the most destructive consequences of strong earthquake shaking in waterfront areas such as ports and harbors. Depending on its initial formation density and its cyclic stress history, cohesionless soils may develop pore pressures high enough to cause a complete loss of shear strength at essentially no effective stress (liquefaction) or cause excessive deformations (liquefaction with limited strain potential) [Seed et al., 1975]. Over the last few decades, a significant amount of laboratory and field research has been focused on identifying triggering mechanisms for liquefaction. More recently, the effort has shifted significantly to the assessment of performance of structures founded on liquefaction prone soils. This evaluation is accomplished through the accurate estimation of the amount of deformation at a given site that may be expected during (or after) the seismic event. While progress has been made on predictive tools useful for cases in which large deformations are likely (e.g., Barlett and Youd, 1995), the ability to predict small to moderate lateral deformations (<1m), a key range of engineering interest for performance-based design, has remained elusive. The ability to accurately and reliably predict deformations over all scales and ranges is a key element in the assessment of performance for new and existing structures on liquefaction prone sites.

Although there are currently a number of constitutive models that can effectively predict liquefaction behavior, there is a universal need for high quality, "element-level" laboratory test data to calibrate and validate these models. While cyclic triaxial testing is an important element in the calibration of "generalized" effective stress models, it is generally accepted that this type of testing is not acceptable as a means for calibrating "simplified" models tailored for seismic site response and performance analyses, which are dominated largely by the cyclic simple shear mode of deformation. Accordingly, only two testing methods can provide the much-needed data for most accurately reproducing field loading conditions: cyclic simple shear testing and hollow-cylinder cyclic torsional shear testing. Unfortunately, even when combining the data from these two methods insufficient data currently exists to describe the behavior at small to moderate levels of deformation. Data from tests incorporating the effects of initial "driving" shear conditions, as would be found at a sloping site, are even more rare. To the authors' knowledge no data is currently available fully describing the evolution of fabric anisotropy following liquefaction.

To address this increasingly urgent need, a comprehensive cyclic simple shear testing program on liquefiable sands has been undertaken using the UC Berkeley Bi-directional Simple Shear Device. The ultimate goal of this program is the development of a comprehensive internet-accessible database consisting of high quality test data for calibration and validation of constitutive models for liquefaction analyses. The simple shear testing described here was performed as part of a collaborative program by the Pacific Earthquake Engineering Research Center (PEER) that includes researchers from UC Davis, UC Los Angeles, UC San Diego and UC Berkeley. This program includes work in centrifuge testing, small strain properties, and modeling, in addition to the large strain property testing described here.

The paper discusses the results of two test series conducted at UC Berkeley. The first series, hereinafter referred to as K_α testing, is performed by applying cyclic shear stresses to a sample experiencing an initial applied shear stress to reproduce "sloping ground" conditions (or similar stress conditions) (cf., Fig. 1). The second series, referred to as "fabric" testing, is a new and innovative series of tests performed on a single sample to examine the evolution of fabric anisotropy resulting from a complex loading stress (or strain) history. These tests provide insight into the behavior of liquefied soils that are subjected to further cyclic loading after a small amount of excess pore pressure has dissipated. Many of the tests performed have new and innovative testing procedures and are designed to provide information and insight into the behavior of soils exhibiting limited deformation potential. Upcoming test series also include 2-directional and irregular loading paths. Most of the test data (to date) is available on the Internet (Kammerer et al., 2000).

LABORATORY TESTING PROGRAM

The testing program focuses on the accurate characterization of cyclic strain softening with subsequent dilatant re-stiffening of fine, poorly graded medium dense to dense sandy soils. These soils exhibit "locking up" or dilation at moderate strain levels that limit the strain potential during a given cycle but allow accumulated deformations with additional cycles of loading. The phenomenon is associated with the accumulation of both transient and permanent strains and shear induced excess pore pressures. Testing was designed to replicate both "level ground" and sloping ground surface conditions. The program includes tests with a variety of densities, initial vertical effective stresses, cyclic stress ratios, and K_α ratios.

Detailed laboratory procedures were developed to assure the highest quality testing possible, and a number of cross-validation techniques have been undertaken. The tests described here were performed undrained on fully saturated samples using the UC Berkeley Bi-directional Simple Shear Device, shown in Figure 2 (Boulanger, 1990). Saturation is achieved through back pressure saturation and a "B-value" check is performed prior to testing. Full saturation allows the direct measurement of excess pore pressure during testing. A very stiff track bearing system greatly limits rocking which is directly measured by an array of vertical LVDTs. The specimens have a high aspect ratio (4" diameter to 0.8" high) to minimize any problems associated with the lack of complementary shear stresses.

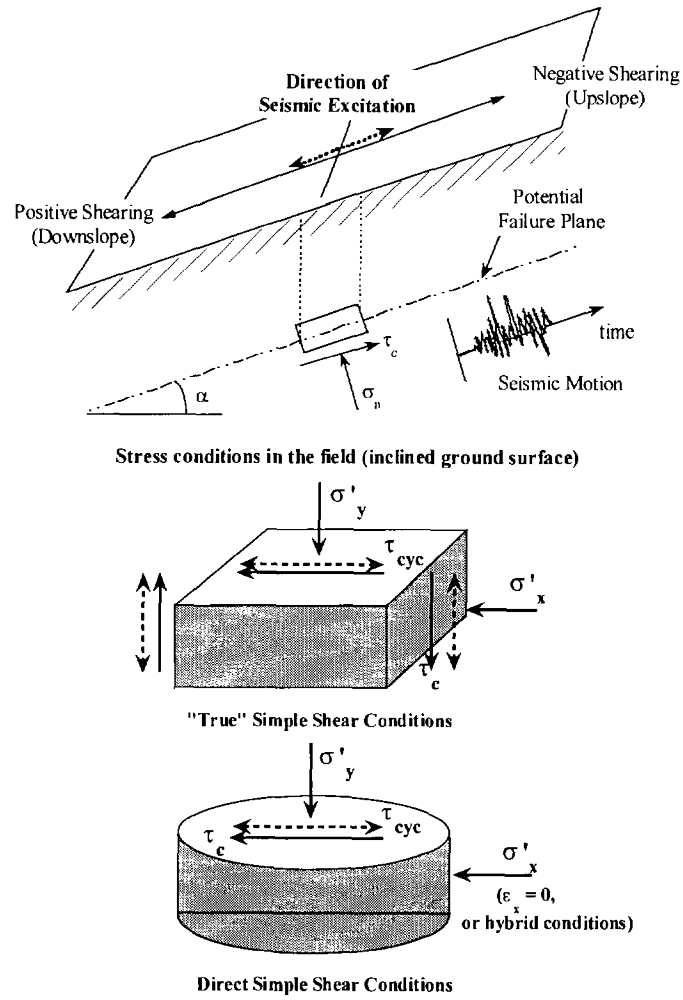


Fig. 1: Idealized In-Situ and Testing Conditions for K_α testing.

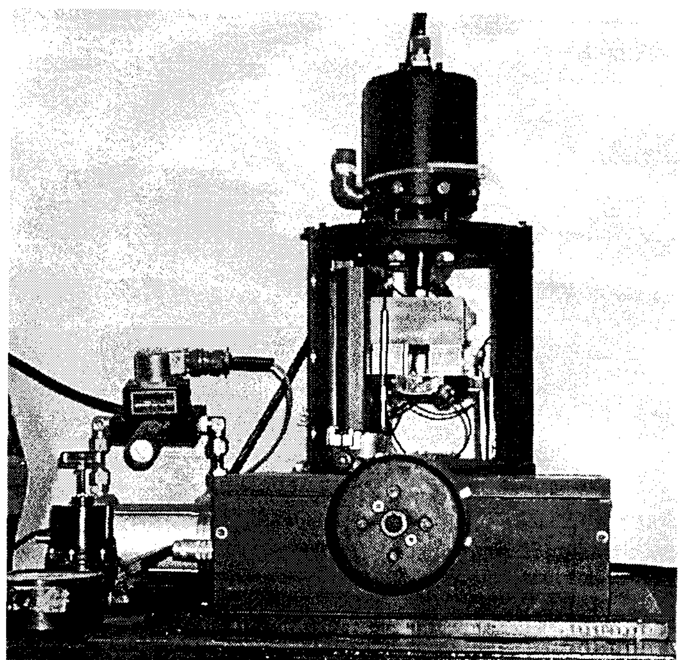


Fig. 2. UC Berkeley Bi-Directional Simple Shear Device (Without Chamber or Sample)

The testing described here was performed at 0.1 Hz under 1-directional horizontal load control. A constant vertical load condition was used during testing. Wire-reinforced membranes were used to assure constant cross-sectional area and maintain K_0 conditions (i.e., $\varepsilon_x = 0$). Partial lateral support, by means of applied chamber (or "cell") pressure minimizes hoop stress loading of the wire membranes. The maintenance of K_0 conditions throughout sample preparation, consolidation and testing is essential to assure the sample is as close to typical in-situ conditions as possible. Though the overall program consists primarily of wet pluviated samples, the tests described herein were dry pluviated and then flooded to mimic the sample preparation procedures used in construction of centrifuge samples at UC Davis. Also essential to good sample preparation for K_α testing is the use of appropriate consolidation techniques for the in-situ condition of interest. For the tests reported here, the shear and vertical stresses were applied proportionately to maintain a constant consolidation stress ratio.

K_α TESTING

The purpose of K_α testing is to reproduce in-situ "sloping ground" conditions or other site conditions where the soil sustains a constant shear stress. The initial shear stress, τ_c, corresponds to the value of the average shear stress, τ_{ave}, for stress controlled cyclic loading. K_α testing is performed by cycling an applied shear stress around the non-zero initial shear τ_c, as shown in Fig 3 for Nevada sand test NSCYC4. The test is characterized by the consolidation shear stress ratio, $\alpha_{\tau c}$, and the cyclic stress ratio (CSR). $\alpha_{\tau c}$, is defined as the ratio of the initial shear stress normalized by the initial effective vertical stress (i.e., $\tau_c/\sigma_c = \tau_{ave}/\sigma_c$). The cyclic stress ratio (CSR) is defined as the amplitude of cyclic shear stress normalized by the initial effective vertical stress (i.e., $(\tau_{max} - \tau_c)/\sigma_c$).

Figure 4 shows the results of one of the K_α tests performed for Nevada sand. The unbalanced shear load allows the sample to accumulate permanent deformation in the "downslope" (i.e., positive) direction. The effects of "lockup" are apparent in the stress strain plot as the soil stiffness increases upon dilation (i.e., decrease in excess pore pressure). The figure also shows the generation of shear induced excess pore pressure as represented by the excess pore pressure ratio, r_u. This term, r_u, is defined as the ratio of the excess pore pressure normalized by the initial vertical effective stress. In the test shown, r_u increases up to a maximum of near 95% at the point of maximum contractancy and a minimum of 65% upon reversal from the dilatant state.

Sets of three tests were included in the testing plan to examine the effect of increasing the consolidation shear stress ratio, $\alpha_{\tau c}$, on the behavior of liquefiable soils. These series are composed of tests with nominally the same relative density and the same CSR but with increasing values of $\alpha_{\tau c}$ of 0, 0.1 and 0.2. The ratio $\alpha_{\tau c}$ was increased by increasing τ_c (recall $\alpha_{\tau c}=\tau_c/\sigma_c$). Figure 5 shows tests performed on samples with a relative density of 90%. The first 26 cycles of each of the tests are plotted. This series was performed to examine the effects of densification on pore pressure generation and displacements. As $\alpha_{\tau c}$ approaches the imposed CSR, the sample undergoes less stress reversal (which occurs as the sample moves past the zero stress line). It can be seen in Figure 5 that the stress reversal for the case where $\alpha_{\tau c}$ =0.2 is small compared to the shear stress imposed. A comparison of the behavior of the samples shows the importance of stress reversal in pore pressure generation and related strain accumulation in 1-directional tests, particularly for moderately dense to dense samples.

Because the increasing values of the consolidation stress ratio represent increasing slope angles (0, 5.5° and 11.5°), the tests presented in Figure 5 show what may be a counter-intuitive result. Namely, for a given value of CSR, the "steeper" slopes show less permanent deformation. Because of the high relative density of the soil and small stress reversals, individual sand grains had less opportunity to unlock and move relative to each other in the steeper samples. As a result, little permanent deformation was recorded and significant excess pore pressure was not generated, as can be seen in Figure 6. Although the driving force is smaller in the tests representing "flatter" soils, these samples softened to a greater extent, allowing deformation to occur. It must be noted that this result only holds in the absence of the transverse (i.e., strike direction) shear stresses and will require further investigation in the bi-directional shear device.

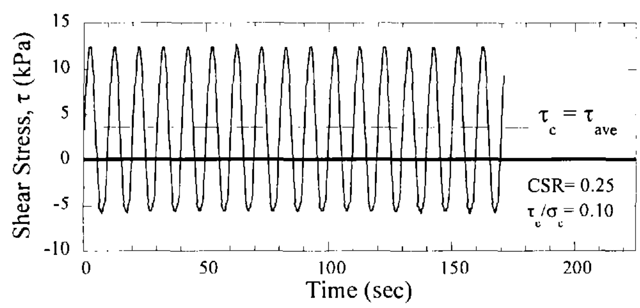
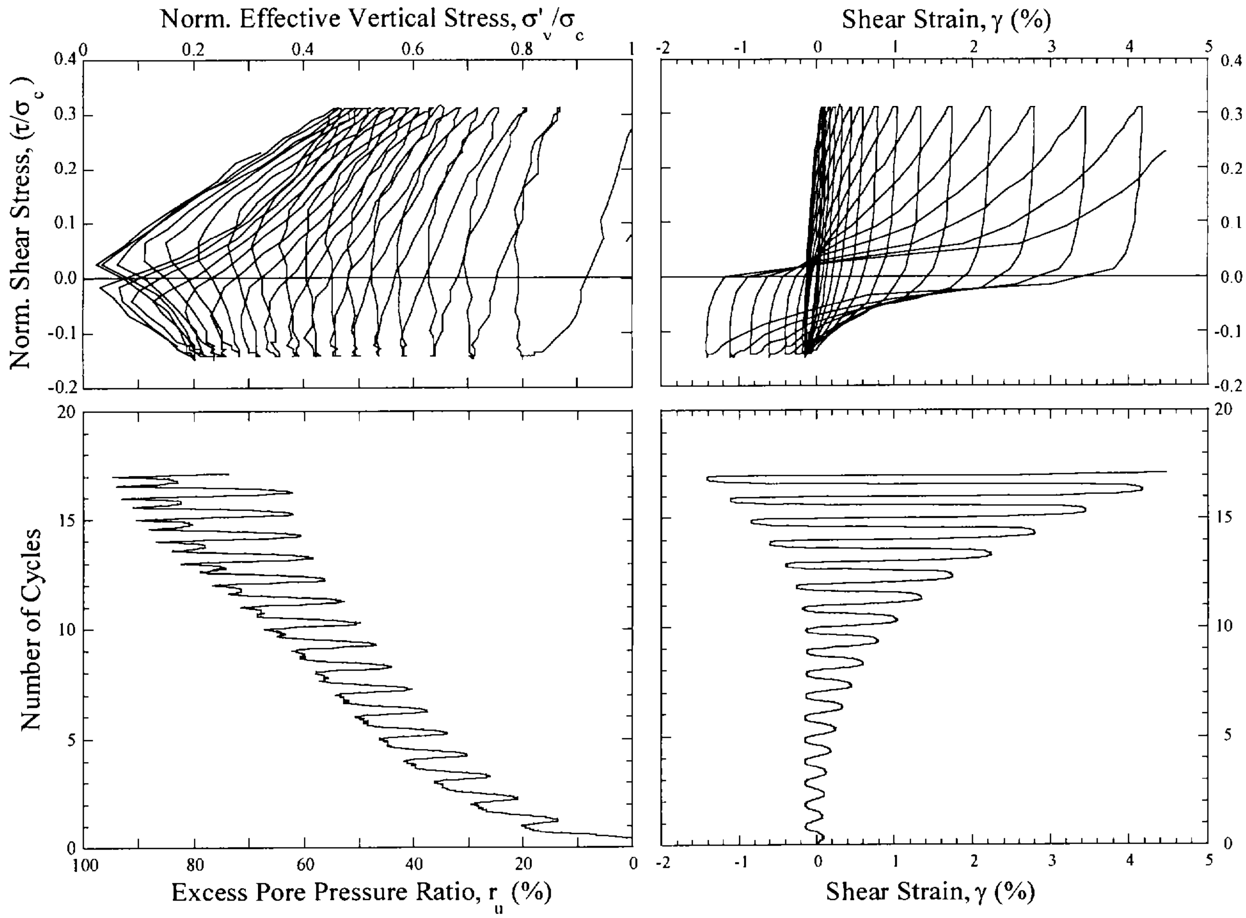


Fig. 3. Loading Time History for K_α test NSCYC4

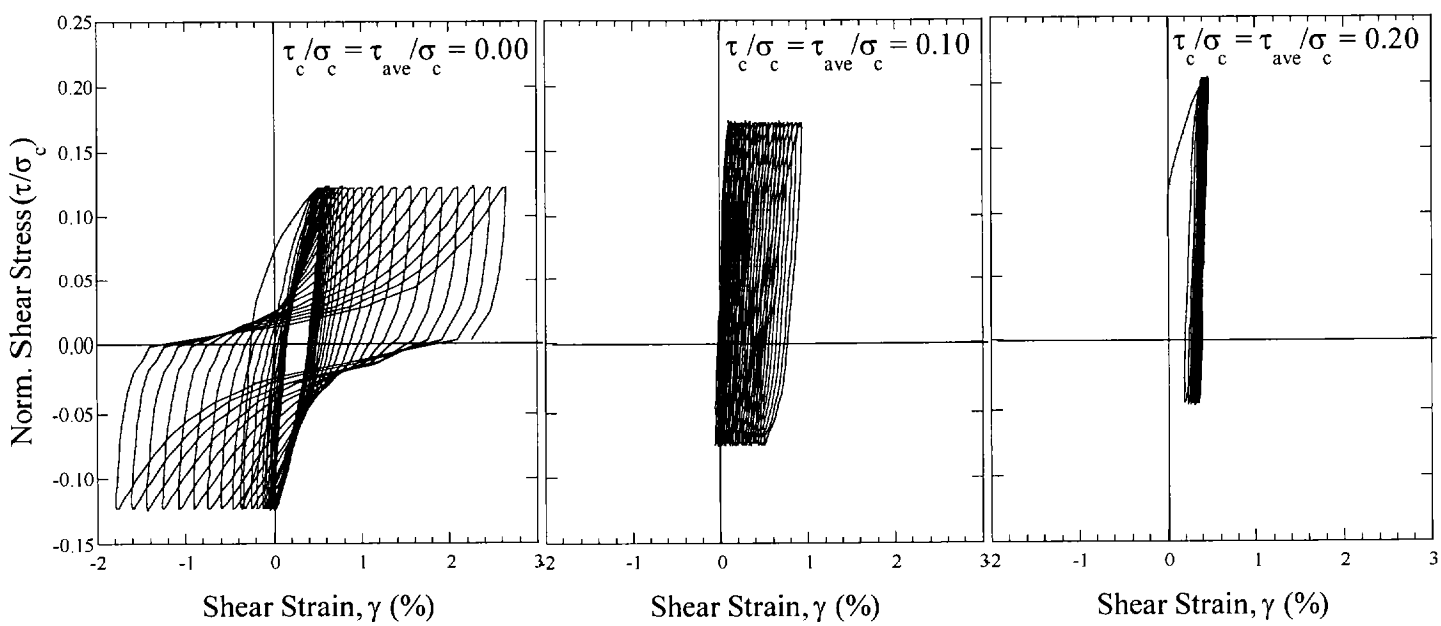
FABRIC TESTS

Fabric testing was designed jointly with a team of researchers at UC Davis as part of the PEER collaborative effort. The purpose of the testing is to examine the behavior of liquefiable soils subjected to identical stress conditions after different loading histories. The fabric testing program is composed of sets of three "undrained" cyclic tests with the same initial conditions. Each set of tests is imposed on a single sample. The tests are separated according to the specimen histories preceding shear, namely: a) virgin or "freshly deposited" conditions, b) controlled drained conditions (with minimal density change) after liquefaction failure, and c) fully reconsolidated conditions with an accompanying change in density. These tests are further detailed below.



Nevada Sand	Test	Condition	D_r (%)	σ_c (kPa)	CSR	$\alpha_{\tau c}$ (τ_c/σ_c)
	NSCYC4	Value	70	40	0.25	0.10

Fig.4: Results of a typical K_α test on Medium Dense to Dense Sample of Nevada Sand.



Nevada Sand	Test	Condition	D_r (%)	σ_c (kPa)	CSR	$\alpha_{\tau c}$ (τ_c/σ_c)
	NSCYC8, 9, 10	Value	~90	200	0.25	as noted

Fig. 5: Effect of Average Shear Stress Ratio (α_{tc}) on the Stress-Strain Response of Dense Nevada Sand.

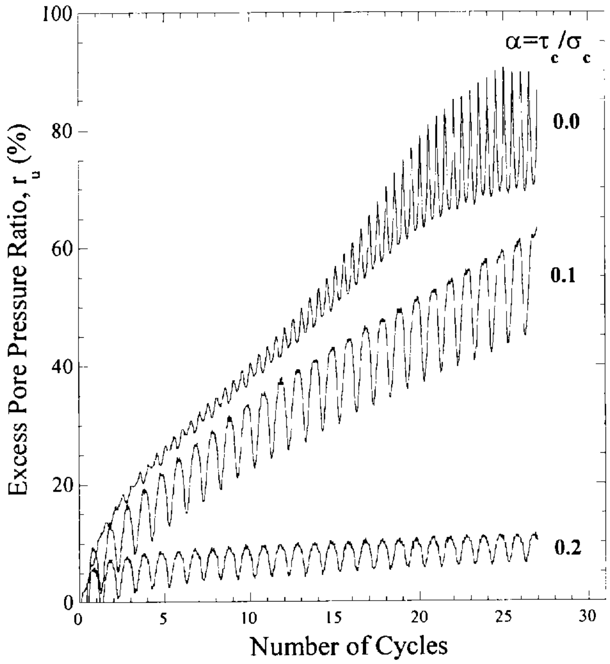


Fig. 6. Excess Pore Pressure Generated during K_α tests.

The first test (i.e., freshly deposited conditions) is designed to replicate in-situ conditions for a soil that has not experienced seismic loading following the pluviation/deposition of the material. This would be the case for soils that either have not experienced seismic loading since initial deposition or have been repluviated due to upward migration of excess pore pressure after a seismic event. The second fabric test provides insight into the behavior of a soil that has been allowed to drain some small amount as it undergoes additional loading. The very limited drainage of the soil only allows minimal changes in density. As a result, this test provides insight into the importance of loading history, through changes in fabric anisotropy. Finally, the last fabric test evaluates the change in response following full reconsolidation of the sample and therefore incorporates the importance of densification processes occurring following the seismic event. After full reconsolidation the pore pressure is increased such that the initial conditions of all three tests are the same.

TESTING PROCEDURE

A brief description of the steps are outlined in the following paragraphs, while full details are presented by Kammerer et al (2000)

Freshly Deposited Sample- Fabric Test 1

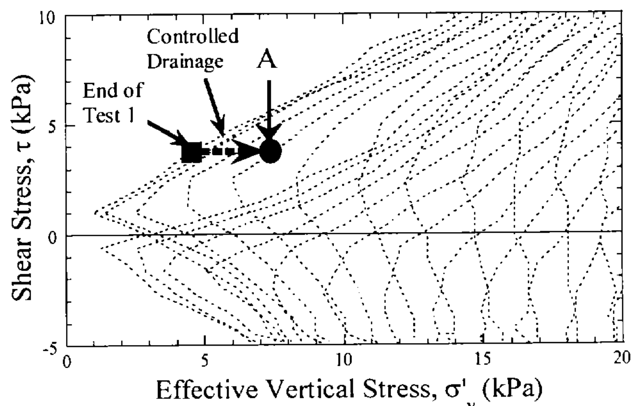
1. A standard undrained cyclic DSS test is performed until the selected failure condition is met (i.e., 6% double amplitude strain). The failure criteria should be chosen such that the maximum amount of pore pressure that can be generated under the conditions of testing is achieved in the last few cycles.

Controlled Drained Sample – Test 2

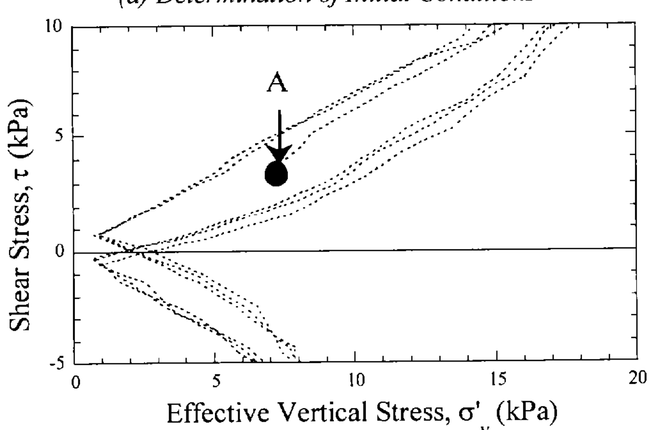
2. The second test is conducted starting from the prevalent stress conditions three cycles prior to termination of Test 1 (i.e., point A in Figure 7(a)). This is achieved by allowing the excess pore pressure to dissipate slightly at the same value of shear stress. This partial dissipation of excess pore pressure causes negligible to minimal changes in sample density.
3. A standard cyclic DSS test with same $\alpha_{\tau c}$ and CSR is performed for three cycles, as shown in Figure 7b.

Fully Reconsolidated Sample – Fabric Test 3.

4. Following fabric test 2, the drain line is opened and the sample is allowed to fully reconsolidate to the initial (shear and vertical) stress conditions. The density of the sample is permanently increased at this point (cf., Figure 8).
5. The internal pore pressure is increased again through the use of backpressure until the conditions that existed at point A are attained. The drain line is then closed. This is carefully performed so that no additional shear is taking place ($\tau = \tau_c$)
6. Finally, a standard cyclic DSS test with the same $\alpha_{\tau c}$ and CSR is performed for three cycles (same as step 3).



(a) Determination of Initial Conditions



(b) Effective Stress Path

Fig. 7 Controlled Drainage Sample – Fabric test 2.

RESULTS

Figure 4 shows the results of a test from a fabric test series. The failure condition for this test was defined as a double amplitude strain of at least 6%. The sample had an initial relative density of 70% and Test 1 was performed with an initial vertical effective stress of 40kPa, a CSR of 0.25, and a value of τ_c/σ_c of 0.1. Note that the maximum pore pressure for this test is reached two cycles prior to termination of this test. Figure 9 shows only the last three cycles of the intial test along with the three cycles of Test 2. It can be seen from Figure 9 that the dissipation of a small amount of pore pressure did not affect the shear strains recorded in a noticeable way. Not surprisingly the strains recorded for the reconsolidated test were much smaller than those observed before as the sample had been allowed to densify during reconsolidation. In this case the sample's relative density increased from 68% to 77%.

SUMMARY

The paper presents selected results of a series of tests directed at evaluating the K_α effects on the stress-strain characteristics of potentially liquefiable materials. Additional testing includes new sets of tests directed at evaluating the effect of fabric following liquefaction. During each of these tests, the sample is subject to the same initial and loading conditions as that experienced during the last three cycles of the freshly deposited sample failed in DSS. However, the sample has a different stress history at the beginning of each test. This type of data provides insight into the mechanisms of evolving "fabric" anisotropy as well as changes in behavior resulting from densification associated with reconsolidation processes.

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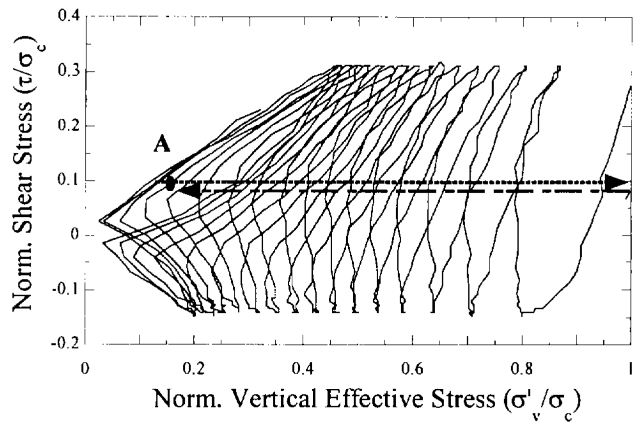
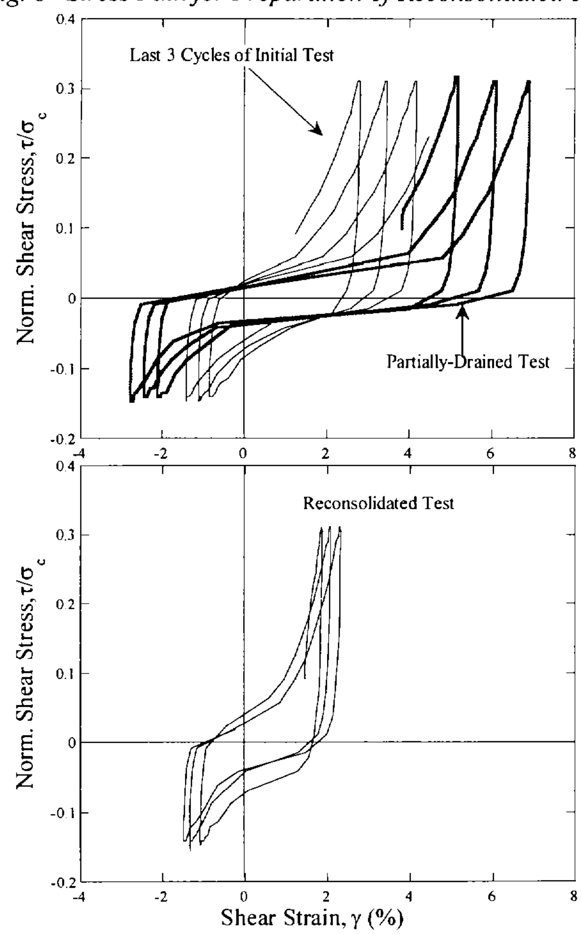


Fig. 8 Stress Path for Preparation of Reconsolidated Test



Test	Condition	D_r (%)	σ_c (kPa)	CSR	$\alpha_{\tau c}$ (τ_c/σ_c)
NSCYC4	Value	70	40	0.25	0.10

Fig. 10. Comparison of Stress-strain Behavior for Each Portion of the Fabric Test on Nevada Sand