Influence of laboratory simulated tube sampling disturbance on undrained shear behavior of a low plasticity synthetic intermediate soil

Influence des perturbations d'échantillonnage de tubes simulées en laboratoire sur le comportement au cisaillement non drainé d'un sol intermédiaire synthétique de faible plasticité

William G. Lukas, Don J. DeGroot, Guoping Zhang
Civil and Environmental Engineering, University of Massachusetts Amherst, MA, USA, wlukas@acad.umass.edu

Jason T. DeJong, Chris P. Krage
Civil and Environmental Engineering, University of California Davis, CA, USA

ABSTRACT: The paper presents results from a laboratory investigation of the effects of simulated tube sampling disturbance on a low plasticity intermediate soil. Specimens consisting of varying proportions of kaolin and silica silt were tested in a triaxial stress path cell using the ideal sampling approach (ISA) which involves applying an undrained strain cycle to simulate tube sampling disturbance in test specimens. The effects of ISA sample disturbance were evaluated by comparing measurements of post ISA reconsolidation strain and undrained triaxial compression shear behavior against undisturbed non-ISA test specimens. Results show systematic trends in soil response with decreasing plasticity to the induced disturbance; for the same degree of ISA disturbance the subsequently measured undrained shear strength not only increased relative to the reference undisturbed test but the percent change increased with decreasing plasticity. This is very different than results from ISA testing reported for clays indicating that the response of intermediate soils to sample disturbance can be very different than that of clays.

RÉSUMÉ : Cet article présente les résultats d'une étude en laboratoire sur les effets de la perturbation de l'échantillonnage de tubes simulés sur un sol intermédiaire de faible plasticité. Des échantillons constitués de proportions variables de kaolin et de limon de silice ont été testés dans une cellule de sollicitation triaxiale à l'aide de (ISA) qui consiste à appliquer un cycle de déformation non drainée pour simuler des perturbations d'échantillonnage de tubes dans des éprouvettes. Les effets de la perturbation de l'échantillon de l'ISA ont été évalués en comparant les mesures de la contrainte de reconsolidation après ISA et du comportement de cisaillement par compression triaxial non drainée contre des échantillons d'essai non ISA non perturbés. Les résultats montrent des tendances systématiques de la réponse du sol avec une plasticité décroissante aux perturbations induites; Pour le même degré de perturbation ISA, la résistance au cisaillement non drainée mesurée ultérieurement non seulement augmente par rapport au test non perturbé de référence, mais la variation en pourcentage augmente avec une plasticité décroissante. Ceci est très différent des résultats des tests ISA rapportés pour les argiles indiquant que la réponse des sols intermédiaires à la perturbation de l'échantillon peut être très différente de celle des argiles.

KEYWORDS: intermediate soils, sample disturbance, sample quality, silts, tube sampling

1 INTRODUCTION

Best practice drilling and sampling methods are well established for collection of good to high quality clay samples (e.g., Hight and Leroueil 2003, Ladd and DeGroot 2006, Lunne et al. 2006). Furthermore, the causes of sample disturbance in clays are well understood and the measure of volume change during laboratory reconsolidaton to the estimated in situ effective stress state has proved to be a robust and valuable indication of clay sample quality (Terzaghi et al. 1997, Lunne et al. 2006). Much less is known about the effects of sample distubance on the measured laboratory behavior of low plasticty intermediate soils such as silts, clayey silts, and sandy silts and what methods should be used to collect high quality samples. Furthermore, no quantitative method has yet been developed to assess the quality of intermediate soil samples.

Baligh et al. (1987) developed the Ideal Sampling Approach (ISA) to numerically study the stress-strain-pore pressure field generated in a soil during simulated tube sampling. The results showed that during undrained penetration a soil undergoes a cycle of axial compression followed by axial extension as it enters the sampling tube. For example, the US Shelby tube (ASTM D1587), with a diameter to thickness ratio $D/t \approx 40$, induces an axial strain cycle with peak strains of approximately ±1% along the centerline of the sampler. Different peak strains are induced in samplers of different geometries. This numerical framework has been used as a basis for laboratory tests that simulate the effects of tube sampling in clays (e.g., Clayton et al. 1992, Siddique et al. 1999, Santagata and Germaine 2002). Collectively this work resulted in an optimization of tube sampler geometry to improve the quality of clays samples.

Very little such experimental work has been performed for low plasticity intermediate soils. The only known ISA testing on silts was performed by Carroll (2013). Additional testing is necessary to better understand how low plasticity intermediate soils respond during tube sampling in order to develop a quantitative sample quality assessment method for these soils. This paper presents results from an experimental program using a triaxial stress path cell to study the effects of simulated tube sampling disturbance, using the ISA method, on synthetic low plasticity index ($PI < 10$) intermediate soils. The test soils, experimental methods, and "undisturbed" and ISA disturbed test results are presented followed by a brief discussion of the significance of the results.

2 TEST SOILS AND EXPERIMENTAL METHODS

2 .1 *Synthetic soil mixes*

Three sets of synthetic soil samples were prepared following the general procedures described by Krage et al. (2015) by mixing silica silt (US-Sil-Co-Sil 250) with kaolin clay (Old Hickory, No. 1 Glaze) by dry weight in proportions of: 50% silica with 50% kaolin (50S50K), 70% silica with 30% kaolin (70S30K), and 85% silica with 15% kaolin (85S15K). These mixtures were selected to produce one reference sample with a plasticity index (PI) > 10 to represent clay like behavior and two low plasticity samples with a PI < 10. The dry powders were thoroughly mixed under vacuum with deionized water at a water content of approximately 1.5 times the liquid limit and slurry consolidated into a 102 mm diameter acrylic cylinder coated with a thin film of 5cS silicone oil. The samples were incrementally loaded in a computer controlled load frame to a final vertical effective stress of 100 kPa. The resulting soil cake was extruded, sealed with multiple layers of plastic film and a petroleum jelly-paraffin wax mixture, and stored in a 10° *C* temperature and humidity controlled room.

Table 1 presents the classification properties for the three mixes. Atterberg Limits were performed in accordance with ASTM D4318 and fines content was determined by ASTM D7928 (hydrometer). One soil cake for each mixture was subsampled by horizontally cutting a vertical slice of the cake into 6 sub-specimens for which water content and hydrometer tests were performed. The resulting water contents and grain size distribution curves were essentially identical indicating that little to no particle segregation occurred during the mixing and the slurry consolidation process.

Table 1. Index and classification properties of the soil mixes

Mixture	*LL*	*PL*	*PI*	Fines Content	USCS
50S50K	31	15	16	88	CL
70S30K	24	15	9	82	CL
85S15K	19	15	4	79	CL-ML

Note: *LL* = liquid limit, *PL* = plastic limit, *PI* = plasticity index, Fines Content = % < 0.075 mm, USCS = Unified Soil Classification System

2 .2 *Experimental Methods*

Tests were performed using a triaxial stress path system with a nominal specimen size of 36 mm diameter by 71 mm height. Test specimens were prepared by first cutting a subsample from a soil cake and trimming it to the target specimen dimensions using a vertical soil lathe and wire saw. Specimen ends were cut flush using a miter box and encapsulated in a latex membrane. 5cS silicone oil was used as the cell fluid to allow for use of an internal load cell. Specimens were back pressure saturated at the estimated sampling effective stress (= capillary pore pressure) and thereafter K_0 consolidated at a constant rate of strain to the target maximum vertical effective stress ($\sigma'_{v,max}$) equal to 400 kPa. After approximately one log cycle of secondary compression the specimens were unload to a target final overconsolidation ratio (OCR = $\sigma'_{v,max}/\sigma'_{vc}$) of 1.8, which corresponds to a target final vertical effective stress (σ'_{vc}) of 222 kPa.

For the "undisturbed" reference specimens, undrained shear was performed at the OCR = 1.8 in triaxial compression mode of shear (CK$_0$UC) using a constant strain rate of 0.5 %/hr. ISA tests were performed by consolidating the specimens in the same manner as the "undisturbed" tests and then performing one full undrained strain cycle at 0.5%/hr using strain limits of either ±1% or ±3%. At the end of the strain cycle the specimen was brought to an isotropic state of stress (i.e., zero deviator stress) to complete the ISA procedure. The back pressure flow pump was set equal to the pore pressure that had developed within a specimen during the ISA cycle and then the value to the specimen was opened. The specimens were reconsolidated using stress control back to the initial pre-ISA anisotropic stress state and thereafter sheared undrained using the same procedure as for the "undisturbed" specimens. All recorded data were processed applying corrections for the membrane resistance and changes in specimen area.

3 TEST RESULTS

3 .1 *Undisturbed undrained stress-strain behavior*

Figure 1 plots the stress-strain and effective stress path results for the three undisturbed tests for each mixture. Table 2 presents a summary of results for the consolidation and undrained shear phases of the tests. All three soils develop a peak shear stress $q_f = (\sigma_v - \sigma_h)_f/2$ at a vertical strain (ε_v) less than 1% and thereafter strain soften with the greater strain softening response for the two lower PI soils. These two soils also had a higher undrained shear strength ($s_u = q_f$) and the lowest *PI* 85S15K soil had the largest effective stress friction angle ϕ' taken at the maximum obliquity $(\sigma'_1/\sigma'_3)_{max} = (\sigma'_v/\sigma'_h)_{max}$. All soils develop positive shear induced pore pressures during the entire shearing process. The end of consolidation void ratio (e_c) decreased from the 50S50K mix to the 70S30K mix and then increased again for the 85S15K mix, which is consistent with packing theory and experimental data for mixing of two different particle size soils. This difference in e_c is believed to be why the 70S30K mix has a slightly higher s_u than the higher silt content 85S15K mix (Note: repeat tests were performed for these soils and the same results were obtained).

Table 2. Consolidation state and undrained shear results for "undisturbed" CK$_0$UC tests

Mixture	$\sigma'_{v,max}$ σ'_{vc} (kPa)	$K_{0,NC}$ K_c	w_c (%) e_c	q_f (kPa) ε_f	$(\sigma'_1/\sigma'_3)_{max}$ ϕ'
50S50K	397	0.59	23	90	2.60
	216	0.73	0.630	0.92	26.3
70S30K	400	0.49	20	108	3.45
	218	0.61	0.565	0.46	33.3
85S15K	401	0.52	24	102	3.96
	219	0.61	0.671	0.48	36.5

Note: $K_c = \sigma'_{hc}/\sigma'_{vc}$, w_c, e_c = water content and void ratio at end of consolidation, ϕ' corresponds to maximum obliquity $(\sigma'_1/\sigma'_3)_{max}$

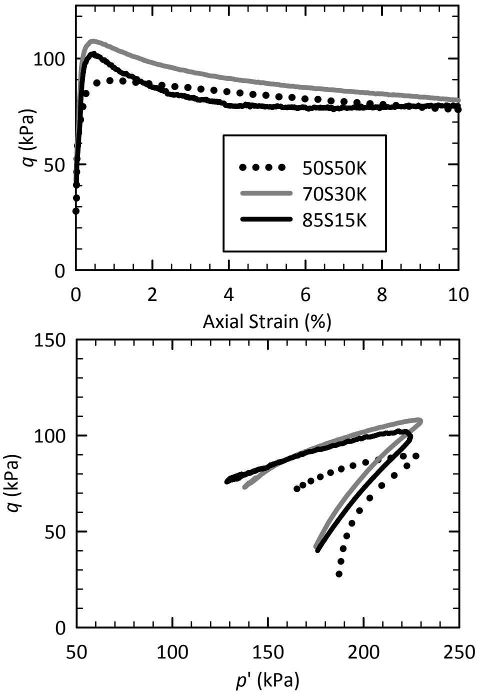

Figure 1. Stress-strain plots and effective stress paths for undrained triaxial compression shear of "undisturbed" specimens.

3 .2 *ISA strain cycling and post ISA behavior*

Figure 2 plots the stress-strain data for the ±1% and ±3% ISA strain cycles. The near identical stress-strain plots during the initial shear for each ISA test condition ("undisturbed", ±1% and ±3%) for all three soils further confirms that the sample mixing and test procedures used were repeatable.

The rate of development of positive shear induced pore pressures increased markedly from the 50S50K soil to the 85S15K soil. This, in combination with the unloading total stress path applied once the peak positive ISA strain was reached (i.e., after +1% or +3%), resulted in a significant migration of the effective stress path towards very low mean effective stress $p' = (\sigma'_v + \sigma'_h)/2$. This is shown, for example, in Figure 3 for the 70S30K soil and is quantified in Table 3 which presents p'/p'_c at the end of ISA cycling for each test. This behavior also corresponds with much lower development of shear stress (i.e., negative *q*; Figure 2) during application of the unloading total stress path. It is evident from these plots that the application of simulated tube samples strains of ±1% and ±3% results in dramatic changes in the specimen effective stress state and this behavior increases with a decrease in *PI*.

Table 3. Mean effective stress at start and end of ISA cycling and post-ISA volume change during anisotropic re-consolidation to σ'_{vc} and K_c.

Mixture	ISA Strain (±%)	At Start-ISA p'_c	At End-ISA p'/p'_c	Post ISA ε_{vol}	Post ISA $\Delta e/e_0$
50S50K	1.0	187	0.61	0.28	0.007
	3.0	188	0.30	1.1	0.030
70S30K	1.0	176	0.24	0.56	0.016
	3.0	176	0.07	1.8	0.051
85S15K	1.0	176	0.09	0.84	0.022
	3.0	177	0.03	2.2	0.057

Note: Lunne et al. (2006) $\Delta e/e_0$ sample quality ratings for clays with OCR = 1 to 2: < 0.04 = very good to excellent; 0.04 to 0.07 = fair to good; 0.07 to 0.14 = poor; > 0.14 = very poor.

3 .3 *Post ISA undrained shear behavior*

At the end of a given ISA cycle the back pressure flow pump was set to match the ISA shear induced pore pressure and the drainage values were opened. Thereafter the specimens were anisotropically consolidated back to the original pre-ISA effective stress state (i.e., σ'_{vc} and K_c values given in Table 2). Table 3 presents the axial and normalized change in void ratio ($\Delta e/e_0$) that occurred during the anisotropic consolidation phase (Note: for these tests $e_0 = e_c$). As anticipated, the post-ISA $\Delta e/e_0$ values increased with an increase in strain cycle from ±1% and ±3%. What was originally not anticipated is that $\Delta e/e_0$ also increased with a decrease in *PI* of the soils. However, as noted in the previous section and tabulated in Table 3, the ISA cycling induced a greater loss in mean effective stress (p'/p'_c) with a decrease in *PI*. As a result, reconsolidation for specimens with the lowest p'/p'_c ratios back to the pre-ISA anisotropic effective stress state required a larger stress application and presumably therefore a greater volume change.

Figures 4 and 5 present the post-ISA undrained shear results in terms of stress-strain and effective stress paths. In all cases there is a loss in initial stiffness (pre-peak) for the 50S50K and 70S30K specimens and there was an increase in q_f, relative to the "undisturbed" specimens, with increasing ISA strain but a corresponding decrease in strain softening response. The 85S15K ±1% and ±3% tests show remarkably different behavior than the "undisturbed" specimen. In both cases the specimens exhibited an initial contractive response that was followed by significant dilation, especially for the ±3% specimen. No matter which one of the various definitions that can be considered for selecting the undrained shear strength of a dilating specimen (e.g., Brandon et al. 2006) the resulting values for both the ±1% and ±3% tests is significantly greater than that of the "undisturbed" specimen.

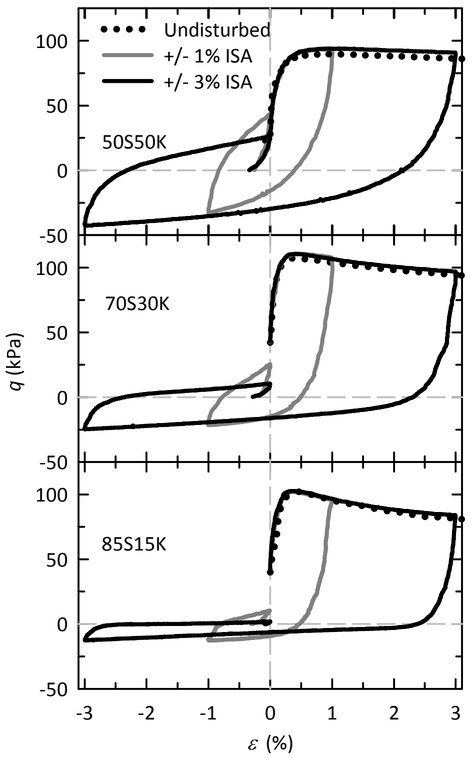

Figure 2. Stress-strain plots for the "undisturbed" tests and during ±1% & ±3% strain cycles for the ISA tests.

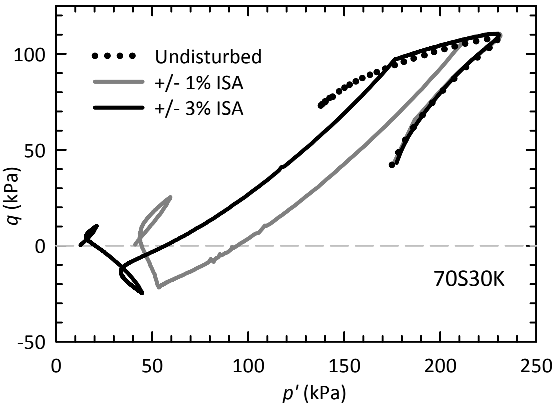

Figure 3. Effective stress paths for the "undisturbed" test and during ±1% & ±3% strain cycles for the ISA tests on the 70S30K soil.

4 SIGNIFICANCE OF RESULTS

The effect of simulated tube sampling disturbance on the soils tested is significantly different from that observed for clays (e.g., Siddique et al. 1999, Santagata and Germaine 2002), especially for the two *PI* < 10 soils. While there was an increase in $\Delta e/e_0$ as the ISA imposed strain damage was increased from ±1% to ±3%, all specimens nevertheless had clay based $\Delta e/e_0$ sample quality ratings of either very good to excellent or fair to good upon reconsolidation to the pre-ISA effective stress state (Table 3). These favorable sample quality ratings are especially significant for the ±3% ISA tests given that the imposed strains were well beyond the "undisturbed" peak shear strength and the subsequently measured undrained shear behavior was markedly different. Such results and those reported by Carroll (2013) and Krage et al. (2015) confirm that the $\Delta e/e_0$ clay based sample quality ratings should not be used for low *PI* intermediate soils, as is commonly seen in the literature.

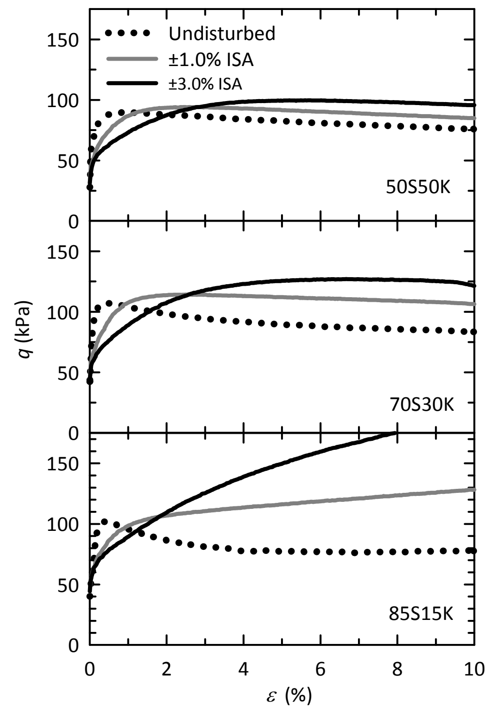

Figure 4. Stress-strain plots for undrained triaxial compression shear of "undisturbed" and post-ISA for the ±1% & ±3% ISA test specimens.

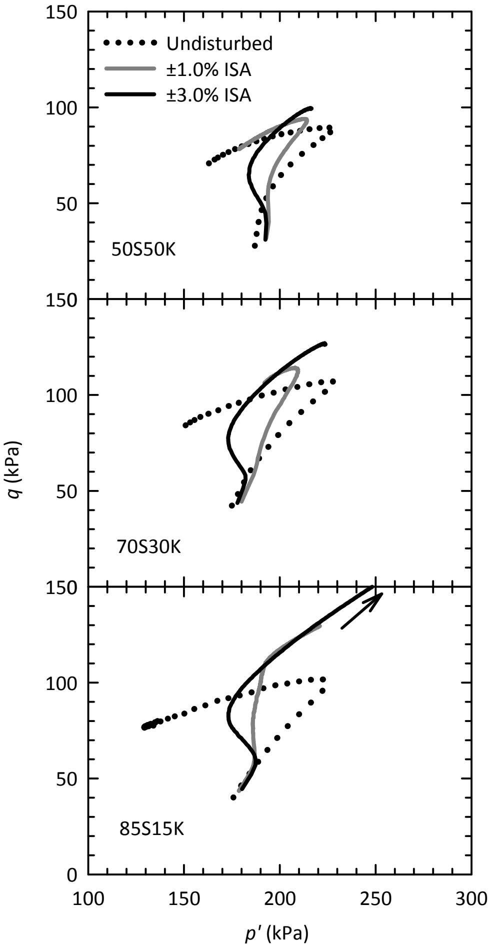

Figure 5. Effective stress paths for undrained triaxial compression shear of "undisturbed" and post-ISA for the ±1% & ±3% ISA test specimens.

Also of importance is that the simulated tube sampling disturbance for the 85S15K, *PI* = 4, specimens resulted in a complete reversal in undrained shear behavior from contractive for the "undisturbed" specimen to highly dilative for the disturbed specimens. Without a method of assessing the degree to which disturbance has occurred in such soils it is not possible to determine whether the laboratory measured behavior is representative of the in situ behavior. In this particular case, the laboratory measured dilative response for the disturbed specimens would be unconservative.

5 CONCLUSIONS

Tests performed on *PI* < 10 synthetic intermediate soil samples that simulated tube sampling disturbance showed very different behavior than that reported in the literature for clays. For the *PI* = 4 samples, "undisturbed" contractive behavior during undrained shear became dilative behavior for the disturbed specimens. Furthermore, the clay based sample quality criteria did not indicate significant disturbance had occured in the specimens. It is evident that more research is needed on understanding the effect of sample disturbance on low *PI* intermediate soils and that a new sample quality framework needs to be developed for such soils.

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