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Liquefaction Behavior of Mississippi River Silts

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ABSTRACT: Civil infrastructure built on alluviums and recent deposits, such as dams, contain significant amount of silts. The static and dynamic behavior of these fine-grained soils has been investigated less than the clay-like or sand-like soils. Low plasticity silts (PI = 6) obtained east of St. Louis in Illinois are known as loess that has been re-deposited by water in the floodplains of the Mississippi River. These silts were reconstituted in the laboratory by slurry at water content above the liquid limit and then consolidated to an initial effective stress. The initial laboratory characterization under monotonic loading included a series of consolidated undrained triaxial compression tests at different effective confinement to determine the critical state parameters. A series of stress-controlled cyclic triaxial compression tests were run under normally and overconsolidated conditions. The liquefaction behavior of the silt at different over consolidation ratios and its relationship to the monotonic behavior is presented and discussed.

INTRODUCTION

The determination of the liquefaction potential of low plasticity silts has been a challenge in geotechnical engineering. Liquefaction is a phenomenon that is typically associated with sands, loss of strength, and large deformations often induced by dynamic loading. In late 1990s, more evidence during and after earthquakes has indicated that liquefaction also can occur in both non-plastic and plastic fine-grained soils. Several criteria have been suggested to assess the liquefaction potential of these soils. One of the first of these was the Chinese Criteria, which has been modified several times. It was recognized early on that as the plasticity of the soil decreases the potential to liquefaction. Some of these modifications are not associated with a magnitude of earthquake or loading intensity. Several researchers in the past 10 years have been focusing on the static and dynamic behavior of non-plastic silts (Brandon, et al. 2006; Boulanger and Idriss, 2004; Fleming and Duncan, 1990; Guo and Prakash, 1999).

Non-plastic silts have characteristics that are common to both sands and clays (Brandon, et al. 2006). Silts are more affected by compression than are sands. However, silts become denser under vibration more easily than do clays. Normally consolidated silts, unlike normally consolidated clays, tend to dilate upon shearing, and the deviator stress continues to increase with increasing strain (Fleming and Duncan, 1990).

Obtaining undisturbed samples of non-plastic silts for triaxial and consolidation testing is very difficult (Fleming and Duncan, 1990). Unlike clays, no apparent cohesion exists to hold the sample together as it is being transferred to a laboratory facility. In addition, methods such as the moist tamped method, which are commonly used to prepare sand specimens, do not produce a silt structure that is comparable to the structure observed in nature. The disturbance of silt samples highly influences their shear strength.

It has been observed that the strong dilation of low plasticity silts in triaxial compression can cause adsorbed gases to escape the pore water (Penman, 1953). This phenomenon has been known to be a major source of error and miscalculation. Also, because of the high absolute dilation of low plasticity silts, determining the undrained shear strength and failure is very complex (Fleming and Duncan, 1990).

LABORATORY TESTS (EXPERIMENTAL PROGRAM)

Description of Materials & Equipment

The soil material being tested is a low plasticity silt which was originally deposited by wind as the upland loesses on the east bank of the Mississippi River in Collinsville, Illinois. The materials were obtained from a dry bank and transported to the UMR laboratories in bulk for testing. The liquid limit is 28 and the PI is equal to 6 with a percent clay fraction of about 16.5%. The soil classifies as a ML, close to the border of the CL-ML region in the plasticity chart.

The experimental program was carried out using a servo-controlled triaxial compression system developed by GCTS, Inc. The equipment is controlled by a program that receives feedback from the multiple sensors on the system. The chamber has a capacity of about 180 psi and the pneumatic actuator that can apply axial load at frequencies of about 5 Hz. The advanced programming capability to stop the test after cyclic loading (when liquefaction is reached) and then perform a static test were very helpful to assess the post-liquefaction behavior of the silt material. A network webcam is mounted inside the geotechnical laboratories and aimed at the cyclic triaxial equipment for public viewing and can be found at: http://geotech.umr.edu/geolab.html

Preparation of Specimens

The specimen preparation techniques for this experimental program were varied and they were evaluated to examine their quality and uniformity. All samples were prepared from silt slurry with a water content of 44%. The amount of water content is very important and has a considerable amount of influence on the uniformity of the samples. As seen by Kuerbis and Vaid (1988) and Romero (1995), if the water content is too low, then air voids can form within the specimen. If the water content is too high, stratification within the silt can be a problem.

Initially a large specimen was prepared in a large diameter consolidometer using radial consolidation and later using thin-walled tubes triaxial specimens were extracted. Additionally, another series of specimens were prepared on a 2-inch diameter split mold with top loading only. The uniformity of the specimens were obtained by examining the change in water content across the sample, since the water content can be directly correlated to the initial density.

It was observed that when specimens were consolidated using only top loading, a significant change in water content ($\Delta w = 3.5\%$) was found from top to bottom. The friction between the silt and the membrane causes a non-uniform density distribution. The problem caused by the friction is more evident were the silt is more distant from the loading source. In order to solve this problem a vacuum pressure equal to the consolidation pressure was applied to bottom of the specimen to equalize stresses. The vacuum pressure was applied after the initial consolidation of the sample was performed using top loading. With this method changes in water content ($\Delta w = 1.4\%$) throughout the sample were reduced.

Static tests and determination of shear strength parameters

A series of tests was conducted on low plasticity silts. The results showed that the undrained stress-strain behavior changed as the OCR was varied. The silt specimens' initial contractive behavior changed to dilative behavior as the OCR increased. The boundary between dilative behavior and contractive behavior was seen at an OCR of about 2. This has been illustrated in Figure 1. The normally consolidated specimen (F2G) shows contractive behavior, while the silt with an OCR of four (F2I) shows dilative behavior. The sample that has OCR of 2 (F2H) shows neither contractive nor dilative behavior. It is important to note that the OCR did not have an effect on the failure criteria and did not change the friction angle. On the other hand, the initial density was the most important factor defining failure and the friction angle.

Another important finding was that the classical steady-state behavior was not seen in the tested silt, even though the pore water pressure stabilized at very high strains. The stabilization of the pore water pressure was caused by cavitation of the pore fluid. This happened when the pore water pressure fell below the initial back pressure used for saturation. Therefore, it is very important to control and monitor the amount of back pressure and the pore water pressure generated in order to ensure the sample stays in its saturated state.

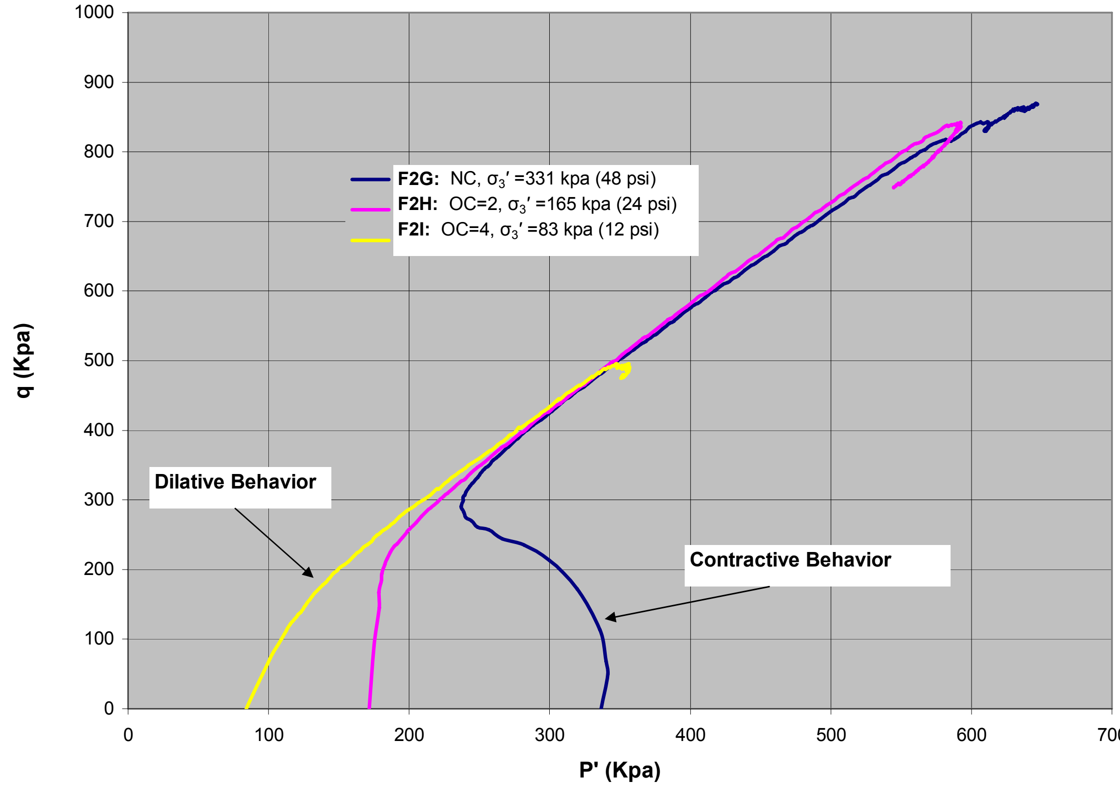
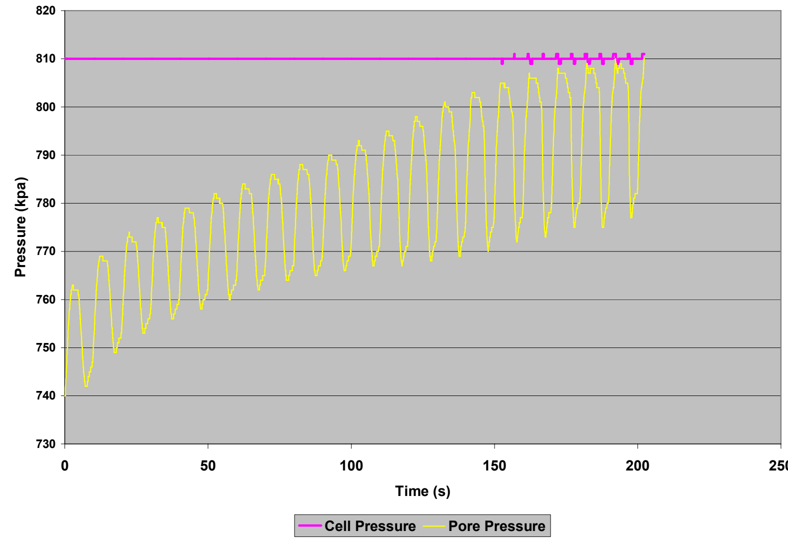


Fig. 1. Stress Paths of Monotonically loaded undrained triaxial tests performed on low plasticity silts with varying OCR

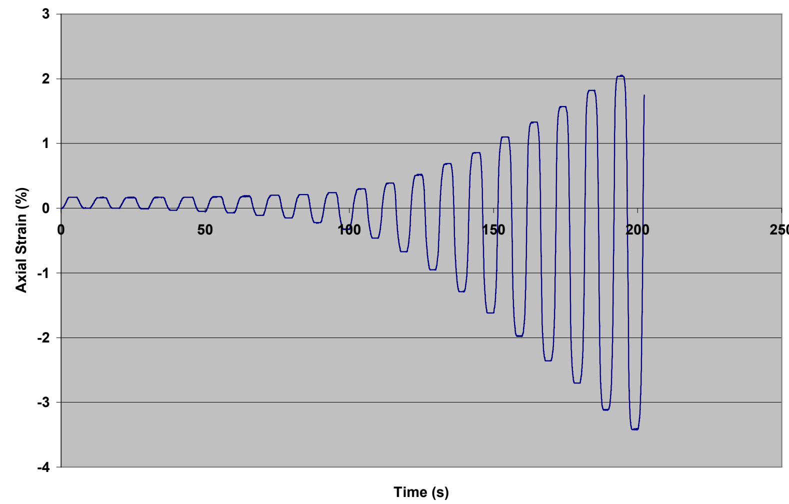
Based on extensive triaxial testing of the subject silt materials, the state parameters were determined for monotonic loading. The normally consolidated line was determined by plotting the void ratio vs. effective stress and the stress paths were traced to find the critical state line. The slope of the NCL or (λ) was found to be 0.05 and the slope of the recompression line (κ) was found to be 0.007. The effective internal angle of friction (ϕ) was determined to be about 35 degrees. This information was used to determine the objectives of the cyclic loading from a wet and dry of critical conditions. Therefore, the cyclic tests were run at corresponding OCR of 1, 1.5, 2 and 4 to capture the different behavior at different initial conditions.

Cyclic Triaxial Testing

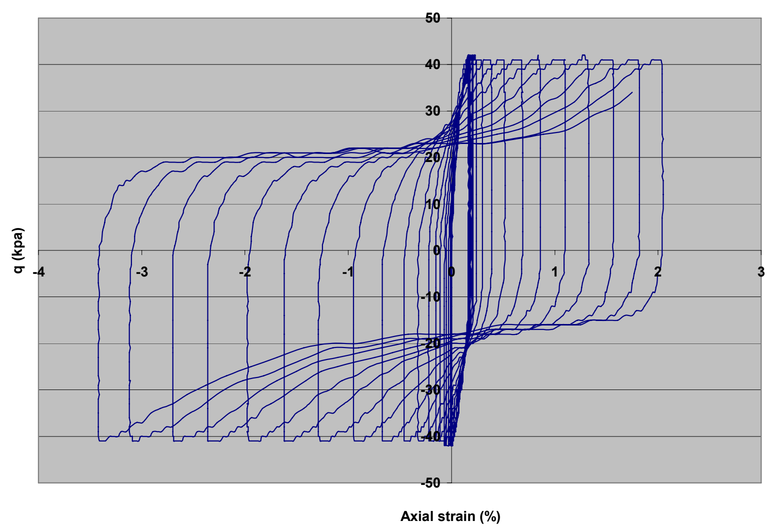
The cyclic triaxial test data are presented herein as typical results of the series of stress-controlled liquefaction tests. The test setup applies a constant cyclic stress to the specimen and measures the response of the deformation and pore pressure buildup. For example, a specimen consolidated to 10 psi tested at a frequency of 0.1 Hz at a cyclic stress ratio of 0.3 are shown for the entire duration of the test in Figure 2a and 2b, respectively. The pore pressure buildup and axial stress vs. time are captured by the data acquisition system and a liquefaction condition can be easily identified. Additionally, the hysterisis curve and degradation of the shear modulus are shown in Figure 2c.



(a)



(b)



(c)

Fig. 3. Typical Results of cyclic testing conducted on NC low plasticity silt

Cyclic tests at different over-consolidation ratios

The effects of overconsolidation and stress history on the liquefaction potential of soils have not received the needed attention. This is partially do to fact that overconsolidation is not a major player in dynamic properties of sands. Even though the effect of overconsolidation has been studied extensively for clay like material less emphasis has been on the liquefaction potential of overconsolidated clay-like soils. Due to the lack of information on stress history with regards to cyclic strength of soils, an experimental study was conducted to analyze the effect of OCR in low plasticity silts.

In an effort to isolate the effect of overconsolidation, the effective confinement pressure at the time of cyclic loading was the same for all the tests. This was achieved by consolidating the specimens to a higher confinement pressure and then lowering the confinement pressure to the base confinement pressure used for all the tests. Overconsolidation ratios of 1.5, 2, and 4 specimens were prepared and tested and the results were compared to the normally consolidated specimens. The overconsolidated tests are summarized in Table 2.

Table 2. Summary of Cyclic Triaxial Testing Program

TEST	Initial confinement pressure σ_3'	Cyclic confinement pressure σ_3'	OCR	CSR	Time to Liquefaction (sec)
D11	52kpa (≈7.5 psi)	35kpa (≈5 psi)	1.5	0.45	22.5
D12	70kpa (≈10 psi)	35kpa (≈5 psi)	2	0.45	31.9
D13	70kpa (≈10 psi)	35kpa (≈5 psi)	2	0.35	212.1
D14	70kpa (≈10 psi)	35kpa (≈5 psi)	2	0.30	461.9
D15	140kpa (≈20 psi)	35kpa (≈5 psi)	4	0.45	211.9
D16	140kpa (≈20 psi)	35kpa (≈5 psi)	4	0.35	-

DISCUSSION OF RESULTS

The ability to perform more sophisticated stress paths is now possible with the servo-controlled equipment. For example, specimens can be consolidated to a desired effective confining pressure and then cyclic loading applied until liquefaction is reached. Then after this failure condition is reached, a static shear test can be performed on the liquefied soil to obtain the post-liquefaction shear strength. Judgment is needed to determine at what state of reconsolidation should the tests be performed, since the liquefaction stage is a transient condition. With time the pore-pressure build-up due to cyclic loading will eventually dissipate.

This process can be examined in the stress path shown in Figure 3. After the specimens were consolidated isotropically to the desired effective confining pressure (e.g., 70 psi), the drainage paths are closed and the cyclic axial loading starts until the specimen liquefies. The GCTS control program is configured to automatically stop the cyclic load when the effective pore water pressure reaches the effective confinement pressure. This section of the test is illustrated in blue in Figure 3. The deviator stress is slowly lowered to zero and the bottom drainage line is opened while keeping the same 70 psi consolidation pressure as the back pressure. The excess pore water pressure slowly dissipates back to 70 psi (illustrated in red). By monitoring the pressure on top of the sample, one can determine when the sample has dissipated all of the excess pore water pressure. Next, the drainage valves are closed in order to perform an undrained monotonic test on the specimen (illustrated in yellow). This procedure can be refined to perform static tests at post-liquefaction conditions, which is being presented in a separate publication by the authors.

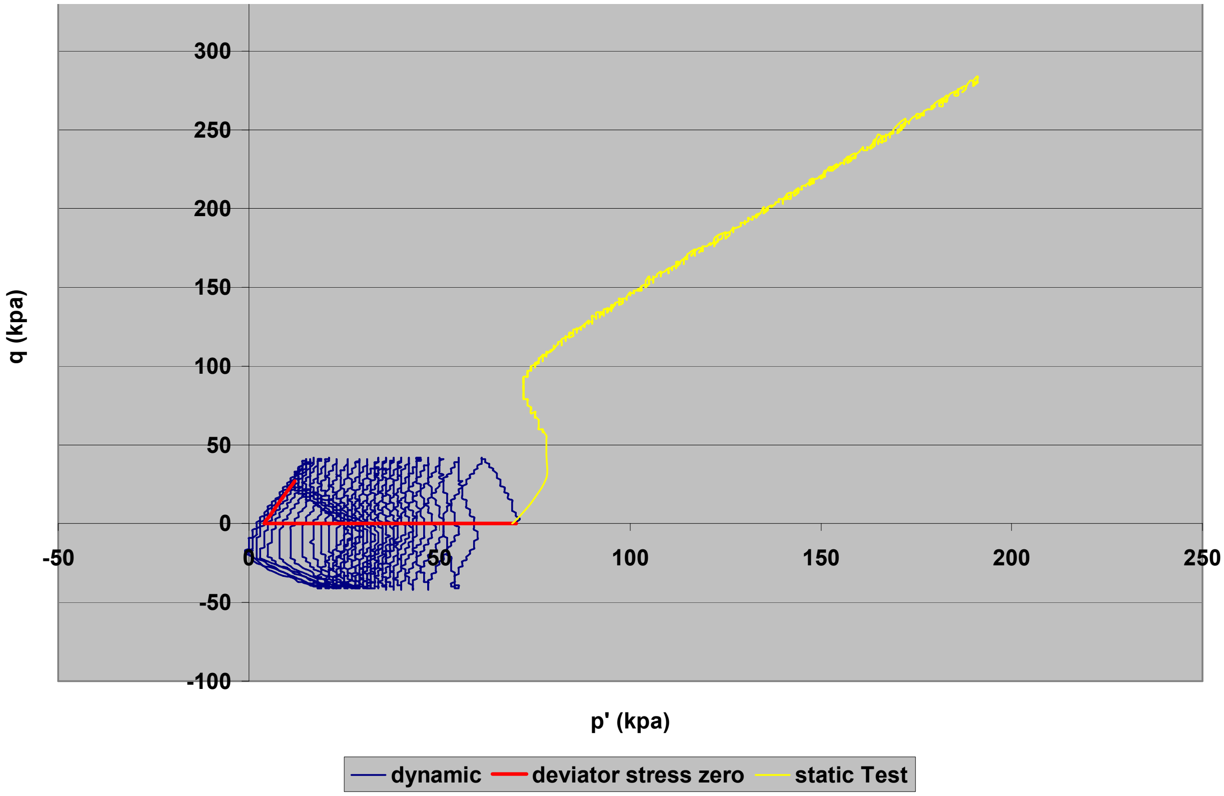


Fig. 3. Result of cyclic and static test conducted on low plasticity silt (Izadi, 2007)

Cyclic stress ratios to liquefaction and the effect of OCR

In order to analyze and compare the effect OCR, the results for the normally consolidated specimens were plotted together with the overconsolidated test results. Figure 4 shows the cyclic stress ratio versus number of cycles to liquefaction for both NC and OC specimens. The normally consolidated specimens were duplicated to ensure the testing procedures are repeatable and accurate, they are very close to each other. Then, the OCR was increased and consequently the resistance to liquefaction increased accordingly. Similarly, the decrease in cyclic strength was also evident with the decrease in cyclic stress ratio (CSR). For the specimens with an OCR of 4 and cyclic stress ratio of 0.35 liquefaction was not reached and there was no evident buildup of pore water pressure. Therefore, further increase of OCR (> 4) was deemed unnecessary.

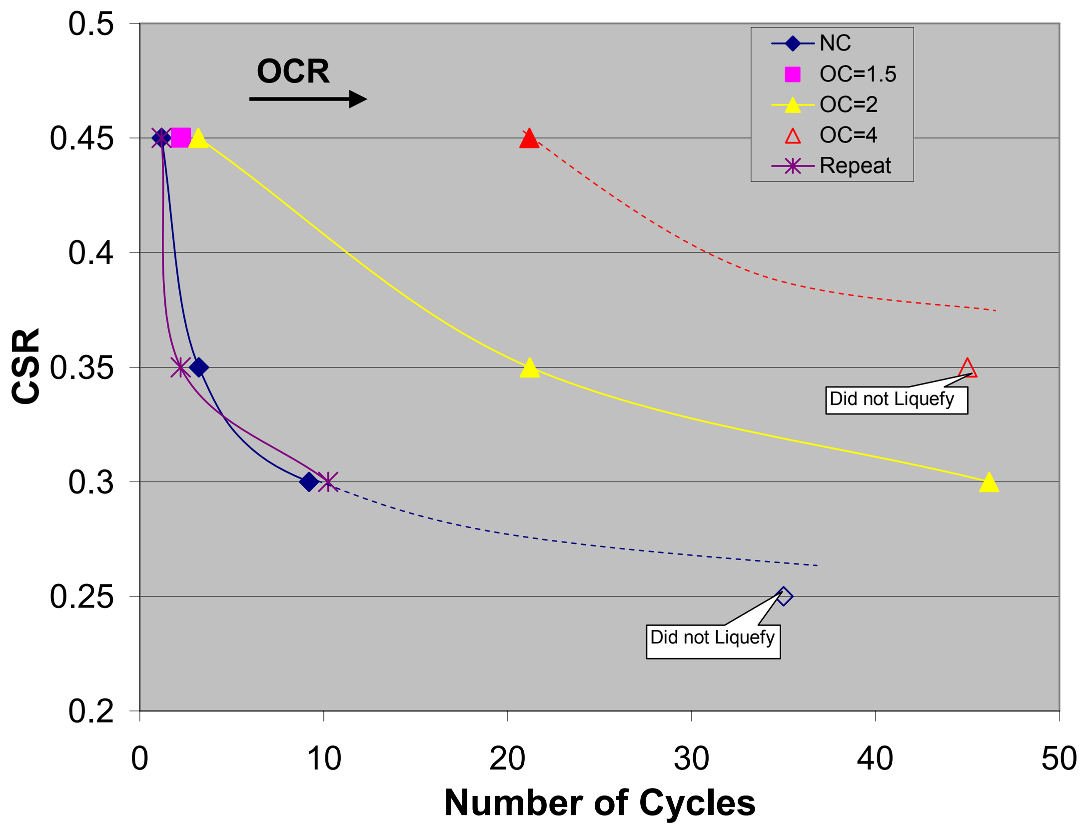


Fig. 4. The effect of Overconsolidation on the Resistance to Liquefaction

Figure 5 illustrates the pore pressure ratio $\left(r_u = \dfrac{\Delta u}{\sigma'}\right)$ versus time to liquefaction for different specimens consolidated at different effective confining stress and different cyclic stress ratios. The p′ - q (Cambridge stress space) plots of a liquefied (D13) specimen and a specimen that did not liquefy (D16) are illustrated in Figure 6 and clearly shows the effect of overconsolidation. It can be noted that the stress path for the NC specimen (D13) moves to the left towards failure as the pore water pressure builds up and the stress path of the specimen (D16) with higher OCR remains stationary over several cycles.

SUMMARY AND CONCLUSIONS

The results presented in this paper are part of a project that studies the fundamental behavior of silts under dynamic loading. Much care was taken in developing the procedure to reconstitute specimens from a slurry. Small variations in water content result on changes in soil density that are directly related to the shear strength of the material. The proposed method using top loading and vacuum from both ends ensures a more uniform specimen density.

Silts have both clay-like and sand-like tendencies from different points of view. Overconsolidation can be induced quite readily and pore pressure builds up easily like in clays. However, dilative behavior in its dense condition can be observed at low levels of deviator stress. The behavior of this low plasticity silts is quite dependent on the level of overconsolidation and clearly the normally consolidated clays particularly are vulnerable to undrained loading. At an OCR of 2.0 the silt starts having a dilative behavior and develops negative pore pressure during static shear. Near this level of overconsolidation is where the phase transformation takes place and the material continues to dilate at large strains. These results are similar to the data shown in Brandon, et al. (2006) and were also repeatable in the UMR laboratories. At an OCR greater than 2.0 the silt has a dilative behavior at low strain. When the deviator stress reaches the failure envelope the stress path moves along the failure envelope or K_f line, but the specimens continue to dilate. Hence, liquefaction will take place at both low CSR and low number of cycles for low OCR silts. However, slight increases in OCR are enough to make the specimen resistant to liquefaction.

Non-plastic or low plasticity silts continue to be difficult to test and their behavior difficult to understand in dynamic loading. It is clear that the effect of OCR on these Mississippian silts impacts their susceptibility to liquefaction.

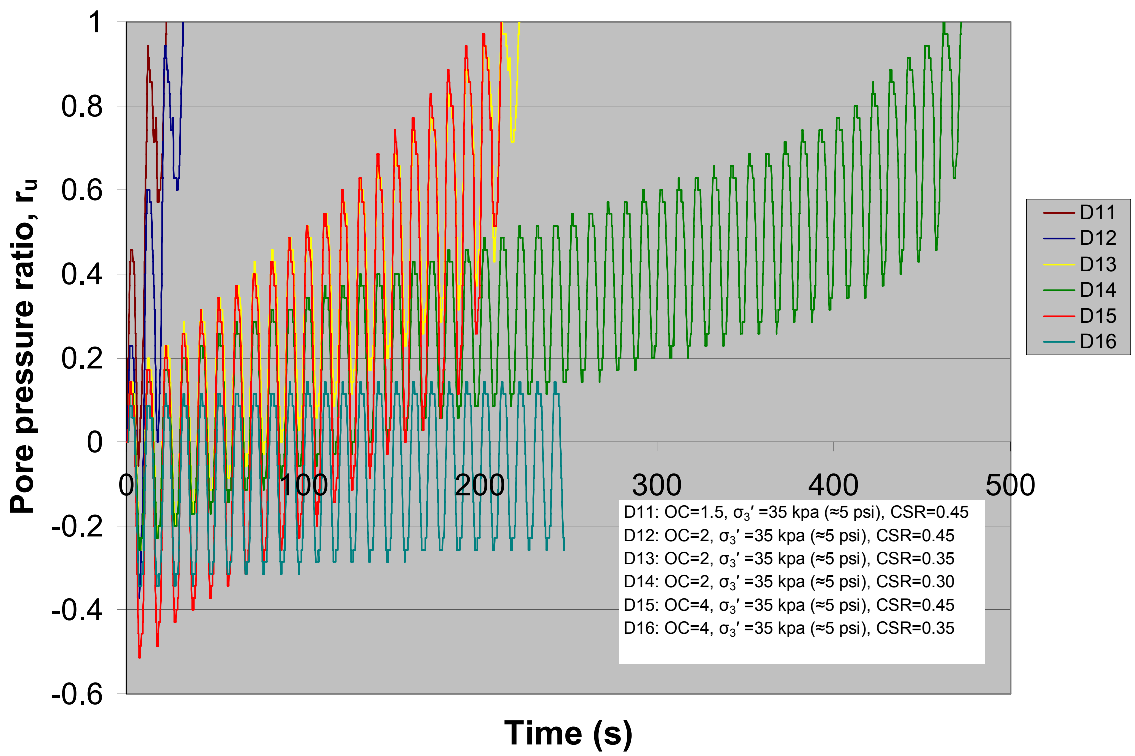


Fig. 5. Build-up of pore pressure ratio vs. time (notice D16 does not liquefy)

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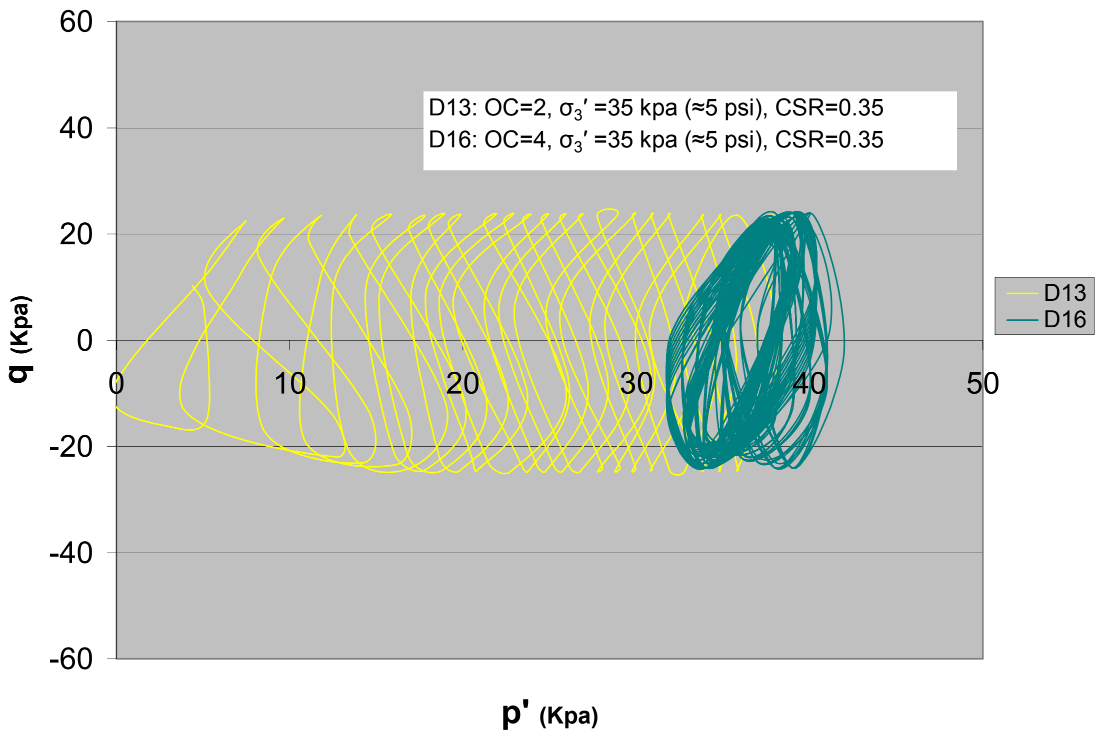

Fig. 6. Specimen D13 and D-16 at the same initial confining pressure and CSR, but different OCR (D13 liquefies and stress path moved to the left).

REFERENCES

Boulanger, R.W. and Idriss, I.M. (2004). "Evaluating the Potential for Liquefaction for Cyclic Failure of Silts and Clays." Center for Geotechnical Modeling, University of California Davis, Report No. UCD/CGM-04/01.

Brandon, T.L., Rose, A.T., Duncan J.M. (2006). "Drained and Undrained Strength Interpretation for Low-Plasticity Silts." *Journal of Geotechnical and Geoenvironmental Engineering*, 132, 250-257pp.

Fleming, L.N., and Duncan, J.M. (1990). "Stress-deformation characteristics of an Alaskan silt." *Journal of Geotechnical Engineering*, 116(3), 377-393.

Guo, T., and Prakash, S., (1999), "Liquefaction of Silts and Silt-Clay Mixtures." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 125, No. 8, 706-710.

Izadi, A., (2007), "Static Behavior of Silts", MS Thesis, University of Missouri-Rolla, 82 pp.

Kuerbis, R., and Vaid, Y.P. (1988), "Sand Sample Preparation-The Slurry Deposition Method." *Soils and foundations*, Vol. 28, No. 4, 107-118.

Penman, A.D.M. (1953). "Shear characteristics of a saturated silt measured in triaxial compression." *Geotechnique*, 3, 312–328.

Romero, S. (1995). "The Behavior of Silts as Clay Content is Increased. MS Thesis, University of California-Davis, 108 pp.