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Effects of disturbance and consolidation procedures on the behaviour of intermediate soils

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ABSTRACT

There is limited experimental information available on soils that exhibit index characteristics and engineering properties intermediate to sands and clays such as low plasticity silts and clays and little guidance in evaluating cyclic strength and the potential for development of strains under earthquake loading. In practice, it often comes down to using either empirical correlations of in-situ penetration tests for sands or perform laboratory testing of field samples and cyclic softening procedures for clays. Penetration tests can greatly underestimate cyclic strength of low plasticity silts and clays while results of laboratory tests are often questioned due to the inability to know the effects of sample disturbance. The ability to obtain reliable test results depends on the soil properties (e.g., plasticity index, fines content, sensitivity), laboratory procedures to mitigate, negate, or quantify the effects of sample disturbance, and field loading conditions. This paper presents results of advanced laboratory testing to characterise two intermediate soils with complementary in-situ penetration data. New test procedures were used to investigate the soils' susceptibility to sample disturbance and help assess the degree in which measured strengths are representative of in-situ strengths. Advanced laboratory testing consists of consolidation tests, and monotonic and cyclic direct simple shear tests.

Keywords: fine-grained soils, liquefaction, cyclic strength, undrained strength, sample disturbance

1 INTRODUCTION

Estimating the monotonic and cyclic strength of intermediate soils, such as silty sands, sandy clayey silts, and low-plasticity silts, is a difficult challenge in practice. For example, if these soils are judged to be liquefiable, it is common practice to estimate their cyclic strengths using standard penetration test (SPT) or cone penetration test (CPT) based liquefaction correlations that were developed primarily for sands and nonplastic silty sands (e.g., Youd et al. 2001). Existing SPT or CPT liquefaction correlations may not, however, adequately predict the in-situ strengths of intermediate soils with higher clay contents. Laboratory tests are rarely performed on sands because conventional tube sampling techniques have been shown to cause excessive sample disturbance that render unreliable results. For clays, measures can be taken to obtain reliable laboratory strength results by reducing the effects of sampling disturbance in field and laboratory procedures. The challenge for intermediate soils is determining the soil characteristics for which in-situ test results should be used when the effects of sample disturbance are too great for reliable laboratory undrained strength measurements, and when laboratory measures that provide direct property measurements should be used in place of in-situ test data.

This paper introduces testing procedures developed to evaluate the effects that sample disturbance and consolidation procedures have on laboratory measurements of monotonic and cyclic undrained strengths in two intermediate soils. To provide context, the effects of disturbance during each step of the sampling process is first described schematically for over consolidated clays. The new testing procedures are then described, after which results from monotonic and cyclic undrained Direct Simple Shear (DSS) tests are presented for samples obtained from: (1) a soft alluvial, low-plasticity clay deposit, for which conventional sampling and testing procedures were expected to work reasonably well and (2) a loose silt and silty sand deposit for which the effects of sample disturbance may potentially be significant. Cyclic undrained DSS strengths are compared to those obtained using existing design approaches and the relative merits of the laboratory test results for estimating in-situ

behaviour and engineering practice are discussed. This paper provides a summary of results performed as part of a comprehensive study as detailed in Dahl (2011) and Dahl et al. (2010, 2014).

2 SAMPLE DISTURBANCE AND TESTING PROCEDURES

2.1 Sampling and disturbance

Laboratory testing procedures for consolidating specimens were developed to reduce effects of sample disturbance in clays. These procedures include SHANSEP, Recompression, and Modified-Recompression techniques that depend on the soil characteristics, load conditions and ability to define a preconsolidation stress (σ'_p).

The effects of sample disturbance are schematically illustrated in Figure 1(a) (modified and expanded after Ladd and DeGroot 2003; Dahl 2011) showing the stress path versus mean effective stress (p') path that a normally consolidated (NC) clay may experience during sampling and testing according to NGI's Recompression technique. The schematic paths for nearly NC clay shown in Figure 1(a) correspond to: (1) in-situ simple shear loading [point 1 to the failure surface] and (2) tube sampling and specimen preparation process followed by recompression consolidation to the in-situ vertical effective stress (σ'_{v0}) and laboratory DSS loading [points 1-11 to the failure surface]. The tube sampling path includes the effects of drilling, tube penetration, tube extraction, transportation, storage, extrusion, trimming, and mounting in the DSS apparatus with each path inducing a certain amount of shear strain and associated loss of effective stress while the void ratio remains relatively unchanged (i.e., minimal drainage or drying). Recompression consolidation causes the void ratio to decrease slightly, and may not fully establish the same p' as existed in situ because the effective horizontal stress (e.g., coefficient of lateral earth pressure at rest, K_0) that develops during recompression may be lower than the in-situ value. The undrained monotonic shearing response is affected by the decrease in void ratio (generally causing an increase in shear strength) and disturbance to the soil structure (generally causing a decrease in shear strength), such that the final shear strength may increase or decrease depending on the soil's characteristics.

Figure 1(b) also includes stress path for over-consolidated clay to illustrate the Modified Recompression technique wherein a specimen is preloaded close to its in-situ σ'_p as illustrated by the path through points 11, 12, and 13. The Modified Recompression technique recommends preloading DSS specimen to 80% of the estimated in-situ σ'_p , and then unloading to the σ'_{v0} to re-establish a reasonable K_0 condition in the DSS device before shearing (Ladd and DeGroot 2003, Lunne et al. 2006). In comparison, recompression of an over-consolidated specimen to the σ'_{v0} alone (point 11) will generally produce lateral stresses (i.e., K_0) that are smaller than the in-situ lateral stresses, and this can lead to the specimen exhibiting a softer and weaker response than would be expected in situ. The Modified Recompression technique is believed to produce an improved estimate of the in-situ behaviour, but requires that the in-situ σ'_p can be estimated or bounded with a reasonable degree of confidence.

2.2 Testings procedure for evaluating susceptibility to disturbance

A test protocol to quantitatively assess a soil's susceptibility to sample disturbance using conventional tube samples was developed as part of a comprehensive testing program. Companion samples were subject to different stress histories to evaluate the soil's sensitivity to some component of the specimen preparation process. The test protocol includes four different specimen preparation techniques as schematically illustrated in Figure 2 for the variation in vertical stress (σ'_v) loading between test specimens over time.

The baseline specimen preparation technique was the NGI's "Recompression technique" [solid line in Figure 2(a)] in which the vertical effective consolidation stress applied to the specimen in the laboratory device (σ'_{vc}) is equal to the estimated in-situ value (σ'_{v0}). Each step during the sampling through storage, and extrusion, trimming, and mounting (E-T-M) process is expected to cause a decrease in σ'_v acting on the specimen from the in-situ condition.

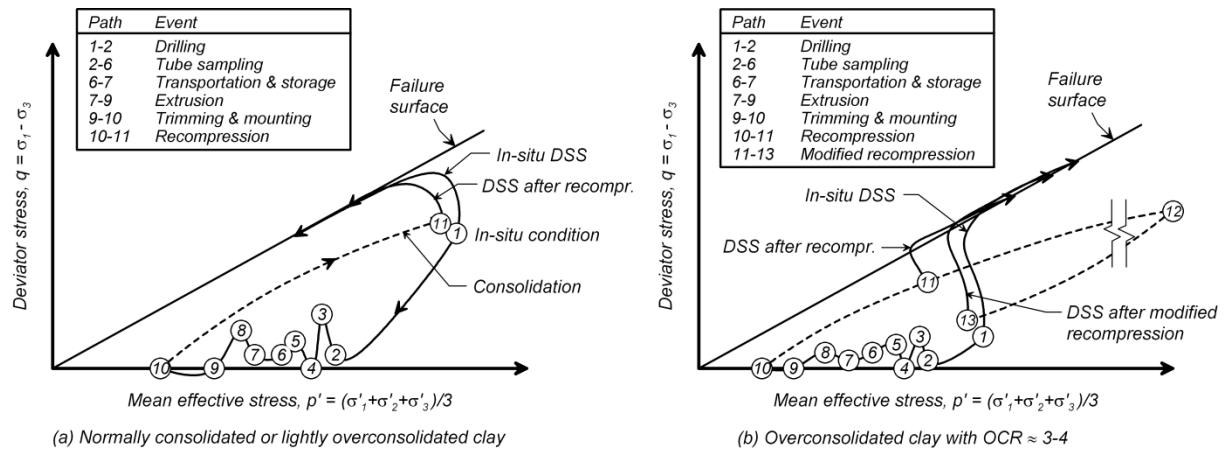


Figure 1. Schematic of stress paths during sampling and undrained monotonic DSS testing of NC and OC clay (modified and expanded after Ladd and DeGroot 2003; Dahl 2011).

The second specimen preparation technique, "laboratory preloading," [solid line in Figure 2(b)] involved consolidating the specimen in the laboratory DSS test device to a $\sigma'_{vc,max}$ that exceeds the estimated σ'_p , and then mechanically unloading the specimen to σ'_{vc} to produce the desired OCR. This process is conceptually similar to a SHANSEP approach. This sequence produces a specimen with a "DSS over-consolidation ratio" of

$$[1] \quad OCR_{DSS} = \frac{\sigma'_{vc,max}}{\sigma'_{vc}}$$

The third specimen preparation technique, "tube preloading," is a non-standard procedure that involves applying a consolidation stress to the sample while it is in the tube prior to the extrusion, trimming, and mounting, or "E-T-M", processes. As shown in Figure 2(c) (dashed line), this was performed by placing an approximately 50-mm-long tube section in a consolidation device and then consolidating to a stress equal to a stress ($\sigma'_{v,tube}$) that was greater than the in-situ value. The sample was then removed from the consolidation device, extruded from the tube, trimmed, and mounted in the DSS device for consolidation to a σ'_{vc} equal to the estimated σ'_{vo} value (similar to the Recompression technique). This specimen preparation technique, when compared to laboratory preloading technique (OCR_{DSS}), may indicate how significant the effects of disturbance from E-T-M and lateral stress conditions in the DSS device have on measured strength results. This sequence produces a specimen with a "tube over-consolidation ratio" of

$$[2] \quad OCR_{tube} = \frac{\sigma'_{v,t}}{\sigma'_{vc}}$$

The fourth specimen preparation technique, "tube and laboratory preloading," is another non-standard procedure that involves tube preloading and a modified recompression loading of the specimen in the DSS device. As shown in Figure 2(d) (dashed line), the sample while in the tube is subjected to $\sigma'_{v,tube}$ followed by E-T-M. The specimen is then subjected to a modified recompression loading to about 80% of $\sigma'_{v,tube}$ in the DSS device, which is conducted in the same manner that the Modified Recompression technique is used for conventional OCR clay specimens to re-establish in-situ K_o conditions (Ladd and DeGroot 2003). The only difference between "tube and laboratory preloading" and "laboratory preloading" is the inclusion of tube preloading and where E-T-M occurs. It was developed to check whether specimens subjected to both tube and laboratory preload produced differences in behaviour relative to specimens subjected to only laboratory preloading. The "tube and laboratory preloading" OCR is defined using the tube preloading stress as,

$$[3] \quad OCR_{tube,DSS} = \frac{\sigma'_{v,t}}{\sigma'_{vc}}$$

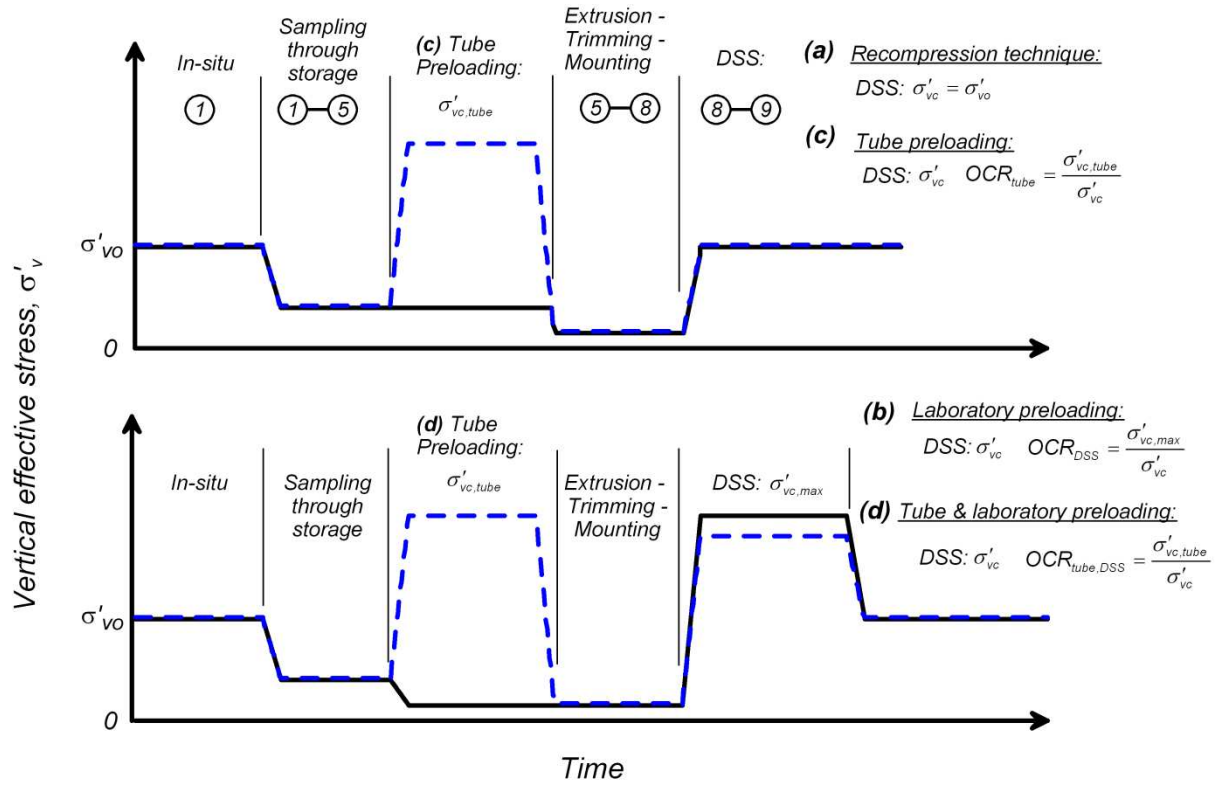


Figure 2. Schematic of the four specimen preparation techniques used to evaluate susceptibility of samples to disturbance from the extrusion through mounting process.

The ability to define any of the above measures of OCR requires that the σ'_p be known, or at least bounded, with some reasonable degree of accuracy. If the in-situ σ'_p is not well defined, then the preloading stresses applied in the laboratory needs to exceed the upper range of possible in-situ σ'_p for the specimen's OCR to be well defined in the laboratory.

3 SOILS TESTED

Laboratory testing was performed on two different soil strata obtained within the Holocene alluvium of Potrero Canyon in southern California. The upper stratum, referred to herein as Stratum A consist primarily of very soft clay (CL) with very loose silt (ML) and occasionally high plasticity clay and elastic silt (CH and MH) per the Unified Soil Classification System (USCS) with a fines content of 79% or greater. The underlying soils, referred to herein as Stratum B are sandier than Stratum A soils and consist of silty fine sand (SM), sandy silt (ML), and sandy silty clay (CL-ML) with a fines content between 35% to 78%. Table 1 provides a summary of the index parameters for Stratum A and B soils.

Table 1: Summary of index characteristics

Soil	Fines Content (%)	Moisture Content (%)	Liquid Limit (%)	Plasticity Index (%)
Stratum A	≥ 93	29-33	36-47	3-24, ave= 19
Stratum B	SM: 35-49 and ML/CL-ML: 50-78	22-36	20-30	<2 and 3-10, ave=6

Samples used in this study were obtained from the same or adjacent soil borings located either below or outside a recently placed 7.6-m-thick test fill with a footprint of 56m by 43m. Measures were taken to minimize disturbance during sampling and handling. This included the use of Osterberg piston sampler, transport in foam lined boxes, storage in a humidifier room, and X-ray imaging for selection of tube sections for testing.

Site investigation of Stratum A and B soils also included in-situ characterisation with cone penetration testing (CPT) and standard penetration testing (SPT). Stratum A soils inside and outside the fill had a

representative CPT cone tip resistance normalized by atmospheric pressure ($q_{cN} = q_c/P_a$) of less than 12 and representative corrected SPT N_{60} values of 3 to 8. Stratum B soils had a representative q_{cN} of 12 to 50 and representative corrected SPT N_{60} values of 5 to 20.

4 MONOTONIC UNDRAINED LOADING

Monotonic undrained DSS tests were performed on the samples prepared using the specimen preparation techniques illustrated in Figure 2 using a GEOTAC DigiShear apparatus. Constant-rate-of-strain consolidation tests were performed on Stratum A and B specimens to define or provide bounds on the in-situ σ'_p both inside and outside the test fill. Specimens were prepared in a latex membrane and confined to zero lateral strain by sixteen 1.6-mm-thick stacked rings. Undrained shearing was performed under constant-volume conditions with free specimen drainage. Changes in vertical stress (σ'_v) that occur to maintain constant height are assumed equivalent to the change in pore pressure (Δu) that would have occurred under undrained conditions. Monotonic shear tests were performed at strain rates of 5%/hr.

Results for Stratum A and B specimens are shown together for comparison purposes in Figure 3(a) and (b), respectively, in terms of normalized shear stress (τ_h/σ'_{vc}) versus shear strain (γ) and normalized shear stress versus normalized effective vertical stress (τ_h/σ'_{vc} versus σ'_v/σ'_{vc}). Five tests were performed on Stratum A specimens and four tests were performed on Stratum B specimens. Table 2 provides details of specimen consolidation stresses (Figure 2) used and normalized undrained shear strengths (s_u/σ'_{vc}) determined at $\gamma=15\%$.

The solid lines in Figure 3(a and b) correspond to specimens prepared using the "laboratory preloading" technique as shown in Fig. 2(b) where specimen were consolidated in the DSS device to OCR_{DSS} values of 1.0 and 4.0. The dashed lines are for samples consolidated in the tube then unloaded and subjected to E-T-M process before consolidation and testing in the DSS device one of two ways. The $OCR_{tube} = 4.0$ experienced only "tube preloading" [e.g., Figure 2(c)] and consolidated in the DSS device to $\sigma'_{vc} = \sigma'_{vo}$ (similar to Recompression technique). The "tube and laboratory preloading" [Figure 2(d)] was consolidated in the DSS device using Modified Recompression technique to $\sigma'_{vc,max} = 0.8(4 \cdot \sigma'_{vo})$ and then unloaded to $\sigma'_{vc} = \sigma'_{vo}$.

Stratum A specimens subjected to consolidation stresses while in the tube (tube and laboratory preloading, and tube preloading) showed significant memory of the preload, which was greater than Stratum B. For Stratum A, the $OCR_{tube,DSS} = 4$ specimen [dashed line, Figure 3(a)] exhibited a stress-strain behaviour that was very similar to the conventional $OCR_{DSS} = 4$ specimen. This indicates it retained memory in the tube and reapplication of $0.80p'$ in the DSS re-established the K_0 conditions in the rings. The shear resistances of the $OCR_{tube} = 4$ specimens were 9-32% lower than those for the $OCR_{DSS} = 4$ specimens or the $OCR_{tube,DSS} = 4$ specimens, but still significantly greater than those for the normally consolidated ($OCR_{DSS} = 1$) specimens. This suggests the specimens retained memory of tube preload but reconsolidation in DSS did not fully re-establish the K_0 condition.

Stratum B specimens subjected to consolidation stresses while still in the tube [dash lines, Figure 3(b)] retained some memory of the preload but to a lesser extent than Stratum A specimens. The $OCR_{tube,DSS} = 4.0$ and $OCR_{tube} = 4.0$ specimen exhibited a stress-strain behaviour that were softer throughout shearing than the $OCR_{DSS} = 4.0$ specimen. Although it is difficult to define an undrained shear strength from the strain-hardening responses, the shear resistance of the $OCR_{tube,DSS} = 4$ specimen was $\approx 29\%$ lower than the $OCR_{DSS} = 4.0$ specimen and the $OCR_{tube} = 4$ specimen was 51% lower than for the $OCR_{DSS} = 4$ specimen. Thus, Stratum B specimens retained less memory of tube preloading than was observed for Stratum A.

The effects that sample preparation stress history had on monotonic undrained DSS responses are attributed to the effects of disturbance during the E-T-M process and the role of initial K_0 conditions. The lower initial K_0 condition for the tube-preloaded specimens would explain why they exhibited greater yielding (softer response) at small strains during DSS shearing than the laboratory-preloaded specimens. At large strains, the tube-preloaded specimens never reach the same shear resistance as the laboratory-preloaded specimens, which may be due to the combined effects of the lower initial K_0 conditions and disturbance to the soils fabric during the E-T-M process.

Table 2: Summary of monotonic and cyclic undrained DSS testing

Lab. Testing Protocol	OCR	Stratum A			Stratum B		
		Consolidation Stress (kPa)	s_u/σ'_{vc} ^a	τ_{cyc}/σ'_{vc} ^b	Consolidation Stress (kPa)	s_u/σ'_{vc} ^a	τ_{cyc}/σ'_{vc} ^b
Laboratory preloading OCR _{DSS}	1	DSS: 212-240	0.24-0.29	0.20	DSS: 226	0.25 0.38 ^c	0.15
	4	DSS: 196 then 49	0.65	0.58	DSS: 328 then 82	1.08	0.44
Tube preloading OCR _{tube}	4	Tube: 196 DSS: 49	0.44 0.56 0.59	0.35	Tube: 314 DSS: 78	0.53	0.37
Tube & laboratory preloading OCR _{tube,DSS}	4	Tube: 196 DSS: 157 then 49	0.65	0.57	Tube: 314 DSS: 250 then 78	0.77	0.44

^a at $\gamma = 15\%$

^b at $N=10$ with Stratum A $b=0.05$ and Stratum B $b=0.135$

^c Sample with highest strength ratio had a $PI = 1$

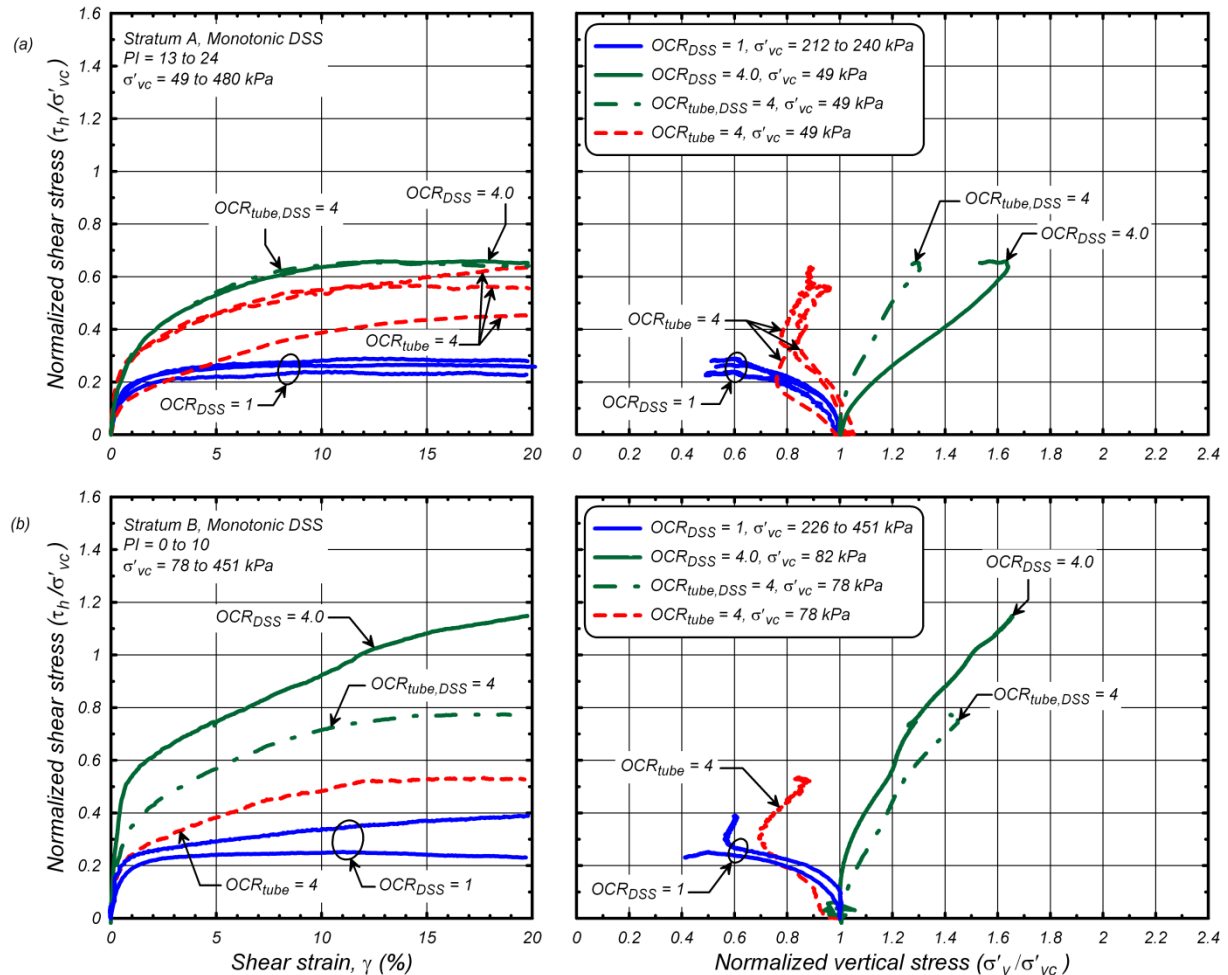


Figure 3. Normalized monotonic undrained DSS responses for (a) Stratum A and (b) Stratum B using different specimen preparation histories.

5 CYCLIC UNDRAINED LOADING

Cyclic undrained DSS tests were performed on the Stratum A and B samples prepared using the same preparation techniques illustrated in Figure 2 and consolidation stresses as the monotonic DSS

specimens. Fourteen and 15 tests were performed on Stratum A and Stratum B specimens, respectively. Cyclic loading at uniform stress amplitudes was produced under strain-controlled loading at a strain rate of 50%/hr. Cyclic loading was continued until at least 5% single-amplitude shear strain was reached.

The combinations of cyclic shear stress ratio (τ_{cyc}/σ'_{vc}) and number of uniform stress cycles (N) causing peak single-amplitude shear strain of 3% are summarized in Figure 4(a), and (b) for Stratum A and Stratum B specimens, respectively. Results are fitted with a power relationship of $CRR = aN^{-b}$ where the cyclic resistance ratio (CRR) is the cyclic stress ratio required to reach the specified failure criterion (i.e., $\gamma = 3\%$) in N cycles, and a and b are fitting parameters. The fitting parameter b was constrained at 0.050 for Stratum A and 0.135 for Stratum B based on at least six test results at $OCR_{DSS} = 1.0$. This provides a baseline to compare the effect of the different specimen preparation techniques and OCR on cyclic strengths with a limited number of test results. Table 2 provides a summary of cyclic strengths determined at $N=10$.

Both soils exhibited an increase in cyclic strengths with increasing OCR while the memory of the tube preloading varied between the soils in the same way as observed for the monotonic undrained strengths. For example, both soils exhibited an increase in cyclic strength of about 180-190% between $OCR_{DSS} = 1.0$ and $OCR_{DSS} = 4$. The slightly lower CRR values for Stratum B specimens may be attributed to specimen characteristics of plasticity and lower fines contents. For Stratum A, the $OCR_{tube,DSS} = 4$ specimen had cyclic strengths that were comparable at about 1-4% lower to those obtained for $OCR_{DSS} = 4$ specimens. The tube-preloading $OCR_{tube} = 4.0$ exhibited a cyclic strength loss at 35-45% compared to $OCR_{DSS} = 4.0$ specimen. For Stratum B the $OCR_{tube,DSS} = 4.0$ specimens had cyclic strengths that were slightly less (10-20% lower) than obtained for $OCR_{DSS} = 4.0$ specimens while the tube-preloading $OCR_{tube} = 4.0$ exhibited a greater cyclic strength loss at 40-50% compared to $OCR_{DSS} = 4.0$ specimen.

6 CONCLUDING REMARKS

The evaluation of the monotonic and cyclic undrained strength of an intermediate soil can often benefit from detailed site-specific in-situ and laboratory testing to better understand its behaviour under different loading conditions and provide greater confidence in selection of design parameters and appropriate engineering procedures for estimating cyclic strengths.

Testing procedures that involved laboratory-preloading, tube-preloading, and tube-and-laboratory-preloading of specimens was introduced for assessing the effects that disturbance during specimen E-T-M can have on subsequent measurements of monotonic undrained strength, and cyclic undrained strength. This testing protocol provides a basis for evaluating the susceptibility of an intermediate soil to sampling disturbance, and thus can be useful for judging the degree to which the cyclic strengths obtained on tube samples are likely to represent in-situ strengths. The selection of appropriate consolidation procedures for samples of intermediate soils can be extremely important for obtaining good estimates of in-situ strengths.

Insight provided by the testing procedures was illustrated in results for two intermediate soils ranging from where laboratory testing was expected to work reasonable well to where the effects of sample disturbance may be potentially significant. The test results for the silty clay of Stratum A were illustrative of a soil that had well-defined in-situ preconsolidation stresses, exhibited stress-history normalized engineering properties (SHANSEP), and retained a significant memory of the fabric preloading imposed by the tube preloading protocol. Laboratory testing in this case was appropriate and provided a basis for estimating strengths and evaluating the benefits of field preloading. The test results for the silt and silty sand of Stratum B demonstrated the soil's ability to retain memory of its tube preloading but difficulty in defining an undrained strength due to the strain hardening response of the low-plasticity specimens meant that it could not be strictly considered in a SHANSEP type framework. The cyclic strengths would be reasonably estimated by the CPT and SPT data, but results of the laboratory testing proved beneficial in verifying that in-situ based estimates were reasonable and in evaluating how field preloading could be used as a remediation method (i.e., strength gain from OCR).

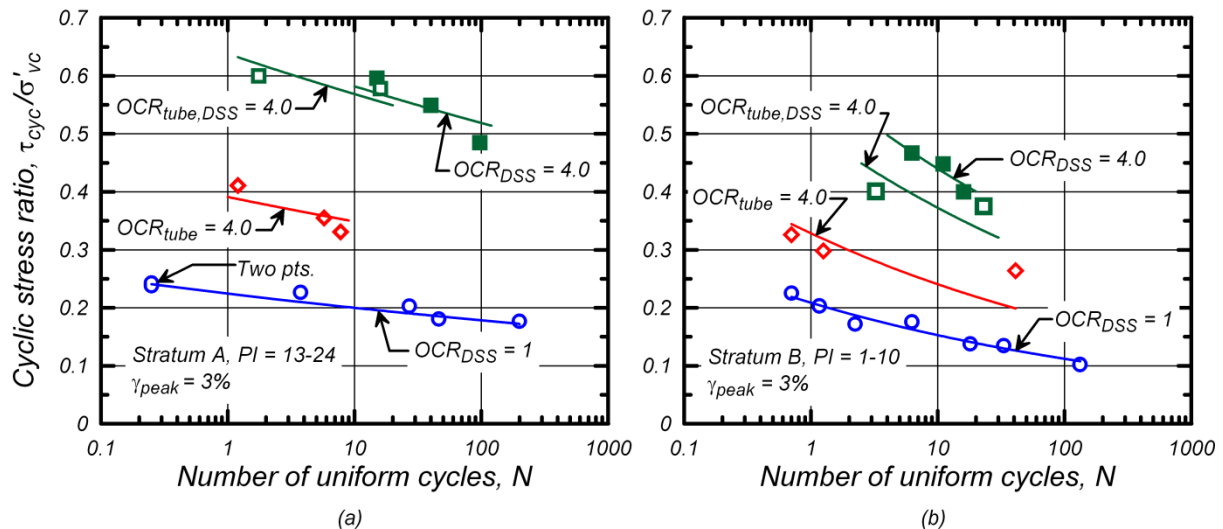


Figure 4. Cyclic stress ratio versus N to cause a peak shear strain of 3% on (a) Stratum A and (b) Stratum B specimens prepared using different specimen preparation histories.

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