



Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

PORE PRESSURE GENERATION UNDER DIFFERENT TRANSIENT LOADING HISTORIES

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ABSTRACT

Current stress-based procedures for characterizing earthquake loading (uniform stress cycles with amplitude = 0.65 of the peak shear stress) has been used for evaluating soil liquefaction hazards for more than 40 years. Since then, the basic mechanics of liquefaction have become better understood, and the capability of experimental apparatuses to simulate earthquake loading in the laboratory has improved significantly. The paper presents results from an experimental study using the cyclic simple shear (CSS) test to evaluate pore pressure generation under transient earthquake loading. The CSS was selected (over cyclic triaxial testing) because of its superior ability to simulate field earthquake loading in laboratory liquefaction testing. A series of eight CSS tests were performed on Nevada Sand under selected loading histories obtained from actual ground motion recordings. The four earthquake ground motions were selected to have different time-domain characteristics (ranging from short to long duration and different frequency content). The specimens were prepared using wet pluviation at two target relative densities (40% and 70%) and consolidated to 100 kPa vertical effective stress before being loaded under undrained conditions. The loose specimens were subjected to ground motions with relatively constant peak shear stress amplitude; the dense specimens were subject to the same ground motions but with scaled factors, magnitude scaling factors, to accommodate the differences in duration. While these different loading histories would be characterized by the same peak cyclic stress (assuming identical site conditions), the generated pore pressure in the lab testing varied depending on the time-domain characteristics of the different motions. The data generated in this study supports the development of improved characterization of earthquake loading.

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Pore Pressure Generation under Different Transient Loading Histories

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ABSTRACT

Current stress-based procedures for characterizing earthquake loading (uniform stress cycles with amplitude = 0.65 of the peak shear stress) has been used for evaluating soil liquefaction hazards for more than 40 years. Since then, the basic mechanics of liquefaction have become better understood, and the capability of experimental apparatuses to simulate earthquake loading in the laboratory has improved significantly. The paper presents results from an experimental study using the cyclic simple shear (CSS) test to evaluate pore pressure generation under transient earthquake loading. The CSS was selected (over cyclic triaxial testing) because of its superior ability to simulate field earthquake loading in laboratory liquefaction testing. A series of eight CSS tests were performed on Nevada Sand under selected loading histories obtained from actual ground motion recordings. The four earthquake ground motions were selected to have different time-domain characteristics (ranging from short to long duration and different frequency content). The specimens were prepared using wet pluviation at two target relative densities (40% and 70%) and consolidated to 100 kPa vertical effective stress before being loaded under undrained conditions. The loose specimens were subjected to ground motions with relatively constant peak shear stress amplitude; the dense specimens were subject to the same ground motions but with scaled factors, magnitude scaling factors, to accommodate the differences in duration. While these different loading histories would be characterized by the same peak cyclic stress (assuming identical site conditions), the generated pore pressure in the lab testing varied depending on the time-domain characteristics of the different motions. The data generated in this study supports the development of improved characterization of earthquake loading.

Introduction

Liquefaction of loose, saturated sand has been the topic of extensive laboratory research over the past 50 years after the devastating earthquakes of 1964 in Alaska and Japan. Cyclic loading due to upward propagating shear waves generate excess pore pressure within saturated soils during seismic events. The upward propagating dynamic shear waves produce an irregular shear stress history of various frequencies and amplitudes in the soils. The duration of the seismic loading is usually assumed to be short enough to prevent drainage, even for clean granular deposits. In-situ index testing (e.g., SPT, CPT and V_s) is the dominant approach in practice to characterize soil liquefaction resistance because of the extensive available databases and past experience. In addition, there are soil characteristics that are hard to simulate in the laboratory, such as aging, cementation and previous seismic history which make in-situ based approaches advantageous.

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Cyclic Resistance Ratio (CRR), can be correlated to in-situ test parameters such as SPT, CPT and V_s , the shear wave velocity [1]. These correlations are generally based on logistic regression of case history data involving sites with liquefiable soils that were subject to strong ground motion. For each site the level of ground motion loading (PGA or CSR) is estimated and plotted as a function of some measure of the soil's density (e.g., $(N_1)_{60cs}$, q_{c1Ncs} , and V_{s1}). The relationships are then developed by creating curves that separate the conditions for which liquefaction has been observed from the cases where liquefaction was not observed. It is important to note this approach is mainly correlation based, and is only able to predict whether the site could potentially experience liquefaction or not. In-situ index testing cannot provide insight on the specifics of excess pore pressure generation and only a very crude estimation on surface deformation.

Specific details of the mechanisms by which soil liquefaction develops can be better understood from laboratory testing. Cyclic triaxial (CTX), torsional, and cyclic simple shear (CSS) tests are the most popular and commonly used methods for soil element-level testing. The CSS test provides better simulations of in-situ stresses for seismic hazard evaluation than CTX because it is capable of producing a more accurate representation of the seismic loading conditions that occur in the field [2]. The 'simple shear' mechanism allows the principal stress axes to rotate smoothly during cyclic loading, as compared to the CTX where the principal axes instantaneously rotate 90 degrees upon loading reversal. CSS tests are performed under K_0 and/or K_α initial conditions; the lateral confinement in simple shear is maintained through the use of NGI-type wire-reinforced latex membranes or stacked rings to provide lateral constrain while applying a vertical stress.

Even though major refinements have been made on evaluating soil liquefaction resistance, the most common way to characterize an earthquake loading, Cyclic Stress Ratio (CSR), is still mainly based on the framework developed by Seed and Idriss [3]:

$$CSR = 0.65 \frac{PGA}{g} \cdot \frac{\sigma_{vo}}{\sigma'_{vo}} \cdot r_d \quad (1)$$

where PGA is the Peak Ground Acceleration, g is gravitational acceleration, σ_{vo} is the total vertical overburden stress, σ'_{vo} is the effective vertical overburden stress, and r_d is the depth reduction factor. Eq. (1) can be modified to account for the effects of the duration of the event by the use of a magnitude scaling factor (MSF) that works to increase CSR for events less than M7.5, and decrease CSR for events greater than M7.5. MSF can be derived by combining correlations of the number of equivalent uniform cycles versus earthquake magnitudes, and laboratory-based relations between CRR and number of uniform stress cycles [4]. In current practice, the potential for liquefaction is evaluated as a factor of safety:

$$F.S. = CRR/CSR \quad (2)$$

This approach worked well in the early days when evaluation of liquefaction was based on a deterministic approach using singular "worst-case" scenarios. However, such an approach is not as desirable within the new Probabilistic Seismic Hazard Analysis framework where many different earthquake scenarios can contribute to the seismic hazard for a given site. Additionally, it cannot capture all aspects of the complicated time-domain characteristics of ground motions.

This paper presents a set of high-quality experimental data that systematically illustrate the response of soils subjected to transient ground motion (instead of an equivalent number of harmonic loading cycles). Such tests can help improve current liquefaction evaluation procedure by incorporating time characteristics of ground motions, and can also aid in the calibration of constitutive models for liquefiable soils.

Testing Program

A laboratory-testing program was performed at the University of Texas at Austin using the modified Geotechnical Consulting and Testing System (GCTS) manufactured Cyclic Simple Shear apparatus (Fig. 2). A total of eight CSS tests were performed on Nevada Sand ($e_{\min} = 0.56$, $e_{\max} = 0.76$, S.G. = 2.67, $C_u = 2$ and $C_c = 1.13$) at two different relative densities. The particle size gradation is shown in Fig. 1. According to the USCS, Nevada sand is classified as a uniform sand (SP). The CSS system uses a closed loop, electro-hydraulically actuated, servo valve that controls shearing in the horizontal direction at the bottom platen under load or displacement controls.

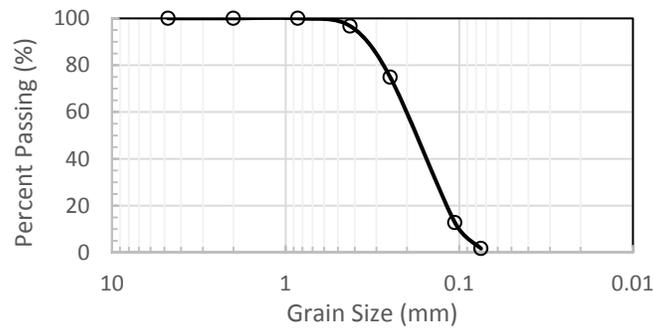


Figure 1. Grain Size Distribution of Tested Nevada Sand

Two linear variable differential transformers (LVDTs) were used to measure the horizontal and vertical displacements. Both LVDTs were installed on the specimen itself for more accurate measurements. The vertical LVDT was used to monitor any volumetric change during consolidation or rocking of the top platen during shear; the shear LVDT was setup horizontally to measure the movement of the bottom platen relative to the top one. An aluminum bracket was installed to minimize rocking during the loading stage (Fig. 2). All specimens were consolidated to 100 kPa vertical effective stress and then sheared under undrained, stress-controlled conditions using transient loading histories developed from actual recorded ground motions. The loading rate was reduced by a factor of five from the real record in order to obtain more accurate and representative measurements of the pore pressure response of the whole specimen (the pore pressures were only measured at the base of the specimen).

Four distinct ground motions (Table 1 and Fig. 3) were selected for the testing program, each with unique temporal characteristics as well as frequency contents. Two motions contain relatively shorter durations (GREECE_PLK_NS and PALMSPR_MVH135) than the other two. PALMSPR_MVH135 consists of a few pulses at low-frequency, while GREECEE_PLK_NS

contains more high-frequency pulses. KOCAELI_CNA000_h2 and LANDERS_MCF_000 were recorded from earthquakes with magnitudes greater than seven. Both of them contain longer durations and feature large amplitude, high-frequency motion. However their temporal characteristics differ, the Kocaeli motion contains eight to ten pulses very close to the maximum amplitude at approximately 11 to 14 seconds. On the other hand, the Landers motion tapers up to the peak pulse at around 11 seconds, and then tapers down to relatively uniform amplitude cycles (Fig. 3). All motions were scaled to desired absolute maximum peak shear stresses before being applied to the specimens. Eight CSS tests are presented in this paper, and they were divided into two groups. The first group contained four tests conducted on loose specimens where the earthquake shear stress time history input motions were scaled to the same CSR. The purpose of the first group was to study the pore pressure generation under a ‘constant’ peak shear stress for ground motions with different temporal and frequency characteristics. The second group consisted of four dense specimens for which the applied CSR values were adjusted based on their corresponding MSF. The adjusted CSR values were used to account for the difference in magnitude and duration of the ground motions and allow for a comparison between measured excess pore pressure under normalized conditions. A further discussion of the MSF calculations is provided later in the results and discussion section of this document.

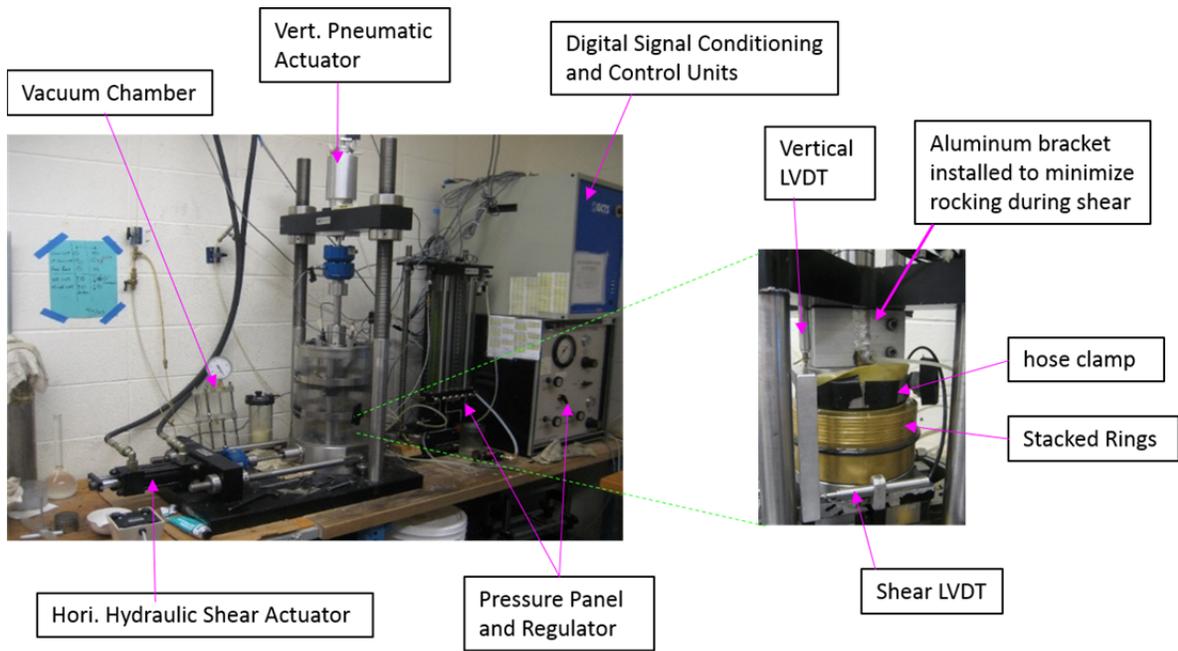


Figure 2. Experimental Setup: Overall setup (Left) and Internal Instrumentation (Right)

Table 1. Summary of Ground Motions

Ground Motion	PEER NGA #	Earthquake	Year	Magnitude
GREECE_PLK_NS	484	Pelekanada, Greece	1987	5.00
PALMSPR_MVH135	527	N. Palm Springs	1986	6.06
KOCAELI_CNA000_h2	1157	Kocaeli, Turkey	1999	7.51
LANDERS_MCF_000	880	Landers	1992	7.28

Sample Preparation

Laboratory approaches to the measurement of liquefaction resistance are limited in engineering practice by the high cost of obtaining “undisturbed” samples. A high quality coarse-grained sample could be collected by the “frozen sampling” technique, which allows preservation of the in-situ properties (e.g., age, cementation, seismic history). Numerous research efforts have been made on studying the effects of different specimen reconstitution methods on the soil behavior. These studies compare the behavior of soil specimens prepared using a variety of laboratory techniques (i.e., dry funnel deposition, water sedimentation, slurry deposition, air pluviation, etc. [5], with the stress-strain behavior from frozen samples [6, 7]. Results show that specimens reconstituted using the method of water sedimentation closely simulate the fabric of the natural alluvial and hydraulic fill sands [7]. As a result the water sedimentation reconstitution technique has been widely adopted in recent liquefaction laboratory research for understanding the liquefaction phenomena [8].

All tested soil specimens were 1” high and 4” in diameter, and stacked rings were used to provide horizontal confinement while allowing shear deformations. Lubricant oil was applied between the stacked rings to minimize frictional resistance during loading. A special split mold (Fig. 4) was designed and manufactured for this study. The new split mold surrounds the stacked rings as well as the latex membrane. When a vacuum is applied the latex membrane is pulled in contact with the stacked rings to avoid any gaps between the two. Once the vacuum was applied, the mold was filled with water and the sand specimens were reconstituted following the wet deposition method on the table of the simple shear apparatus. In order to achieve a better saturation, a designated amount of sand mixed with water was boiled in a volumetric flask prior to pluviation.

To create loose soil samples, the split mold was filled with de-aired water and a screen was placed at the bottom of the split mold. The saturated sand was then deposited using a preparation method similar to that of [8] to create uniformly loose specimens. Zero drop height was used to create specimens with loose fabric. The screen was then pulled up slowly raining the sand through it with zero drop height.

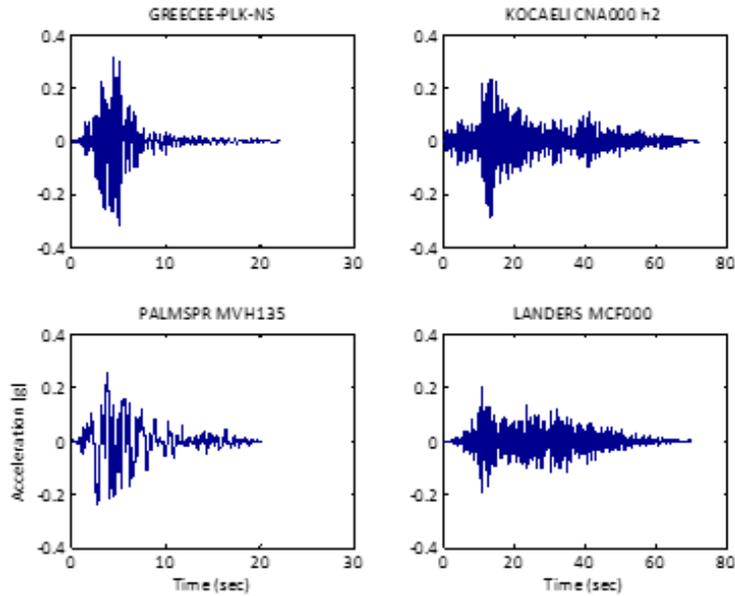


Figure 3. Recorded acceleration time histories.

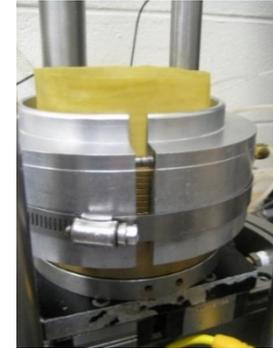


Figure 4. Picture on Split Mold.

The dense specimens were prepared in two lifts. Half of the amount of designated sand was siphoned into the split mold for each lift, and densification was achieved by surface vibration. After leveling the top of the second lift, the top platen was placed on top of the sand and sealed by a hose clamp on top of O-rings. A seating vertical stress and small vacuum (about 10 kPa) were applied to the specimen before the split mold was removed. At this point, the height of the specimen was recorded and density was calculated. The specimen was then back pressure saturated using traditional techniques. Effective cell pressure (15 kPa) and vertical stress (50 kPa) were maintained. After a “B-value” of 0.92 or greater was achieved, the specimen was consolidated to the desired final stresses. A lower B value was expected, due to the smaller particles size of Nevada Sand and a higher density was targeted. The effective cell pressure was brought up to 30 kPa and vertical stress to 100 kPa. The change in specimen height was monitored, and the final specimen density was calculated. Prior to the application of the transient loadings, no horizontal shear stress was imposed on the specimen so that level ground conditions were simulated during testing. An approximately constant vertical load was maintained during the shearing stage by a pressure regulator. The average measured specimen rocking during shearing (calculated as the difference in vertical displacement between the center and edge of the specimen) was 0.05mm (0.25% specimen height). The shearing stage terminated after the entire ground motion history was applied or a single amplitude shear strain of 15% was achieved.

CSS Test Results and Analysis

A total of eight cyclic simple shear tests representative of level ground conditions are included in this study. For the loose specimens (Test 1-4), all the shear stress time history input motions were scaled to a CSR of 0.21. These tests compare the soil response (in term of excess pore pressure generation and deformation) under different temporal and spectral characteristics while maintaining a relatively constant peak shear stress. For the dense specimens (Test 5-8), MSF were applied to adjust the CSR values in order to account for differences in ground motion’s duration based on the simplified evaluation procedure [3]. Since specific ground motions were

selected for this study, MSF were derived from the No. of equivalent cycles [4]:

$$MSF = \left(\frac{N_{M=7.5}}{N_M} \right)^b \quad (3)$$

$$CSR_{M=7.5} = \frac{CSR_{apply}}{MSF} \quad (4)$$

where b is a curve fitting parameter of the CSR versus number of cycles to liquefaction curve under harmonic loading. A b of 0.298 was calculated for dense Nevada Sand specimens prepared following the same specimen preparation procedures used in this study. This b value is comparable with the value suggested by Idriss [9] on clean sand (0.337). $N_{M=7.5}$ is number of uniform cycles for $M = 7.5$, and is equal to 15. The number of equivalent cycles, N_M , was calculated based on the procedures suggested by [10]. With the MSF adjustments, the effectiveness of current liquefaction evaluation procedure could be reviewed. Table 2 summarizes the densities and measured CSR for all specimens. The CSR values were calculated from the measured peak stress. Tests 1-4 provided CSR values close 0.205, and therefore, the peak amplitudes of input motion were relatively ‘constant’. The CSR/MSF values provided insight on adjusted ground motion durations. For test 5-8, the CSR/MSF values are close to 0.27, and therefore, the input ground motion durations are relatively ‘constant’.

Table 2. Summary of CSS Tests

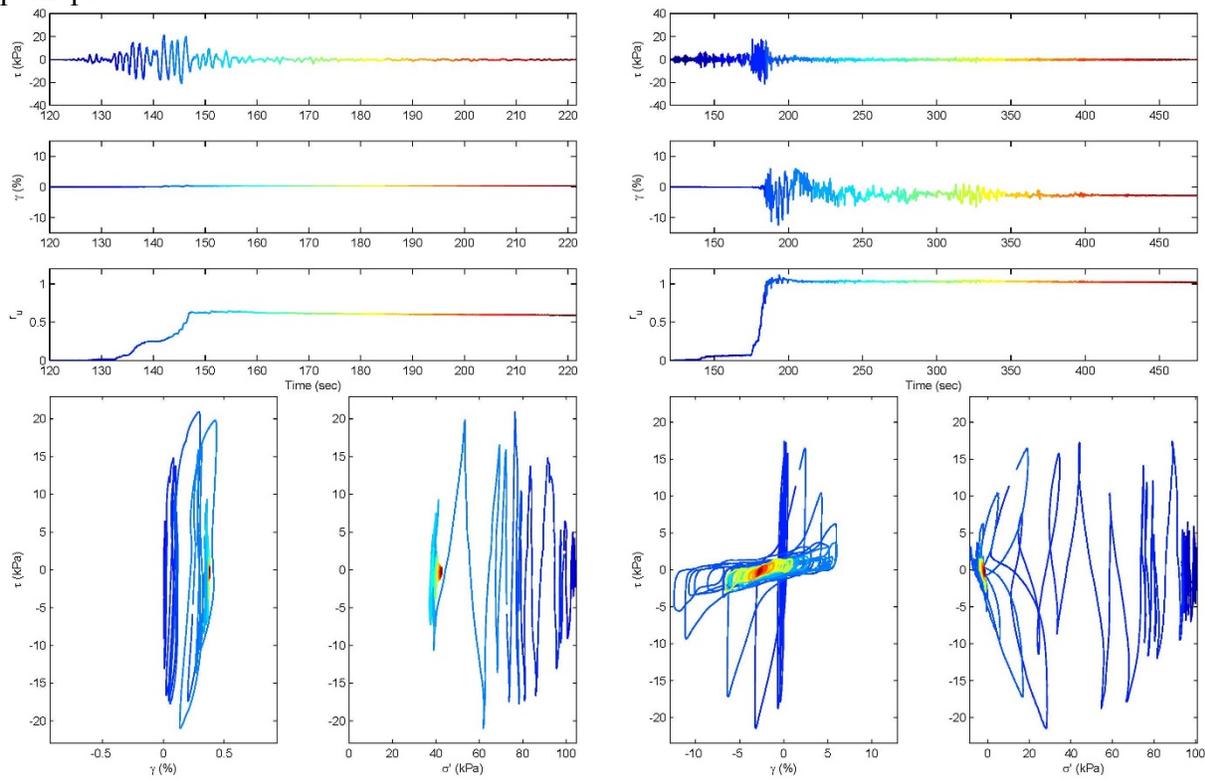
Test No.	D_r (%)	Ground Motion	N_{eq}	MSF	CSR	CSR/MSF
1	41	GREECE-PLK-NS	N/A	N/A	0.206	N/A
2	37	KOCAELI CNA000 h2	N/A	N/A	0.202	N/A
3	40	PALMSPR MVH135	N/A	N/A	0.205	N/A
4	47	LANDERS MFC000	N/A	N/A	0.208	N/A
5	73	GREECE-PLK-NS	11.85	1.07	0.286	0.264
6	74	KOCAELI CNA000 h2	14.94	1.00	0.276	0.276
7	72	PALMSPR MVH135	7.29	1.24	0.345	0.270
8	73	LANDERS MFC000	12.86	1.05	0.274	0.260

CSS test results are shown in Figs. 5 and 6. Plots for input shear stress, shear strain response (γ), pore pressure ratio (r_u), stress-strain and stress path are shown for each of the tests. Each plot traces was color-coded with respect to time to allow for direct comparison between the time history and stress-strain and stress path plots. The stiffness of soil decreased rapidly upon the triggering of liquefaction ($r_u = 1.0$). Because the closed loop, electro-hydraulically actuated apparatus could not catch up with the dramatic change in soil stiffness, the shear stress loading generated by the CSS apparatus did not match the original ground motion record after that point. For Tests 2 and 6, the later part of the input stress histories were diminished or skipped because liquefaction was initiated at the early part of motion.

For Tests 1-4, shear stress time histories with constant peak shear stress was applied to the loose specimens. Tests 2, 3 and 4 reached liquefaction while the pore pressure ratio in Test 1 leveled out at $r_u = 0.67$. Tests 1 and 4 did not show significant strains (less than 0.5% and 2% peak-peak strains, respectively) and thus exhibited limited shear softening. On the other hand, Tests 2 and 3 featured strains as high as 20% (peak-peak) with large reductions in shear stiffness. Limited

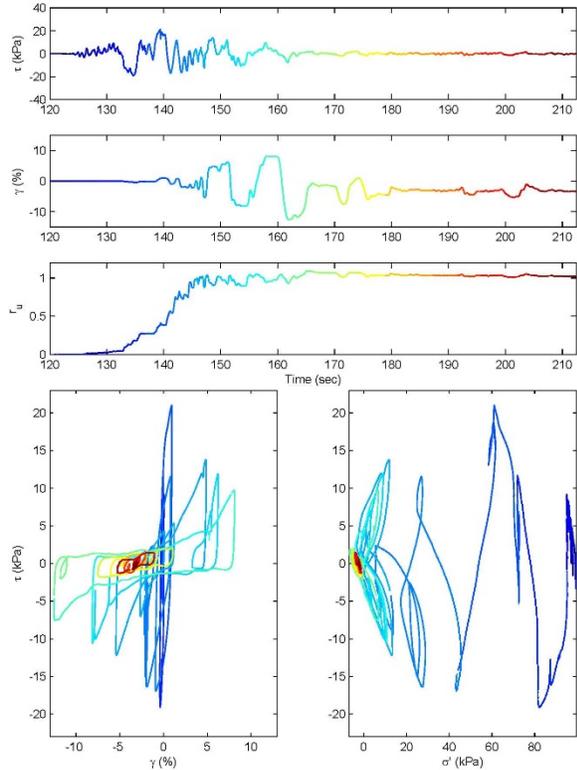
shear strain was observed in Test 4 because liquefaction was not reached until nearly the end of the ground motion. Comparing Tests 1 and 3, ground motion containing lower frequency pulses (PALMSPR_MVH135) may have a more severe impact to the soil specimen. These results suggest that the strain-induced deformations of a liquefied soil may be more closely related to the level of loading that occurs after triggering of liquefaction, rather than the measures of total loading that are often used in existing empirical procedures. This observation implies that there is a benefit to identifying the timing of liquefaction. Since the strains are shown to increase dramatically after liquefaction has been initiated, knowledge of the timing of liquefaction, and the subsequent post-liquefaction loading, could allow for better prediction of the effects of liquefaction and seismic performance. While a great deal of research has been dedicated to the study of a liquefiable soil's response to harmonic loading, there is a distinct lack of high quality testing conducted using complex transient loading histories, as would be observed during an actual event.

The dense sand tests, Tests 5-8, were conducted using loading histories with similar MSF adjusted CSR values. Therefore, each of the four tests should, based on the CSR based liquefaction procedures, have a similar binary outcome, liquefied or not liquefied. However, test results showed Tests 6 and 7 reached liquefaction, but only limited pore pressures ($r_u \sim 0.35$) and deformations were generated for Tests 5 and 8. The results presented here indicate that the pore pressure response of a soil subjected to transient loading can be highly variable, and suggest that perhaps

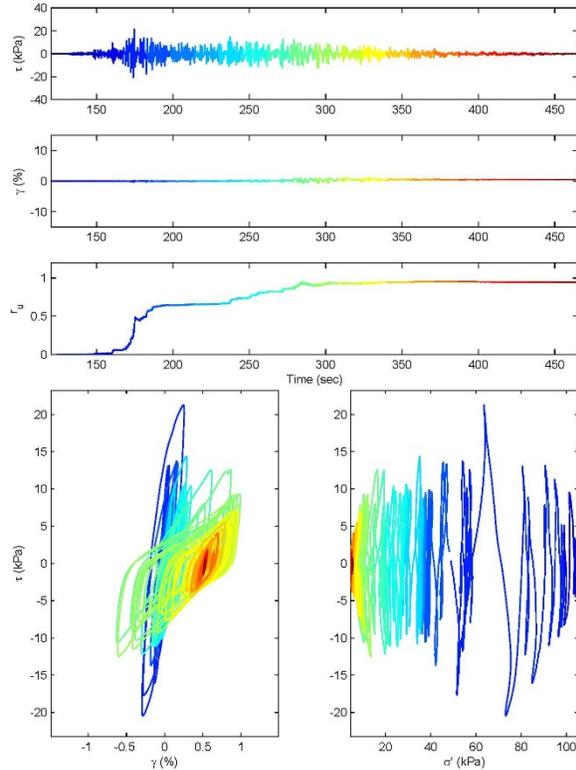


Test No.1. GREECE, $D_r=41\%$, $CSR=0.21$

Test No.2. KOCAELI, $D_r=37\%$, $CSR=0.21$

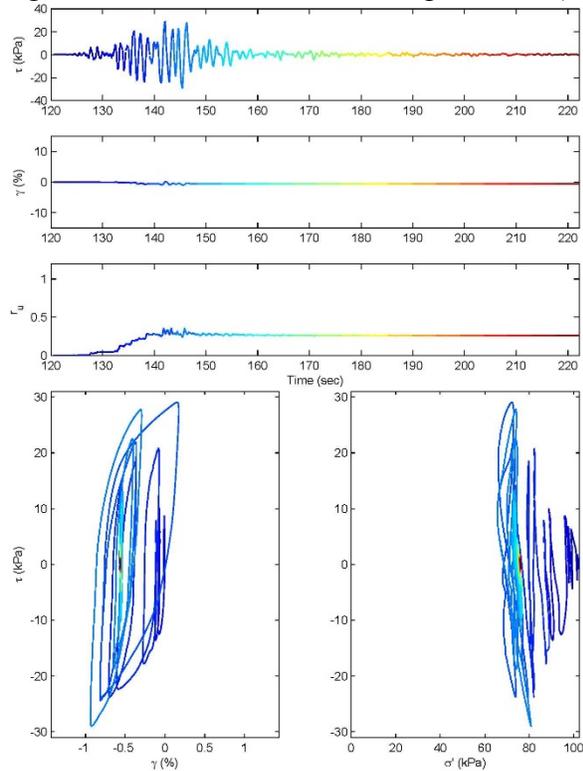


Test No.3. PALMSPRM, $D_r=40\%$, $CSR=0.21$

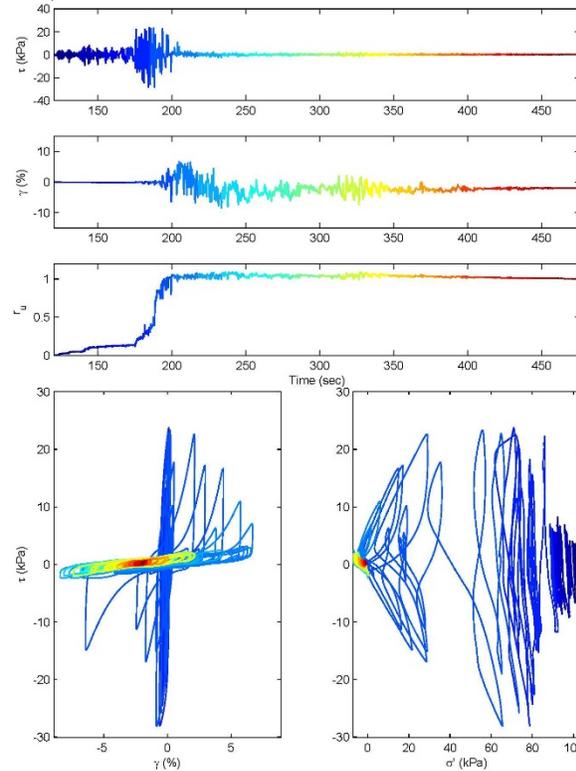


Test No. 4. LANDERS, $D_r=47\%$, $CSR=0.21$

Figure 5. Results for loose specimens (Test 1-4)



Test No.5. GREECE, $D_r=73\%$, $CSR=0.293$



Test No.6. KOCAELI, $D_r=74\%$, $CSR=0.271$

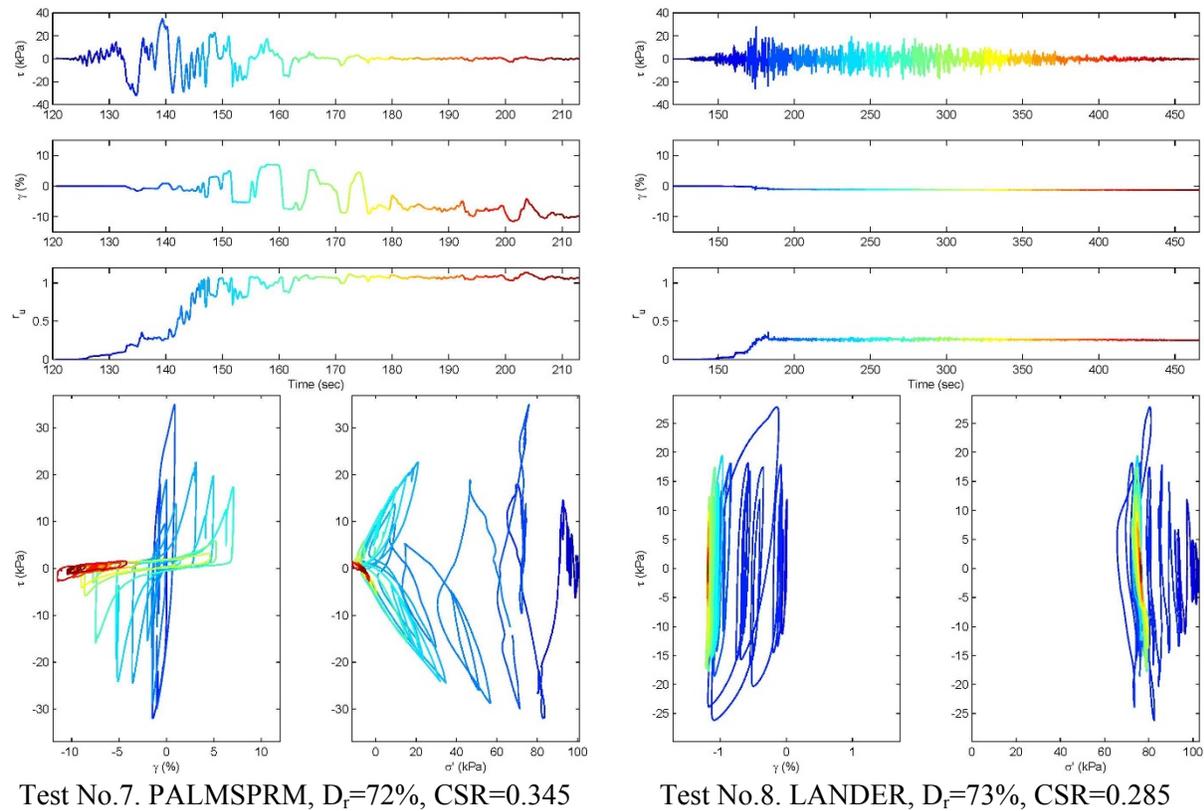


Figure 6. Results for dense specimens (Test 5-8)

the current standard of practice, which characterize the earthquake loading using peak parameters as well as a magnitude scaling factor, are may not able to capture all of the important temporal and frequency domain characteristics of a ground motion that contribute to the generation of pore pressure in a soil deposit.

Conclusions

Improved characterization of earthquake loading is important to improve soil liquefaction hazard evaluation. The loose specimen test result suggests that there could be significant benefits to being able to identify the timing of liquefaction, as it could greatly improve predictions of the effects of liquefaction. MSF adjusted CSR values were applied to the dense specimens, and the test results may indicate that the current simplified liquefaction evaluation procedure is not enough to describe soil response under earthquake loadings. While the experimental data presented in this paper is limited, the results show the dependence of the excess pore pressures on the time domain characteristic of the ground motions. These time domain characteristics might not be fully accounted for the current peak parameters and magnitude scaling factors. The preliminary results reported in this study suggests the need for the development of improved, and more informative, procedures for the evaluation of liquefaction potential, the effects of liquefaction, and improved constitutive models for liquefiable soils.

Acknowledgments

The research described in this paper was supported by National Science Foundation, George E. Brown, Jr. Network for Earthquake Engineering Simulation Research program, under Grant No. 0936408. The authors would also like to acknowledge the efforts of Ms. Patricia Bennett, an undergraduate student at The University of Texas at Austin, for her contributions to this work.

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