Laboratory study of impact of drainage during sampling of intermediate soils

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ABSTRACT: This paper presents a laboratory investigation of the influence of simulated tube sampling disturbance on lightly overconsolidated intermediate soils by varying their plasticity, degree of sampling disturbance, and drainage conditions during sampling. Samples consisting of varying proportions of kaolin and silica silt to result in three plasticity indices of nonplastic, 4, and 16% were mixed as a slurry and then consolidated to the pre-designed overconsolidation ratios. All specimens were tested in a stress-path triaxial cell using the ideal sampling approach that involved applying both drained and undrained shearing with strain cycles of ±0.5%, ±1.0%, and ±3.0% corresponding to three different degrees of tube sampling disturbance. Both undrained and drained disturbance increased the strength of the intermediate soils tested, however, the drained soils exhibited an even stiffer response. The drained tests had little reconsolidation strain, implying clay-based sample quality assessment methods do not apply.

Keywords: Sample disturbance; silt; laboratory testing; triaxial.

1. Introduction

Baligh et al. [1] developed the Ideal Sampling Approach (ISA) to numerically study the stress-strain-pore pressure field generated in soils during tube sampling. The results showed that during tube penetration a centerline element of soil to be sampled is subjected to an undrained strain cycle consisting of 1) a compressive strain of magnitude ε_{zz} ahead of the sampler, 2) an extension strain of magnitude $-\varepsilon_{zz}$ once the soil has entered the sampler and 3) an unloading strain back to zero percent strain as the soil moves farther into the sampler (Figure 1). Different peak strains, and thus varying degrees of disturbance, are induced in the soil by samplers of different geometries. This numerical framework has been used as a basis for conducting laboratory element tests to simulate the effects of tube sampling in clays (e.g., [2 - 4]), Irish silts [5], and reconstituted low plasticity index (PI < 10) silts [6]. Results from the clay studies led to recommendations on tube sample geometry to improve sample quality (e.g., [7-8]).

All published results from ISA testing involved performing the ISA strain cycles undrained which is considered to well represent tube sampling in clays. However, for intermediate soils such as silts, clayey silts, and sandy silts with decreasing plasticity and decreasing clay fraction it is possible that drainage may occur in situ during and after tube penetration. If such were the case it could have an important impact on soil properties such as void ratio, laboratory measured shear behavior, and evaluation of sample quality. This paper presents results from an experimental program using a triaxial stress path cell to compare the effect of performing ISA simulation of tube sampling undrained versus drained on a low plasticity intermediate soil.

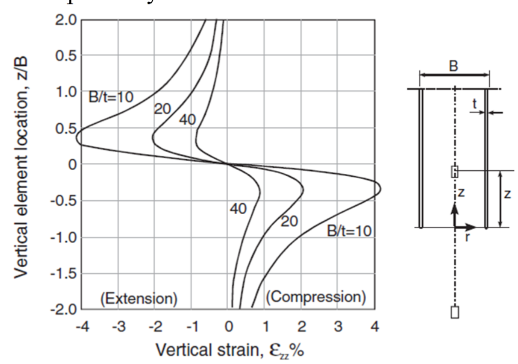


Figure 1. Strain contours for centerline element during sampler penetration [1].

2. Methods

2.1. Sample preparation

Three different mixtures of silica silt (US-Sil-Co-Sil 250) and kaolin clay (Old Hickory, No.1 Glaze) were used to create synthetic soils of varying properties [6, 9]. The mixtures were 50S50K (e.g. 50% silt and 50% kaolin by dry mass), 85S15K, and 98S02K. Table 1 presents a summary of the index properties for the three mixtures. The 50S50K mix was prepared to represent a reference low plasticity clay (PI = 16), while the 85S15K mix represented a low plasticity (PI = 4) clayey-silt and the 98S02K mix represented a non-plastic (NP) silt. The 50S50K mixture had sufficient clay content to enable free-standing specimens and a slurry consolidometer was used to make a soil cake from which four specimens could be trimmed. The 85S15K and

98S02K specimens were prepared individually using a vacuum split mold similar to [10].

Table 1. Summary of Index and Undisturbed Parameters of the Three Soil Mixtures [6].

Soil	50S50K	85S15K	98S02K
LL (%)	31	20	18
PI (%)	16	4	NP
% Silt	50	66	71
% Clay	38	13	3.5
USCS	CL	ML-CL	ML
$K_{0,NC}$ (-)	0.59	0.52	0.36
K_c (-) @ OCR = 1.8	0.73	0.61	0.51
w_c (%)	23	24	25
e_c (-)	0.630	0.671	0.680
q_f (kPa)	90	102	352@ ε=10%
ε_f (%)	0.92	0.48	*10*
$(\sigma'_1/\sigma'_3)_{max}$	2.60	3.96	4.71
$\phi'_{mo,TC.}$ (°)	26	36	40
$\phi'_{mo,TE.}$ (°)	29	40	44

2.2. Triaxial undrained and drained ISA testing

After mounting in the triaxial testing apparatus the specimens were back pressured at 300 kPa until saturated (B-value > 0.95 within 5 minutes of increasing the cell pressure 50 kPa). The reference "undisturbed" 50S50K and 85S15K specimens were K_0 consolidated (CK_0) to a maximum vertical effective stress (σ'_v) of 400 kPa and unloaded to 222 kPa resulting in an overconsolidation ratio (OCR) equal to 1.8. The 98S02K reference undisturbed specimen was anisotropically consolidated (CA) to the same maximum σ'_v and final OCR using K_0 values estimated from the measured triaxial compression effective stress friction angle angle (ϕ'_{mo}) taken at the maximum obliquity $(\sigma'_1/\sigma'_3)_{max}$ and the [11] relationship among K_0, ϕ'_{mo} and OCR. For all tests, loading and unloading during consolidation were performed at axial strain rates of 0.2%/hr and 0.05%/hr, respectively. Undrained shear in compression loading (CAUC), i.e. increasing vertical stress (σ_v) at constant horizontal stress (σ_h), and extension unloading (CAUE), i.e., decreasing σ_v at constant σ_h, were performed at an axial strain rate of 0.5%/hr.

All ISA tests were anisotropically consolidated using the same vertical stress, OCR and K_0 values as the reference undisturbed tests (Table 1). The ISA strain cycle was performed strain controlled and either undrained or drained and with peak ISA strains of either ±0.5%, ±1.0%, or ±3.0% representing different levels of tube sampling disturbance (Figure 1). Following the ISA strain cycle, the deviator stress was removed to an isotropic stress state by decreasing σ_v at constant σ_h until $\sigma_v \approx \sigma_h$ to complete the ISA simulation of tube sampling. While it is possible that tube sampling and handing could be partially drained, the drained ISA tests were performed fully drained to represent the extreme condition of potential drainage due to sampling. Upon completion of the ISA strain cycle, specimens were anisotropically reconsolidated from their post-ISA stress state to the pre-ISA state with σ'_v equal to 222 kPa and σ'_h set to the OCR = 1.8 K_0 value and sheared undrained in triaxial compression. Drained ISA shearing was performed at strain rates of 0.25%/hr for the 50S50K specimens and 1.0%/hr for the 85S15K and 98S02K specimens. Undrained ISA shearing and final undrained shear for all specimens was performed at a strain rate of 0.5%/hr. Lukas et al. [6] presents more details on the methods of specimen preparation, test procedures and the undrained ISA test results.

3. Results

3.1. Reference undisturbed shear behavior

Figure 2 presents the reference undisturbed undrained shear in compression loading (CAUC) and extension unloading (CAUE) of the three soils and Table 1 presents the undrained shear parameters. The 98S02K specimen exhibits dilative behavior during undrained compression shear almost immediately, while the 85S15K and 50S50K both exhibit post-peak contractive behavior (Figure 2). At large strains, the 85S15K specimen begins to exhibit dilative behavior. During the triaxial extension unloading tests the 50S50K specimen developed negative shear induced pore pressure while the 85S15K and 98S02K specimens developed positive shear induced pore pressure throughout shear (Figure 2). The CAUC results are used as the frame of reference (i.e., "undisturbed") for investigating the influence of ISA simulation of tube sampling on the undrained shear behavior of the soil mixtures. While the CAUC and CAUE failure envelopes represent the limiting stress states during ISA testing.

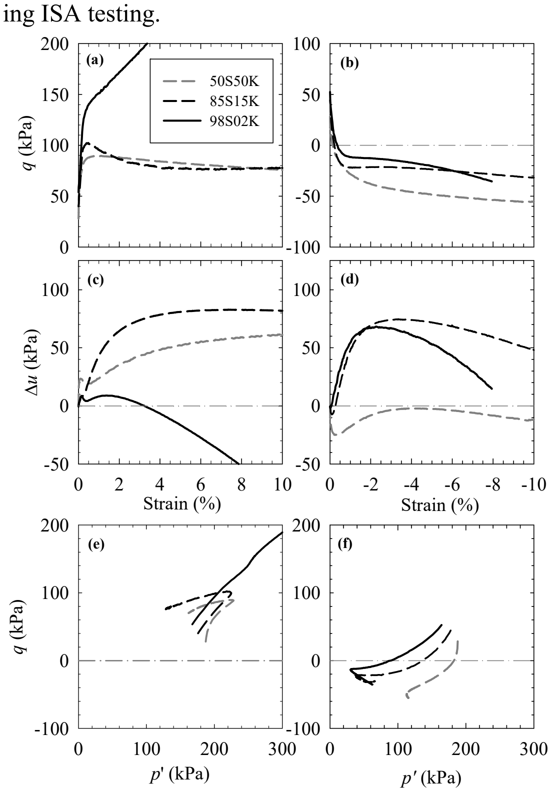


Figure 2. Undrained CAUC (a, c, e) and CAUE (b, d, f) behavior of three soil mixtures tested: a and b) stress-strain, c and d) shear-induced pore pressure, e and f) effective stress paths.

3.2. Undrained and drained ISA shearing

Figure 3 presents the stress-strain and effective stress path plots for the reference undisturbed and the undrained and drained ISA tests with ±3.0% strain for the three soils. The compression and extension failure envelopes plotted in Figure 3 represent the effective stress friction angles (Table 1) at the maximum obliquity $(\sigma'_1/\sigma'_3)_{\max}$ as measured in triaxial compression (CAUC) and triaxial extension (CAUE). Up to a compressive strain of 3% the undrained ISA test is identical to the reference undisturbed CAUC test, as should be expected. Upon reversal of the ISA strain to extension the specimens undergo significant loss of mean effectives stress ($p' = (\sigma'_v + \sigma'_h)/2$) and in the case of the 85S15K and 98S02K specimens the effective stress path essentially reaches the extension failure envelope. At completion of the ISA process the normalized mean effective stresses reduced to $\Delta p'/p'_c$ equal to 0.70 (50S50K), 0.97 (85S15K) and 0.98 (98S02K).

For drained ISA testing the effective stress path follows a prescribed 45 degree line in q-p' space as the ISA loading is conducted by either increasing or decreasing σ_v at constant σ_h and no pore pressures are generated. Drained ISA results in a slightly stiffer response for the 50S50K specimen and a much stiffer, strain hardening, response for the 85S15K specimen, which is completely different than the strain softening response during undrained ISA testing. During the extension phase of both the undrained and drained ± 3% ISA tests conducted on the 85S15K specimen the effective stress paths reach the extension failure envelope prior to reversal of the strain cycle, albeit at very different p' values. The stress-strain curves are essentially identical for the drained and undrained ± 3% ISA tests performed on the 98S02K specimens, with significant dilative behavior. However, upon completion of the ISA strain cycle the undrained ISA specimen ends up at a markedly lower p' stress state.

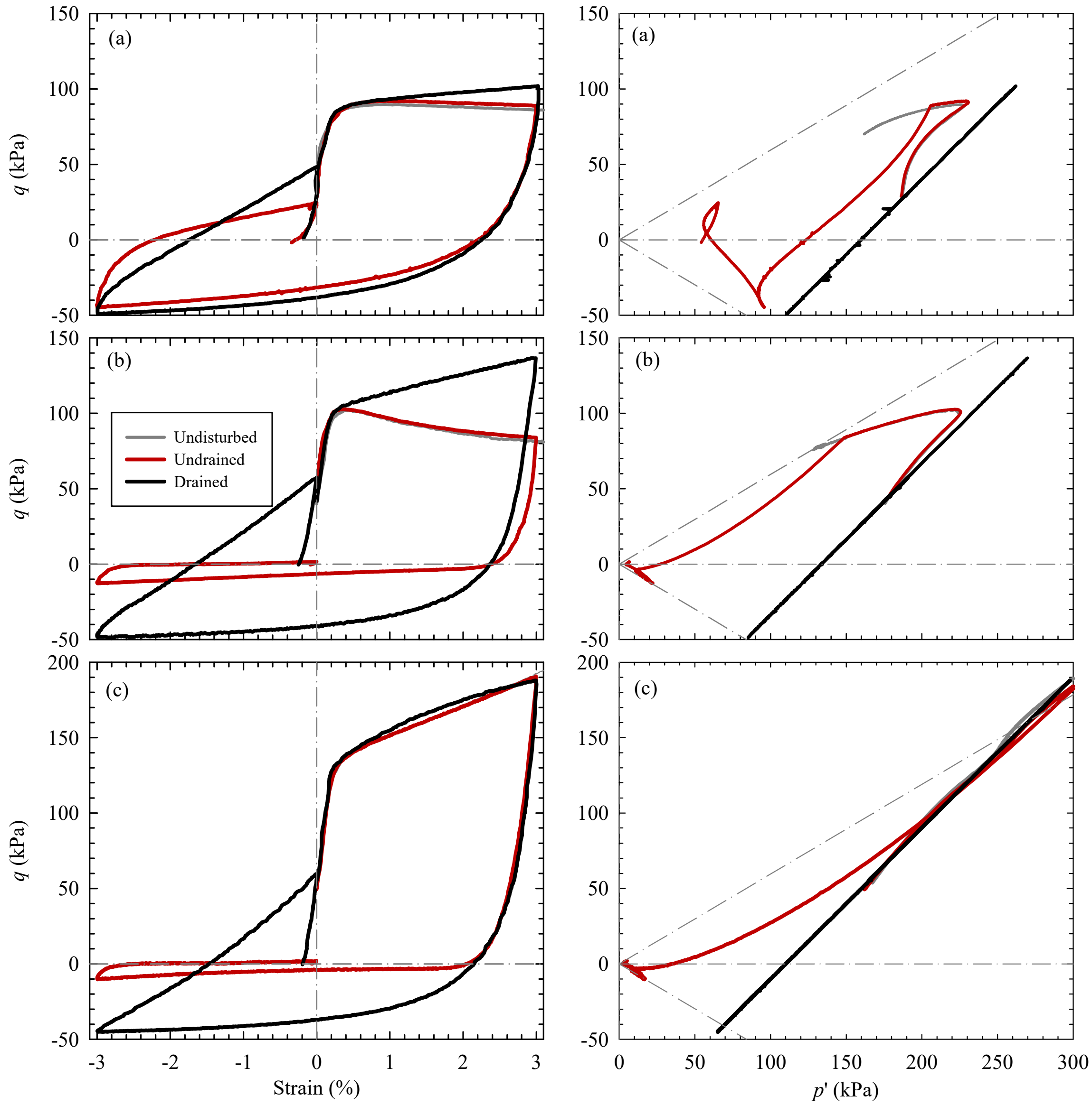


Figure 3. Stress-strain (left) and effective stress paths (right) for undisturbed undrained and drain ±3% ISA tests performed on soil mixes: a) 50S50K, b) 85S15K, and c) 98S02K.

Table 2. Normalized change in void ratio $\Delta e/e_0$ for drained ISA and post-ISA reconsolidation.

Soil	ISA ε_{zz} (%)	Undrained ISA		Drained ISA			
		Post-ISA $\Delta e/e_0$ (-)	e_c, pre-ISA e_c, post-ISA	ISA $\Delta e/e_0$ (-)	Post-ISA $\Delta e/e_0$ (-)	Total $\Delta e/e_0$ (-)	e_c, pre-ISA e_c, post-ISA
50S50K	0.5	0.003	0.625 0.625	-0.001	0.001	0.000	0.618 0.621
	1.0	0.007	0.616 0.611	0.008	0.001	0.009	0.615 0.610
	3.0	0.030	0.603 0.582	0.041	0.002	0.043	0.630 0.599
85S15K	0.5	0.002	0.659 0.654	0.015	0.001	0.016	0.610 0.603
	1.0	0.022	0.612 0.598	0.036	0.002	0.038	0.612 0.595
	3.0	0.057	0.626 0.591	0.087	0.001	0.088	0.646 0.587
98S02K	0.5	0.009	0.675 0.667	0.012	0.001	0.013	0.688 0.680
	1.0	0.017	0.659 0.648	0.033	0.002	0.035	0.710 0.690
	3.0	0.045	0.671 0.641	0.070	0.002	0.072	0.644 0.596

3.3. Post-ISA reconsolidation and undrained shear

Table 2 and Figure 4 present the normalized change in void ratio $\Delta e/e_0$ during drained ISA testing (equal to zero for undrained ISA) and during post-ISA reconsolidation back to the pre-ISA consolidation stress state (i.e., σ'_v = 222 kPa). The e_0 value used for the ISA phase of the drained ISA tests and for the reconsolidation phase of the undrained ISA tests is the value at the end of consolidation prior to ISA shearing. The e_0 value used for the reconsolidation phase of the drained ISA tests is that at the end of drained ISA shearing. Also presented are the void ratios at the end of post-ISA reconsolidation (e_c) and just prior to the final undrained compression shear. In all cases $\Delta e/e_0$ increased with an increase in ISA strain level, whether the ISA shearing was conducted undrained or drained, reflecting the increasing damage caused to the specimens with increasing simulation of tube sample disturbance. However, for a given soil and ISA strain level, the drained ISA tests underwent a greater to much greater total reduction in void ratio with essentially all the reduction taking place during the drained ISA phase with little to no additional void ratio reduction during post-ISA reconsolidation to the pre-ISA stress state.

Figure 5 presents the deviator stress q, the shear induced pore pressure Δu, and undrained secant stiffness $E = \Delta q/\varepsilon_a$ versus strain for the final undrained compression shear for the reference undisturbed tests and both the drained and undrained ±1.0% and ±3.0% ISA tests; the ±0.5% tests were omitted for clarity. Figure 6 presents the effective stress paths for all tests and in all cases the set of nine tests performed for each soil reach the same failure envelope for a given soil and depending

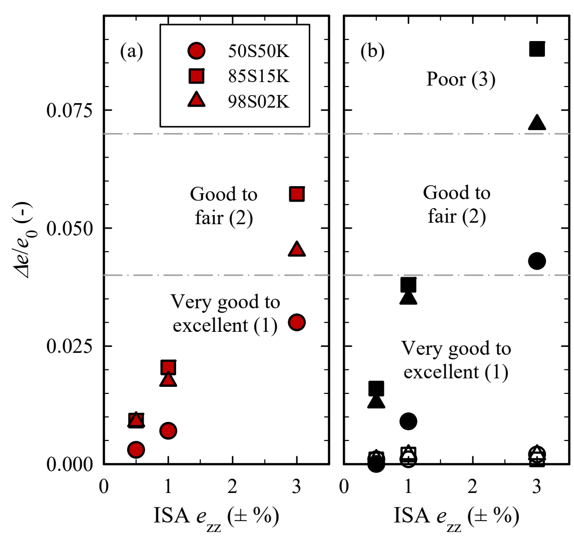
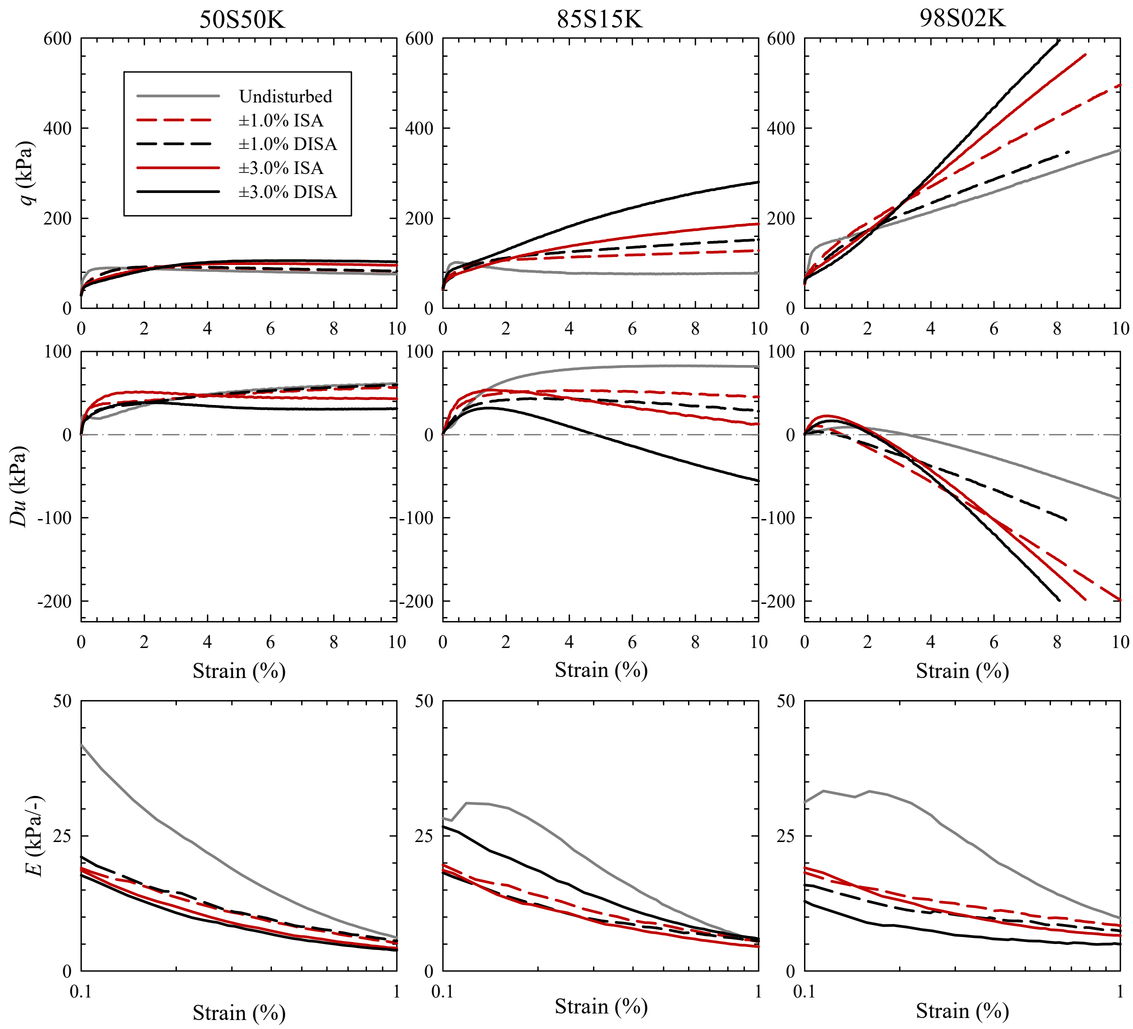


Figure 4. Summary of $\Delta e/e_0$ during ISA and post-ISA reconsolidation: a) undrained ISA and b) drained ISA. Red symbols are post undrained ISA reconsolidation, white are post drained ISA reconsolidation, and black are both drained ISA and post drained ISA reconsolidation.

on the soil and specific test conditions, either strain soften down the failure envelope (i.e., contractive behavior) or strain harden up the failure envelope (i.e., dilative behavior). For the 50S50K tests there is little difference among the tests performed with ±0.5% ISA and also ±1% ISA. For the ±3% ISA tests, both the undrained and drained ISA specimens initially have a greater rate of positive pore pressure development and a corresponding lower rate of shear stress development relative to the undisturbed test. This results in the effective stress path for the two ISA tests migrating to the left of that for the undisturbed test (Figure 6). However, upon continued shearing the undisturbed specimen starts



Comparison of post-ISA undrained shear behavior for both drained and undrained ISA tests with ±1.0% and ±3.0 strain cycles for each soil: a), b) and c) stress-strain; d), e) and f) shear induced pore pressure, and g), h) and i) secant stiffness.

to strain-soften and develop greater positive pore pressure while the ISA specimens reach a maximum shear stress that is maintained with continued shearing. Overall, for the 50S50K soil there is little practical difference in the undrained shear behavior whether the ISA straining was performed undrained or drained and for all ISA values.

The 85S15K specimens show a marked difference in behavior between the reference undisturbed test and the ISA tests, especially for the ±1% and ±3% ISA tests. Just ±0.5% ISA straining, whether undrained or drained, changes the disturbed shear behavior from contractive to dilative (Figures 5 and 6) and for the ±1% and ±3% ISA tests the shear behavior is completely different than the reference undisturbed specimen. In comparing undrained and drained ISA behavior, there is little difference between the ±0.5% and ±1% ISA tests while for the ±3% ISA tests, the drained ISA specimen has a significantly greater rate of increase in shear stress such that at 10% axial strain the shear stress is 50% greater. This corresponds to the significant differences in pore pressure response with the drained ISA specimen developing negative shear induced pore pressure beyond 5% axial strain while the undrained ISA specimen pore pressure remains positive. It is likely that this difference in behavior is due to the greater total volume change taking place during the ISA and reconsolidation phases for the drained test.

The reference undisturbed 98S02K specimen and all of the disturbed ISA specimens exhibit a small initial contractive response quickly followed by a reverse to dilative behavior with development of negative shear induced pore pressure (Figures 5 and 6). There are marked differences in the shear stress-strain response with the reference undisturbed test having the stiffest behavior initially but then all of the ISA specimens developing much greater rate of shear stress increase with increasing strain. In stress path space, all of the specimens follow the same effective stress path. Comparing the undrained and drained ISA tests the undrained ±1.0% ISA test has higher q and lower Δu during shear than the drained ±1.0% ISA, which was not the case for the 50S50K and 85S15K soils. The ±3.0% ISA test follows the pattern found for the other soils with the drained ISA specimen developing greater shear stress and less Δu than the undrained ISA specimen.

For all three soils there was a decrease in the secant stiffness $E = \Delta q/\varepsilon$ with disturbance however by approx-

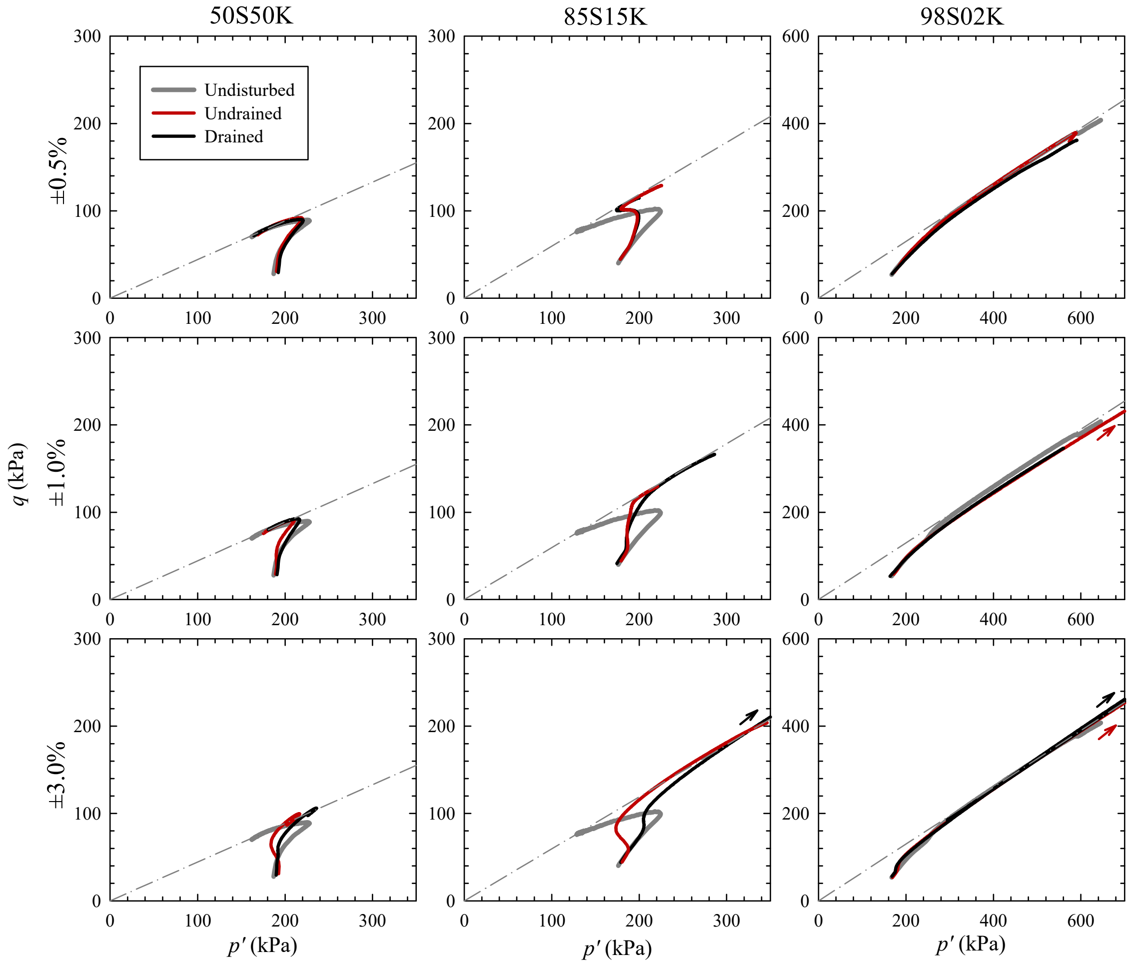


Figure 5. Post-ISA undrained shear effective stress paths for undisturbed reference specimen (grey), undrained ISA specimens (red), and drained ISA specimens (black).

imately 1.5% strain all tests converge to the undisturbed E value (Figure 5). For the 50S50K and 98S02K tests E decreased with increasing ε_{zz}. For the 50S50K tests both drained and undrained ISA had similar decreases for a given ε_{zz} while for the 98S02K tests the drained ISA tests had lower E values. For the 85S15K there was no trend in the decrease in E for ε_{zz} or drainage during ISA, with the drained ε_{zz} = 3.0 test showing the smallest decrease in E.

4. Discussion

Overall, the difference in the undrained shear behavior across all of the reference undisturbed specimens and the disturbed ISA tests, whether conducted undrained or drained, ranges from minor (e.g., 50S50K with ±1% ISA) to very significant (e.g., 85S15K with ±3% ISA). In the case of the 85S15K specimens, the undrained shear behavior changes completely from contractive behavior for the reference undisturbed specimen with a clear peak shear strength followed by straining softening to dilative behavior with continuous strain hardening for the disturbed ISA specimens.

The main difference in shear behavior between undrained and drained ISA is that the latter specimens tended to have greater strain hardening response which can be of consequence depending on how a representative undrained shear strength (s_u) is selected for design. For example, [12] proposed several options for selecting s_u for a soil exhibiting dilative behavior including $q_{\max}$, the peak principal stress ratio $((\sigma'_1/\sigma'_3)_{\max})$, $\Delta u_{\max}$, Skempton's $\bar{A}_f$ parameter = 0, reaching the K_f line, and a limiting strain of 4%. Figure 7 applies these criteria to the 85S15K specimens for the reference undisturbed tests, the ± 3% undrained ISA tests and for the ± 3% drained ISA tests and Table 3 and presents s_u and strain at failure (ε_f) for all tests. None of 50S50K tests and only the 85S15K test with ±3.0% ISA reached the $\bar{A}_f = 0$ line. For the 85S15K and 98S02K tests, q_{max} was at the end of the test except for the undisturbed 85S15K test.

All of the [12] failure criteria for the 50S50K and 85S15K tests result in higher s_u than the reference undisturbed specimens. For the 50S50K tests this is in contrast to findings on the influence of sample disturbance on natural clay specimens (e.g., [13]) which showed generally decreasing shear strength with disturbance. The loss of strength for natural soils was attributed to destructuration of the soil and not densification, while for these tests, given the soils are young, unstructured soils, the disturbance evidently results in densification and increased shear strength. For the 85S15K tests s_u increased and ε_f decreased with in-

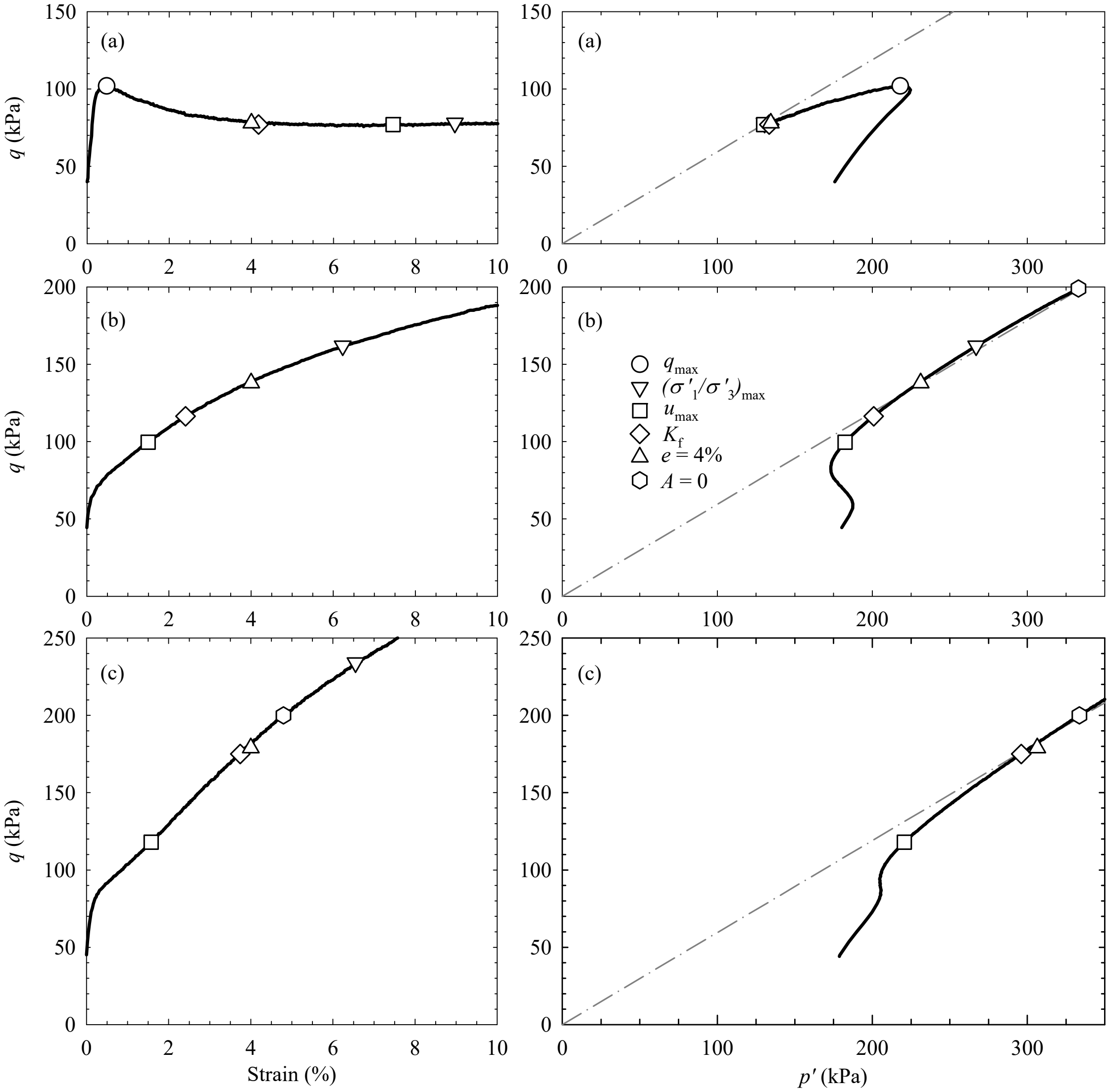


Figure 6. Brandon et al. [12] undrained shear strength definitions for 85S15K: a) reference undisturbed behavior (top row), b) undrained ± 3% ISA (middle row) and c) drained ± 3.0% ISA (bottom row).

creasing disturbance. For the ε_{zz} = 0.5% tests there was little difference between the drained and undrained s_u values, however for ε_{zz} = 1.0 and 3.0% the drained s_u values were greater than those of the undrained by 21% and 67% of the undisturbed strength, respectively. For the 98S02K tests s_u both decreased and increased with disturbance and neither the drained or undrained tests were consistently larger; however, as Table 3 shows, ε_f decreased with disturbance for all tests and failure criteria (with the exception of ε_f = 4%). These results for all tests reflect the increased stiffness of the soil due to densification during simulated sampling disturbance which is especially clear in the ε_f = 4% values.

The essentially zero $\Delta e/e_0$ during reconsolidation for all the drained ISA tests on these low OCR soils implies an excellent quality sample based on the notion of sampling being an undrained process for fine grained soils. The lower the change in void ratio during laboratory reconsolidation to the in situ effective stress state the better the quality of the sample (and assuming no swelling was allowed to occur during any stage of the test). While no quantitative sample quality criterion exists for triaxial specimens of low plasticity and non-plastic intermediate soils it is nevertheless interesting to note for comparative purposes the sample qualities using the clay based $\Delta e/e_0$ criterion of [13] which was developed for clay soils with a PI range of 6% to 43%. The undrained ±3% ISA specimens would be rated as very good to excellent ($\Delta e/e_0$ < 0.04, highest rating out of four) for the 50S50K specimen and fair to good (0.04 < $\Delta e/e_0$ < 0.07; second highest rating) for both the 85S15K and 98S02K specimens. In the case of all the drained ISA tests the near zero post-ISA reconsolidation $\Delta e/e_0$ values (0.001 to 0.002) would rate the samples as very good to excellent even though in the case of the 85S15K specimens the undrained shear behavior differs significantly from the reference undisturbed behavior.

Indeed, [5] and [14] provide indirect evidence of the challenge in assessing the quality of silts that may have densified during sampling. Various type of tube samples of a non-plastic (PI = 0) silt were sampled from a high

Table 3. Summary of failure criteria determinations for all tests. *eot* denotes end of test

Soil	Test Type	$(\sigma_1\text{-}\sigma_3)_{max}$		$(\sigma'_1/\sigma'_3)_{max}$		u_{max}		K_f line		$A_f = 0$		Mean Change
		q_f	ε_f	q_f	ε_f	q_f	ε_f	q_f	ε_f	q_f	ε_f	(%)
50S50K	Undisturbed	90	0.92	78	8.48	70	14.70	80	6.70	--	--	N/A
	±0.5% ISA_U	92	1.69	85	7.11	74	15.44	89	4.26	--	--	6.8
	±0.5% ISA_D	90	1.55	80	8.76	72	14.88	85	5.24	--	--	3.0
	±1.0% ISA_U	91	2.76	86	7.53	76	14.96	90	4.40	--	--	7.9
	±1.0% ISA_D	94	2.56	88	7.43	81	11.78	94	3.27	--	--	12
	±3.0% ISA_U	100	5.19	99	5.04	84	1.74	88	2.03	--	--	17
	±3.0% ISA_D	106	6.46	106	5.45	84	1.94	99	3.33	--	--	24
85S15K	Undisturbed	102	0.47	78	8.95	77	7.45	77	4.17	--	--	N/A
	±0.5% ISA_U	116	*eot*	114	8.83	104	4.90	105	5.20	--	--	32
	±0.5% ISA_D	109	*eot*	105	7.79	102	5.88	101	4.83	--	--	27
	±1.0% ISA_U	128	*eot*	125	8.33	115	4.52	113	3.74	--	--	45
	±1.0% ISA_D	152	*eot*	145	8.00	120	3.03	131	5.03	--	--	64
	±3.0% ISA_U	187	*eot*	162	6.23	100	1.49	116	2.40	199	12.65	69
	±3.0% ISA_D	280	*eot*	234	6.55	118	1.57	175	3.74	200	4.795	136
98S02K	Undisturbed	*352*	*eot*	288	7.21	157	1.33	275	6.66	197	3.23	N/A
	±0.5% ISA_U	*363*	*eot*	301	6.66	124	0.50	249	4.39	198	2.42	-1.8
	±0.5% ISA_D	*340*	*eot*	282	6.57	101	0.33	238	4.64	152	1.22	-12
	±1.0% ISA_U	*496*	*eot*	370	6.50	102	0.39	230	2.95	153	1.2	3.7
	±1.0% ISA_D	*347*	*eot*	316	7.11	94	0.42	280	5.71	130	1.04	-9
	±3.0% ISA_U	*563*	*eot*	402	5.99	106	0.73	310	4.44	186	2.26	18
	±3.0% ISA_D	*595*	*eot*	476	6.38	100	0.88	407	5.48	168	2.13	28

way construction site in Ireland for which piezocone tests indicated that the deposit was loose to very loose. Thick walled blunt angled, British U100 sampling tubes, which are well known to produce poor-quality samples in clays (e.g., [15]), nevertheless produced "excellent" quality samples based on the $\Delta e/e_0$ criterion. It was, however, concluded that the low $\Delta e/e_0$ values actually resulted from significant disturbance (densification) occurring during sampling and that the measured modulus and undrained shear strength for those samples were too high for the proposed design, i.e., unsafe.

5. Conclusions

The major difference in undrained shear after sampling disturbance simulation using undrained or drained ISA is the soil stiffness/rate of strain hardening. Undrained ISA testing on the young, non-structured intermediate soils tested results in the loss of a peak strength at low strain followed by strain softening, increased tendency to dilative behaviour, increased soil stiffness and an increase in the rate of strain hardening. These problems are exacerbated when ISA is performed drained, which is possible for standard tube sampling of silts ([5]). This in turn has an important effect on the selection of the undrained shear strength for intermediate soils depending on which criteria is used.

The most significant outcome of the results comparing undrained and drained ISA is that little to no volume change occurred during reconsolidation for all drained ISA tests which, if using clay-based sample quality assessment methods implies a good to excellent quality sample in spite of the tube sampling disturbance.

This result is most significant for the 85S15K specimens because while the post-ISA undrained shear behavior for the drained and undrained ISA are largely similar, the $\Delta e/e_0$ for the drained test is almost zero, suggesting a near perfect sample even through the behavior is completely different than the undisturbed specimen, especially for ε_{zz} = 1.0 and 3.0%.

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