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# Undrained Response of Clean and Silty Sands

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# UNDRAINED RESPONSE OF CLEAN AND SILTY SANDS

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ABSTRACT

An experimental investigation was undertaken to study the effect of small amounts nonplastic fines on the undrained shear response of sands. Mixtures of Ottawa sand containing 0, 5, 10 and 15% nonplastic silts were studied in a triaxial set up under undrained conditions. The response of the mixtures was summarized based on four characteristic states observed during undrained shearing. These states are the flow liquefaction state, the phase transformation state, the quasi steady state and the critical state. The effects of silt content and initial fabric on relationships describing these characteristic states are highlighted in this paper.

## INTRODUCTION

Traditionally, studies of soil behavior have focused on either clean sands or soft clays. Often geotechnical engineers fit the behavior of many transitional geomaterials to these classifications. However, some geotechnical failures, especially those related to liquefaction, have underscored the importance of a deeper understanding of the behavior of transitional or 'nontextbook soils', such as silty and clayey sands and cemented sands. The effect of small amounts of fines on the cyclic behavior of sand has been extensively studied (see Yamamuro and Lade 1999, Salgado et al 2000 and Carraro et al. 2003). The results of an experimental study on the effect of fines on the undrained monotonic behavior of sands are presented here. The results are presented in the critical-state soil mechanics framework to facilitate use of the data in the determination of parameters of constitutive models for these nontextbook soils. In addition, an effort is made to present the results highlighting the stages of the undrained shear response of sands that have significance in geotechnical practice.

## BACKGROUND

Many important studies of the behavior of silty sands have focused on studying the cyclic behavior of silty sands using triaxial tests. Been and Jefferies (1985) tested Kogyuk sands with different percentages of nonplastic silty fines in order to draw critical state boundaries. The authors noted that the slope and the intercept of the critical-state line increased with addition of fines. Zlatovic and Ishihara (1997) investigated the effect of initial fabric and the percentage of fines on sand behavior. Three methods of sample preparation were used in their testing program (moist tamping, air pluviation, and water pluviation). The critical state of sand in stress space ($p'$ *vs.* $q$ space) was found to be unaffected by the initial fabric of the specimens. The contractiveness of silty sand was found to increase with the addition of silt. Thevanayagam (1998) and Thevanayagam et al. (2002) investigated the effects of addition of silt on sand behavior and provided a qualitative framework describing the evolution of sand fabric in the presence of silt. They also showed the downward translation of the critical-state line in $e$ *vs.* $p'$ space. Ni et al. (2004) showed that the overall dilativeness of sand decreases with increasing fines content at a given void ratio.

## EXPERIMENTAL PROGRAM

All the experiments in this program were performed on standard ASTM C 778 sand (commonly known as Ottawa sand). Ottawa sand is a silica sand with rounded to subrounded particles. The sand is classified as SP according to the USCS classification system. The uniformity coefficient and the mean grain size of the sand particles are equal to 1.43 and 0.39 mm, respectively. The nonplastic silt (referred to as SIL-CO-SIL) used in the experiments was obtained by crushing the sand particles. The grain size distributions of the different sand-fine mixtures used are provided in Figure 1. The maximum and minimum void ratios of the sand-fine mixtures were estimated using the procedure outlined in ASTM D 4253 and D 4254, respectively, and are given in Table 1.

Table 1. Maximum and minimum void ratio for sand-silt mixtures

| % silt | $e_{max}$ | $e_{min}$ |
|---|---|---|
| 0 | 0.78 | 0.48 |
| 5 | 0.70 | 0.42 |
| 10 | 0.65 | 0.36 |
| 15 | 0.63 | 0.32 |

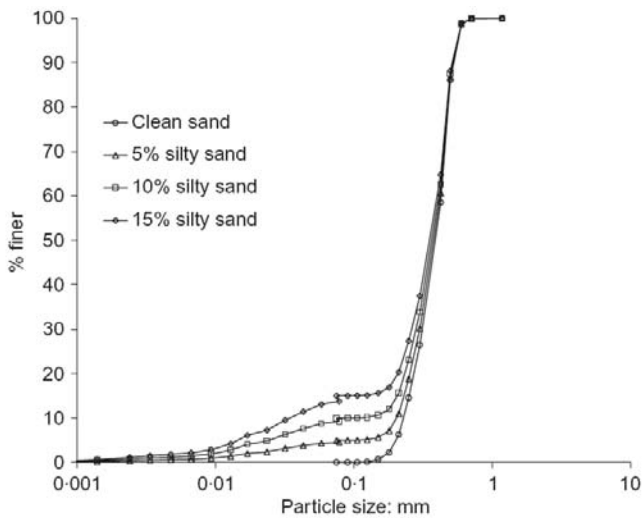


*Figure 1. Grain size distribution curves for Ottawa sand and sand-fine mixtures*

The CKC automatic triaxial testing system (Soil Testing Equipment Co, San Fransisco, CA) (Chan 1981) was used for performing the triaxial tests. Silty sand specimens were prepared using mainly two methods: slurry deposition (SD) and moist tamping (MT). The prepared triaxial specimens were subjected to saturation, isotropic consolidation, and monotonic shear under undrained conditions. Further details of the apparatus, sample reconstitution techniques and experimental protocols are outlined in detail elsewhere (Murthy 2006, Murthy et al. 2007).

CHARACTERISTIC STATES

Fifty-nine undrained monotonic triaxial compression tests were perfomed on sand-fine mixtures in this experimental program. The results of these tests show four characteristic states encountered during undrained shear: undrained instability state (UIS), quasi steady state (QSS), phase transformation state (PTS) and critical state (CS). Figure 2 shows in schematic form the undrained behavior of sandy soils in triaxial compression. This behavior is represented in stress-strain space (axial strain vs. mean effective stress - $\varepsilon_1$ vs. p') and stress space (mean effective stress vs. deviator stress - p' vs. q).

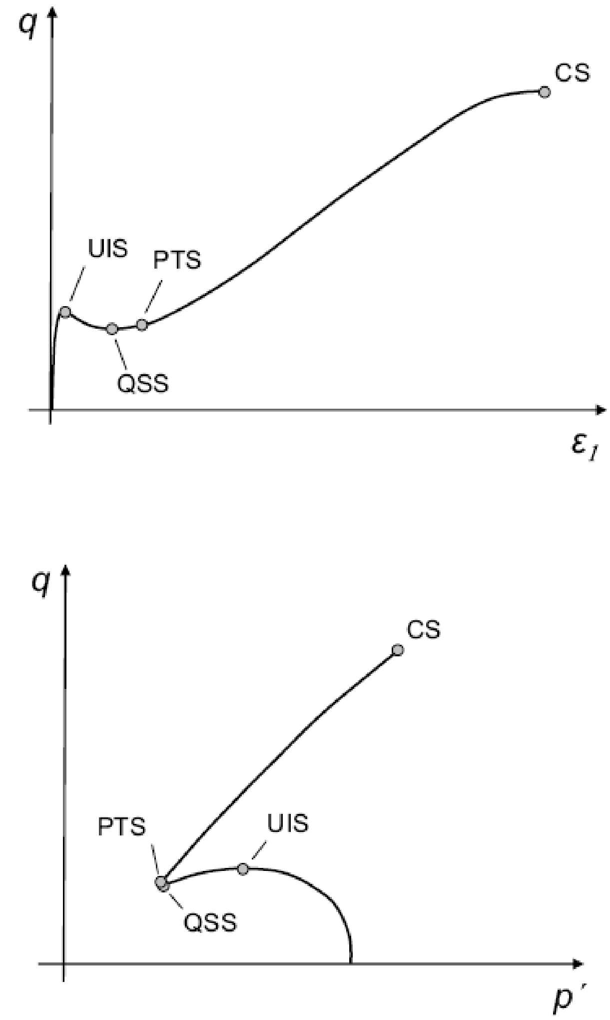


*Figure 2. Typical undrained response of sandy soils in triaxial compression.*

*Undrained Instability State (UIS)*
The undrained instability state represents the state that constitutes the onset of flow liquefaction during undrained shear. It is the state at which q reaches a local temporary maximum. The UIS state vanishes for tests that start from soil states that are well below the CS line. The UIS is of interest in geotechnical design as it corresponds to a peak in strength of the sand at relatively low strains.

*Quasi Steady State (QSS)*
The quasi steady state is defined as the state at which the deviatoric stress (q) reaches a local minimum in undrained

shearing. The QSS represents the minimum strength of the soil at small strains.

*Phase Transformation State (PTS)*
The phase transformation state is the state at which the sand response changes from contractive to dilative. It is associated with a minimum in mean effective stress.

*Critical State (CS)*
Critical state is the state at which a soil reaches a combination of stress and void ratiofor which the soil deforms at constant stress (p', q) and void ratio (e) (Roscoe et al. 1958)

RESULTS

The critical state is characterized by stable values of density and stresses (including pore pressures) with continuous shearing. The stresses and void ratio of the soil at the critical state are plotted in *e vs. ln p'* space in Figure 3. The data presented in the figure does not distinguish between various sample preparation methods or the initial state (i.e., mean effective stress and void ratio).

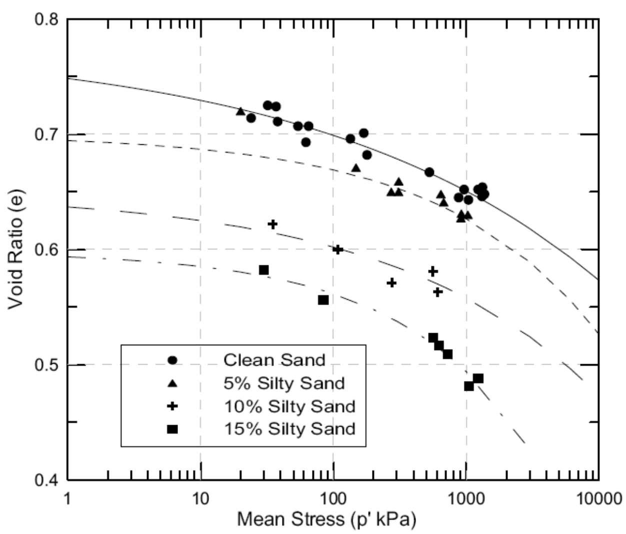


*Figure 3. Critical state of clean and silty sands*

The critical state locus is represented through a power function of the form:

$$e_c = \Gamma - \lambda \left( \frac{p'}{p_A} \right)^{\xi} \tag{1}$$

where $p_A$ is a reference stress (usually taken as the atmospheric pressure), Γ, λ and ξ are fitting parameters (Li and Wang 1998). The slope of the critical-state line in stress space (p' vs. q) is denoted as $M_{CS}$, which is related to the critical-state friction angle ($\varphi_{CS}$). A least squares regression was used to obtain the critical-state parameters from the triaxial test data (see Table 2).

Table 2. Critical-state parameters obtained from regression of experimental data.

| % of silt | Γ | λ | ξ | $M_{CS}$ ($\phi_{CS}$) |
|---|---|---|---|---|
| 0 | 0.780 | 0.081 | 0.196 | 1.216 (30.4°) |
| 5 | 0.700 | 0.030 | 0.366 | 1.237 (30.9°) |
| 10 | 0.650 | 0.048 | 0.296 | 1.311 (32.5°) |
| 15 | 0.584 | 0.020 | 0.646 | 1.367 (33.8°) |

The addition of small amounts of silt to the sand causes a downward translation of the critical state locus. The critical-state friction angle, however, increases with addition of silt. This increase in the friction angle can be attributed to the "wedging effect" that the angular silt particles have between the sand grains. The critical state loci in both e vs. ln p' space and in p' vs. q space are widely used benchmarks for quantification of the sand behavior. Different parameters have been proposed that express the distance between a given state and the critical state locus. The state parameter (ψ) (defined as the difference between the void ratio at a given mean effective stress state and the critical-state void ratio at the same stress level), a commonly used parameter, is used in this paper.

Due to the non uniqueness of the PTS in both stress space and *e vs. ln p'* space, it is beneficial to study the PTS in a given test in terms of the state parameter. Li and Dafalias (2000) proposed an equation that quantifies the dependence between the stress ratio at phase transformation and the state parameter at PTS as follows:

$$\eta_{PT} = M_{CS} e^{k_d \psi_{PT}} \tag{2}$$

where $k_d$ is a fitting parameter and $\eta_{PT}$ is the stress ratio at the PTS. Figures 4 through 6 show the $\eta_{PT}$ plotted against the state parameter at the PTS.

For these mixtures of sand with fines, the experimental data clearly indicate that the stress ratio at phase transformation increases with increasing state parameter, as suggested by equation 2.

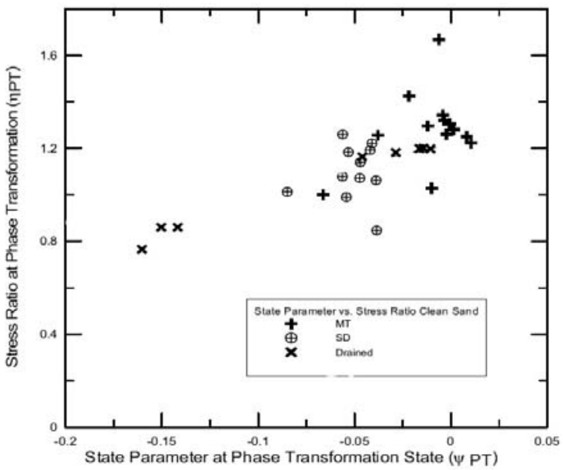


*Figure 4. State parameter vs. stress ratio at PTS for clean sands*

In order to estimate the shear strength of the soil at phase transformation, a means of predicting the mean effective stress at PTS is necessary. The 'flow potential' parameter introduced by Yoshimine and Ishihara (1998) relates the initial mean effective stress to the mean effective stress at

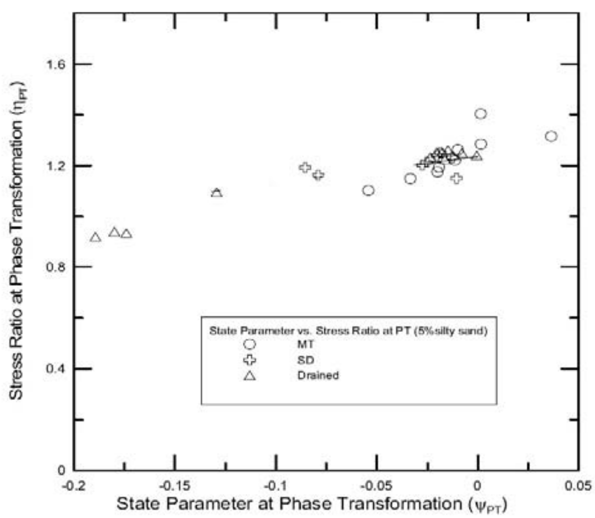


*Figure 5. State parameter vs. stress ratio at PTS for 5% silty sands*

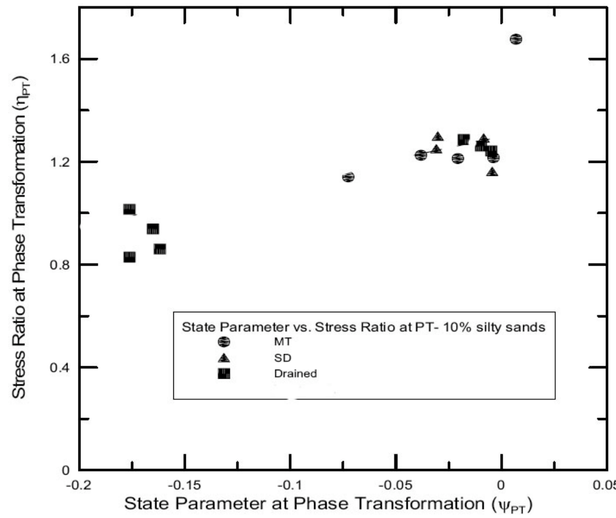


*Figure 6. State parameter vs. stress ratio at PTS for 10% silty sands*

the PTS as:

$$u_f = 1 - \frac{p'_{PT}}{p'_o} \tag{3}$$

Murthy et al. (2007) developed a relation to establish this flow potential given the initial conditions of the soil:

$$u_f = \exp\left( - \left( \frac{\Gamma - e_o}{\alpha + \gamma . \left( \frac{p'_o}{p_A} \right)^n} \right)^\beta \right) \tag{4}$$

where α, β, γ and n are constants that can be determined by least squares regression on a given set of undrained triaxial compression tests. Figure 7-9 shows the flow potential defined in equation 4 plotted against the void ratio of the specimens for a given value of initial mean effective stress. The experimental data are plotted together with the analytically generated curves for various mixtures of clean and silty sands.

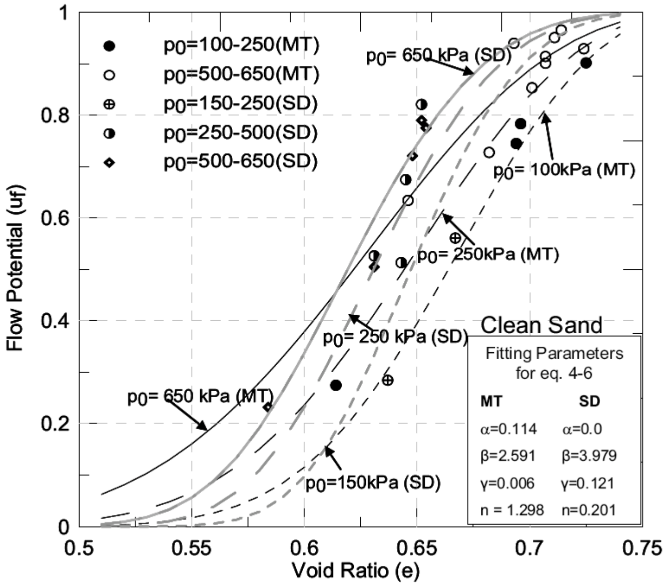


*Figure 7 Flow potential vs. void ratio for clean sand*

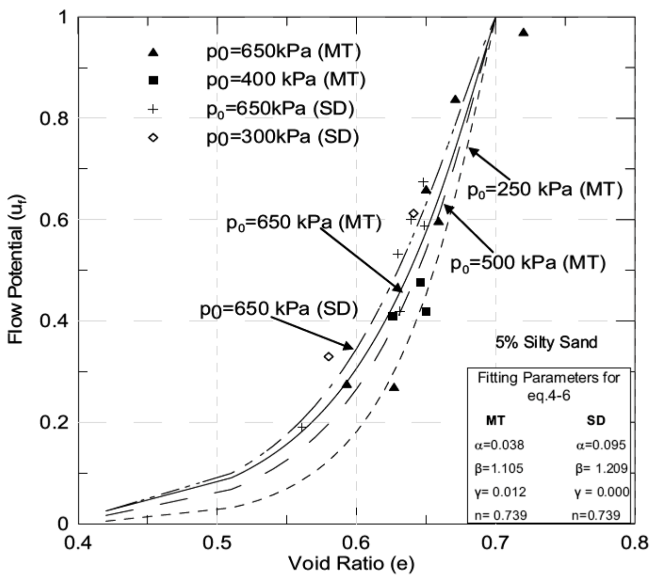


*Figure 8 Flow potential vs. void ratio for 5% silty sand*

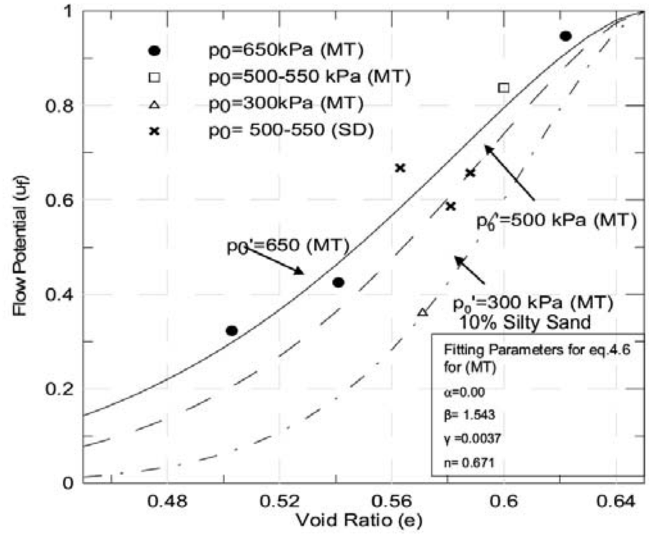


*Figure 9 Flow potential vs. void ratio for 10% silty sand*

The difference in the axial strains required to reach the QSS and the PTS is more significant for specimens with initial states on or below the CSL. The axial strain required to reach the QSS can be 20% to 40% smaller than the axial strain required to reach the PTS (Murthy et al. 2007). The stress ratios at the PTS and QSS are plotted against the initial state parameters for the sand-fine mixtures in Figure 10. It is seen that the stress ratios at these states lie in a narrow band.

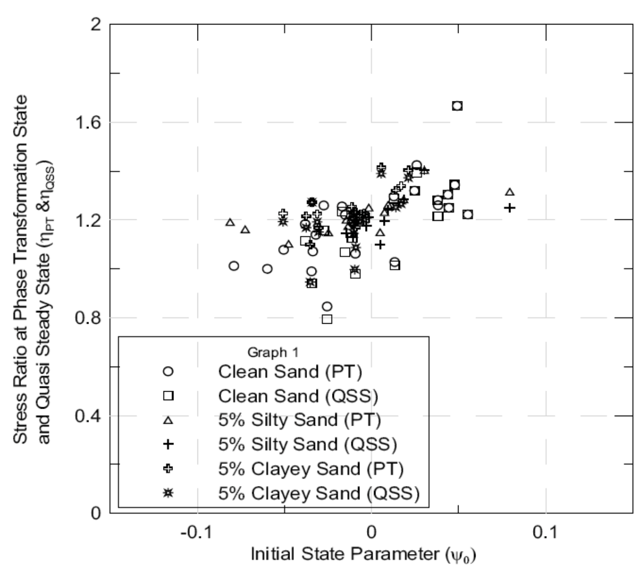


*Figure 10 Stress ratios at PTS and QSS vs. initial state parameter for sand- fine mixtures*

The undrained instability state constitutes the onset of liquefaction. The axial strain required to reach the UIS in the tests performed in the context of this study falls mainly in the 0.4 to 0.8% range, with larger strain values being associated with higher values of UIS shear strength. The shear strength at the UIS is strongly influenced by the initial fabric and stress state. The stress ratio at the UIS is presented against the initial mean stress in Figures 11-14. The data indicates that the MT specimens certainly have larger strengths than their SD counterparts at smaller strain ranges.

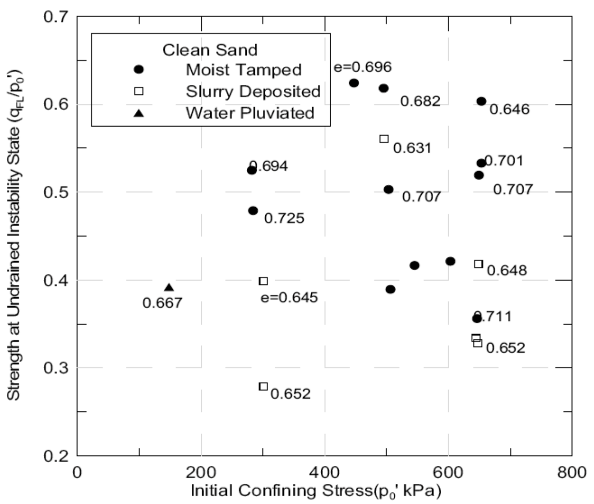


*Figure 11 Strength at UIS vs. initial confining stress in clean sands*

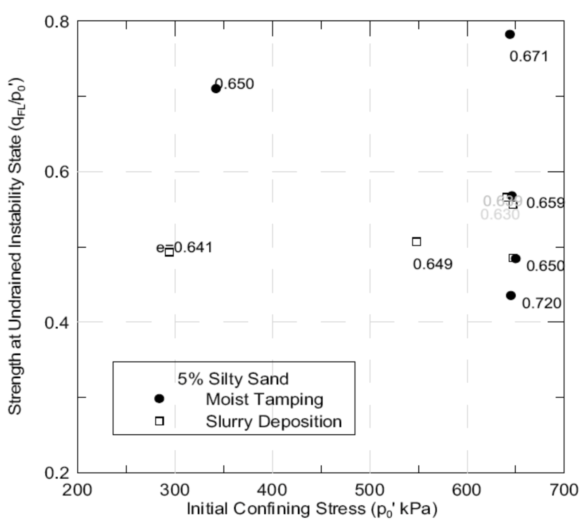


*Figure 12 Strength at UIS vs. initial confining stress in 5% silty sands*

As suggested by the triaxial test data, the effect of fabric or initial sample preparation method is small at the PTS and negligible at the CS. It can be concluded that the initial fabric of the sand influences only the early stages of shearing, with its impact erased at larger strains. As noted by Ishihara (1993), the mean effective stress at the UIS shows a strong correlation to the initial mean effective stress, with their ratio being generally around 0.6. This was generally found to be true even in this testing program for the clean sand and the three sand-fine mixtures considered here.

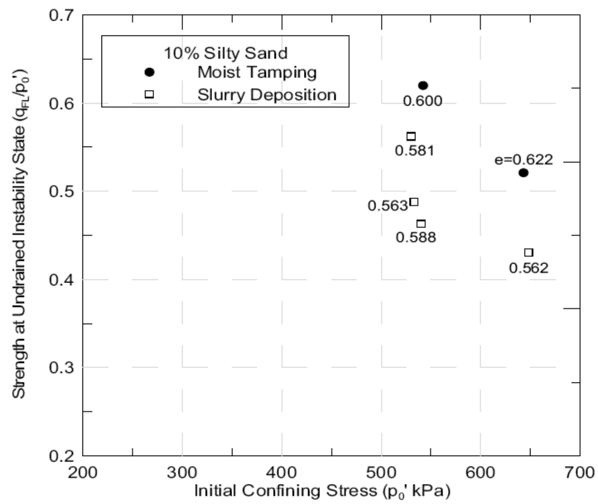


*Figure 13 Strength at UIS vs. initial confining stress in 10% silty sands*

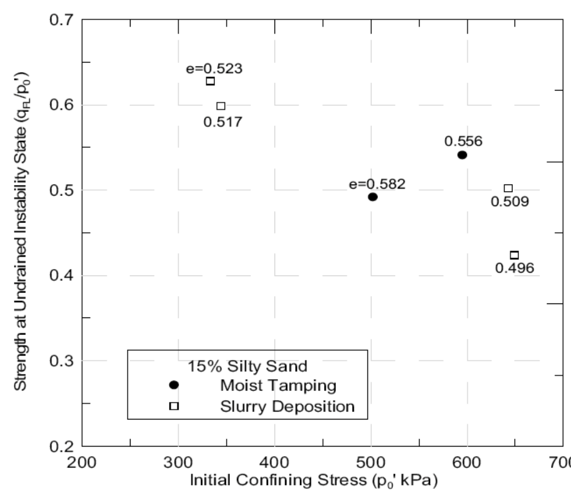


*Figure 14 Strength at UIS vs. initial confining stress in 15% silty sands*

## CONCLUSIONS

A series of undrained triaxial compression tests were performed on clean and silty sand specimens with nonplastic silt content ranging from 5-15%. Specimens were prepared using the slurry deposition and moist tamping methods. The main objective of this experimental program was to shed some light on the very distinctive states of the monotonic undrained response of sands with addition of silt.

An increase in the nonplastic fines content of the sand leads to a downward shift of the critical-state line in stress-void ratio space and to an increase in the critical-state friction angle. Moreover, the experimental results suggest that the presence of small amounts of nonplastic fines does not alter the nature and the general characteristics of the monotonic undrained behavior of sands. Constitutive modeling concepts and approaches developed for clean sand can be extended to silty sand by simply selecting appropriate values for the model input parameters. Finally, the initial fabric of the specimen appears to have a significant effect in the early stages of shearing. The moist tamping specimen preparation technique used in this study produced specimens that had considerably larger shear strength at the undrained instability state and a slightly smaller flow potential than their slurry-deposited counterparts; these trends can be attributed to the inherent differences in their initial fabric. The present data supports also the notion that these differences in fabric have negligible impact on response at large strains, leading to a unique fabric at critical state.

## REFERENCES


ASTM (2004). Annual Book of ASTM Standards: Soil and Rock (1), Vol. 04.08. West Conshohocken, PA: American Society for Testing and Materials.

Been, K. & Jefferies, M. G. (1985). A state parameter for sands.Geotechnique 35, No. 2, 99–112.

Been, K., Jefferies, M. G. & Hachey, J. (1991). The critical state of sands. Geotechnique 41, No. 3, 365–381.

Been, K. & Jefferies, M. (2004). Stress–dilatancy in very loose sand. Can. Geotech. J. 41, No. 5, 972–989.

Carraro, J. A. H., Bandini, P. & Salgado, R. (2003). Liquefaction resistance of clean and nonplastic silty sands based on cone penetration resistance. J. Geotech. Geoenviron. Engng ASCE 129, No. 11, 965–976.

Chan, C. K. (1981). An electropneumatic cyclic loading system. Geotech. Test. J. 4, No. 4, 183–187.

Ishihara, K. (1993). Liquefaction and flow failure during earthquakes: The 33rd Rankine Lecture. Geotechnique 43, No. 3, 351–415.

Lade, P. V. and Yamamuro, J. A. (1997). Effects of nonplastic fines on static liquefaction of sands. Can. Geotech. J. 34, No. 6, 918–928.

Li, X. S. & Wang, Y. (1998). Linear representation of steady-state line for sand. J. Geotech. Geoenviron. Engng ASCE 124, No. 12, 1215–1217.

Li, X. S. & Dafalias, Y. F. (2000) Dilatancy for cohesionless soils. Geotechnique 50, No. 4, 449–460.

Murthy T.G. (2006) Study of the static undrained response of sandy soils in the critical state framework, PhD thesis, Purdue University, West Lafayette, IN 47906.

Murthy T.G., Loukidis D., Carraro J.A.H., Prezzi M., & Salgado R. (2007) Undrained monotonic response of clean and silty sands, Geotechnique, 57,3, 273-288.

Ni, Q., Tan, T. S., Dasari, G. R. & Hight, D. W. (2004). Contribution of fines to the compressive strength of mixed soils. Geotechnique 54, No. 9, 561–569.

Roscoe, K., Schofield, A. N. & Wroth, C. P. (1958). On the yielding of soils. Geotechnique 8, No. 1, 22–53.

Salgado, R., Bandini, P. & Karim, A. (2000). Shear strength and stiffness of silty sand. J. Geotech. Geoenviron. Engng ASCE 126, No. 5, 451–462.

Thevanayagam, S. (1998). Effect of fines and confining stress on undrained shear strength of silty sands. J. Geotech. Geoenviron. Engng ASCE 124, No. 6, 479–491.

Thevanayagam, S., Shenthan, T., Mohan, S. & Liang, J. (2002). Undrained fragility of clean sands, silty sands and sandy silts. J. Geotech. Geoenviron. Engng ASCE 128, No. 10, 849–859.

Yoshimine, M. & Ishihara, K. (1998). Flow potential of sand during liquefaction. Soils Found. 38, No. 3, 189–198.

Zlatovic´, S. & Ishihara, K. (1997). Normalized behavior of very loose non-plastic soils: effects of fabric. Soils Found. 37, No. 4, 47–56.