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ABSTRACT

Sampling and testing of soils to measure engineering properties, such as monotonic and cyclic undrained shear strengths, requires an understanding of the potential effects of sampling disturbance and the selection of appropriate laboratory testing procedures. For clays, past research has provided insights on how sampling methods and laboratory testing procedures can be used in practice to assess and minimize sample disturbance effects. For sands, past research has shown that conventional tube sampling techniques cause excessive disturbance to the soil fabric, such that subsequent measurement of monotonic or cyclic strengths can be greatly in error and misleading. For intermediate soils, the effects of disturbance and consolidation procedures on monotonic and cyclic strengths are not well understood. In the present study, a test protocol was developed to assess the effects that disturbance during sample extrusion, trimming, and mounting have on subsequent measurements of compressibility, monotonic undrained strength, and cyclic undrained strength. Detailed laboratory tests were performed on tube samples from deposits of low-plasticity silty clay, for which conventional sampling and testing were expected to work reasonably well, and low-plasticity clayey sand, for which the effects of sample disturbance were of primary concern. Test results using this protocol for these two soils are presented and discussed.

INTRODUCTION

Sampling and testing of soils to measure engineering properties, such as monotonic and cyclic undrained shear strengths, requires an understanding of the potential effects of sampling disturbance (herein used broadly to refer to the drilling, sampling, storage, transportation, extrusion, trimming, and mounting of specimens in preparation for laboratory testing). For clays, past research has provided insights on how block and tube sampling methods and laboratory testing procedures can be used in practice to assess and minimize sample disturbance effects. For sands, past research has shown that sample disturbance using conventional tube sampling methods is excessive and that sample disturbance can only be reliably minimized by using frozen sampling techniques, which are generally prohibitively expensive in practice. For this reason, the in-situ cyclic strength of sand is commonly evaluated using penetration test-based correlations whereas the in-situ cyclic strengths of clays can be assessed using conventional tube sampling and laboratory testing procedures.

Soils that have characteristics intermediate to those associated with sands (e.g., cohesionless soils) and clays (e.g., cohesive soils), such as very low plasticity clayey silts or clayey sands, can be difficult to evaluate because it is unclear whether liquefaction correlations developed primarily for sands are applicable or whether the results of cyclic laboratory tests will be excessively influenced by the effects of sample disturbance. Clear guidelines on how to approach the evaluation of engineering properties for such intermediate soils are not yet established, and thus it is often beneficial for site-specific evaluations to systematically explore the soil behavior, using information from in-situ and laboratory tests, as part of the overall evaluation of expected in-situ properties.

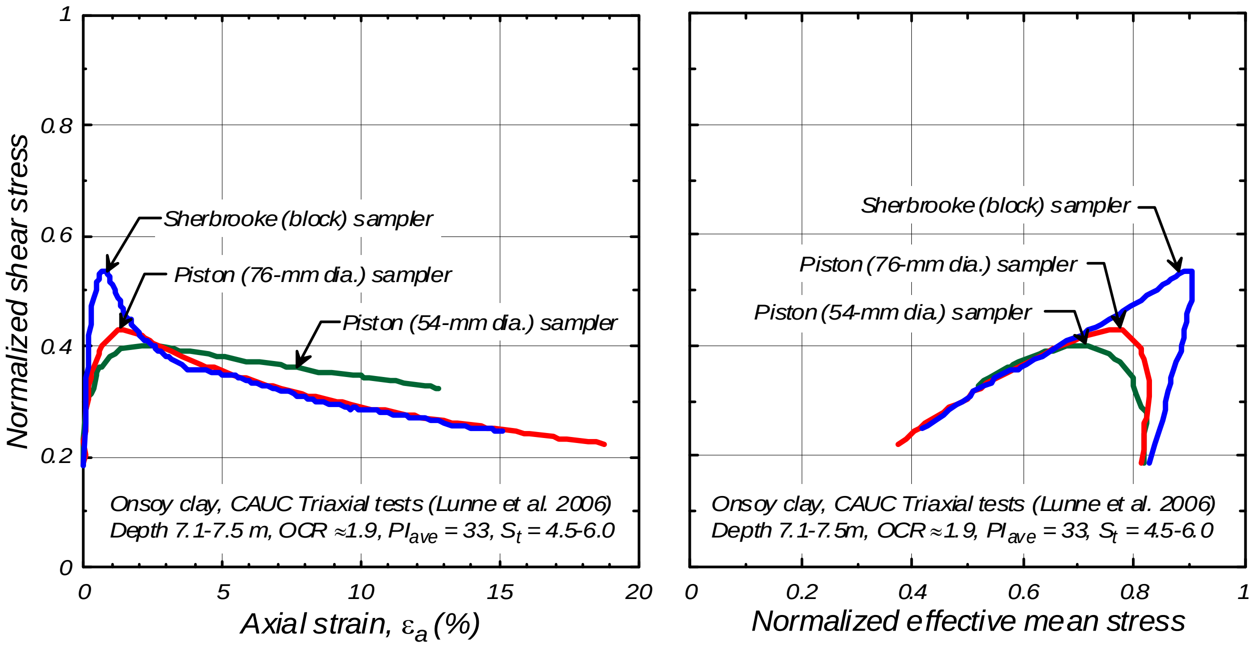


Fig. 1. Comparison of the CAUC triaxial test responses of Onsoy clay specimen obtained by Sherbrooke (block) and piston samplers (after Lunne et al. 2006).

This paper presents findings from laboratory testing programs on tube samples from two different soil deposits, along with a description of a set of testing procedures that were developed for assessing the potential effects of sampling disturbance on the test results. Examples of sample disturbance effects for clays and sands are first described to provide conceptual understanding and a framework for discussions. The testing procedures being used to evaluate sample disturbance effects on tube samples are then described schematically, after which the results of tests are presented for samples 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 medium-stiff/medium-dense alluvial clayey sand deposit, for which the effects of sample disturbance were of primary concern. Finally, the implications of the results for engineering practice are discussed.

EXAMPLES OF SAMPLE DISTURBANCE EFFECTS

Clays

The effects of sample disturbance on the stress-strain response of clays has been well illustrated in the literature and can vary significantly depending on sampling methods, laboratory testing procedures, and soil characteristics. For example, results of anisotropically-consolidated undrained triaxial compression (CAUC) tests on specimens of Onsoy clay (OCR ≈ 1.9; plasticity index, PI ≈ 33; sensitivity, S_t = 4.5-6.0) are compared in Fig. 1 (Lunne et al. 2006). These specimens were consolidated in the laboratory to their in-situ effective stresses, per the Norwegian Geotechnical Institute's (NGI) Recompression technique (e.g., Bjerrum and Landva 1966), prior to undrained shearing. The specimen obtained using a Sherbrook block sampler (trimmed to a cross-sectional area of 50 cm^2) exhibited the greatest initial stiffness, greatest peak shear resistance, and the most pronounced post-peak strain softening. The specimens obtained using piston samplers (both untrimmed) showed softer response and lower peak shear resistances, with the detrimental effects of sample disturbance being greater for the smaller 54-mm-diameter specimen than for the larger 76-mm-diameter specimen. The shear resistance at higher strains, however, was greatest for the 54-mm-diameter specimen, which may be attributed to it having a lower void ratio after recompression consolidation (i.e., greater disturbance can be expected to result in larger volumetric strains during recompression consolidation).

The results of CAUC triaxial tests on block and piston specimens of low-plasticity clay from Eidsvold (OCR ≈ 2; PI = 13-19, S_t = 2-5), as shown in Fig. 2 (Karlsrud et al. 1996, as presented in Lunne et al. 1997), illustrates a different effect that sample disturbance may have on soil behavior. The block sample exhibited an initial stiff response during undrained shearing, a well defined peak shear resistance, and significant post-peak strain softening (similar to the response of the Onsoy block specimen shown in Fig. 1). In contrast, the piston specimen, although initially softer, exhibited strain hardening behavior at larger strains and eventually reached a greater shear resistance than did the block specimen. In this case, the block specimen developed about 1.0% volumetric strain during recompression consolidation to the in-situ stresses whereas the 54-mm-diameter piston specimen developed about 3.1% volumetric strain during recompression

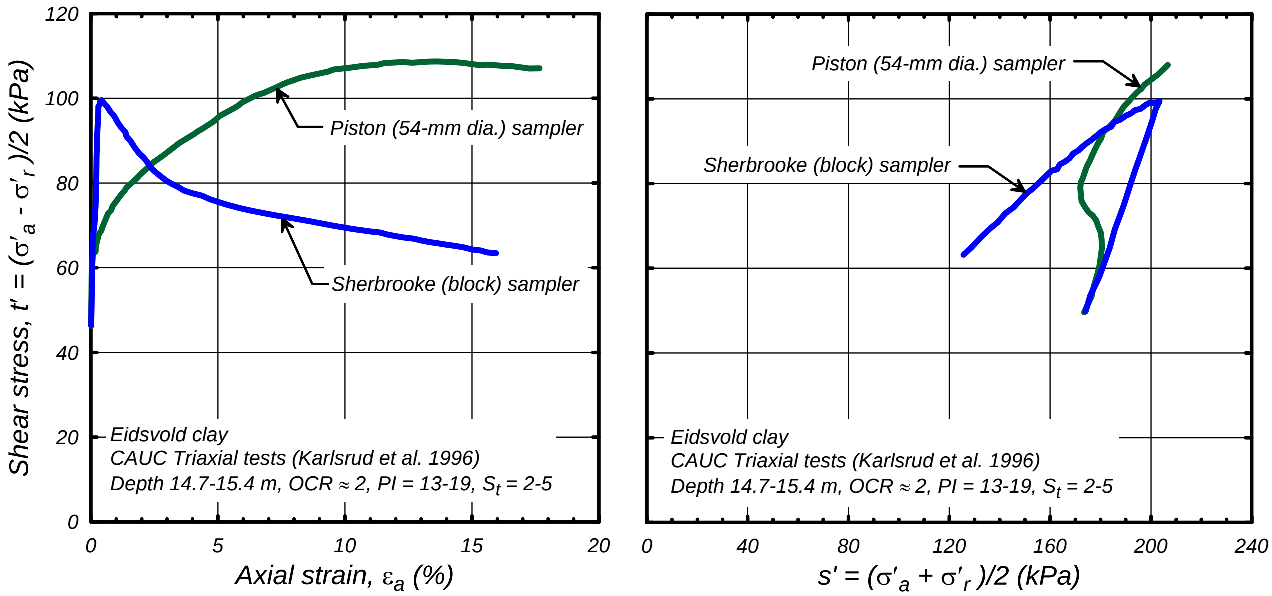
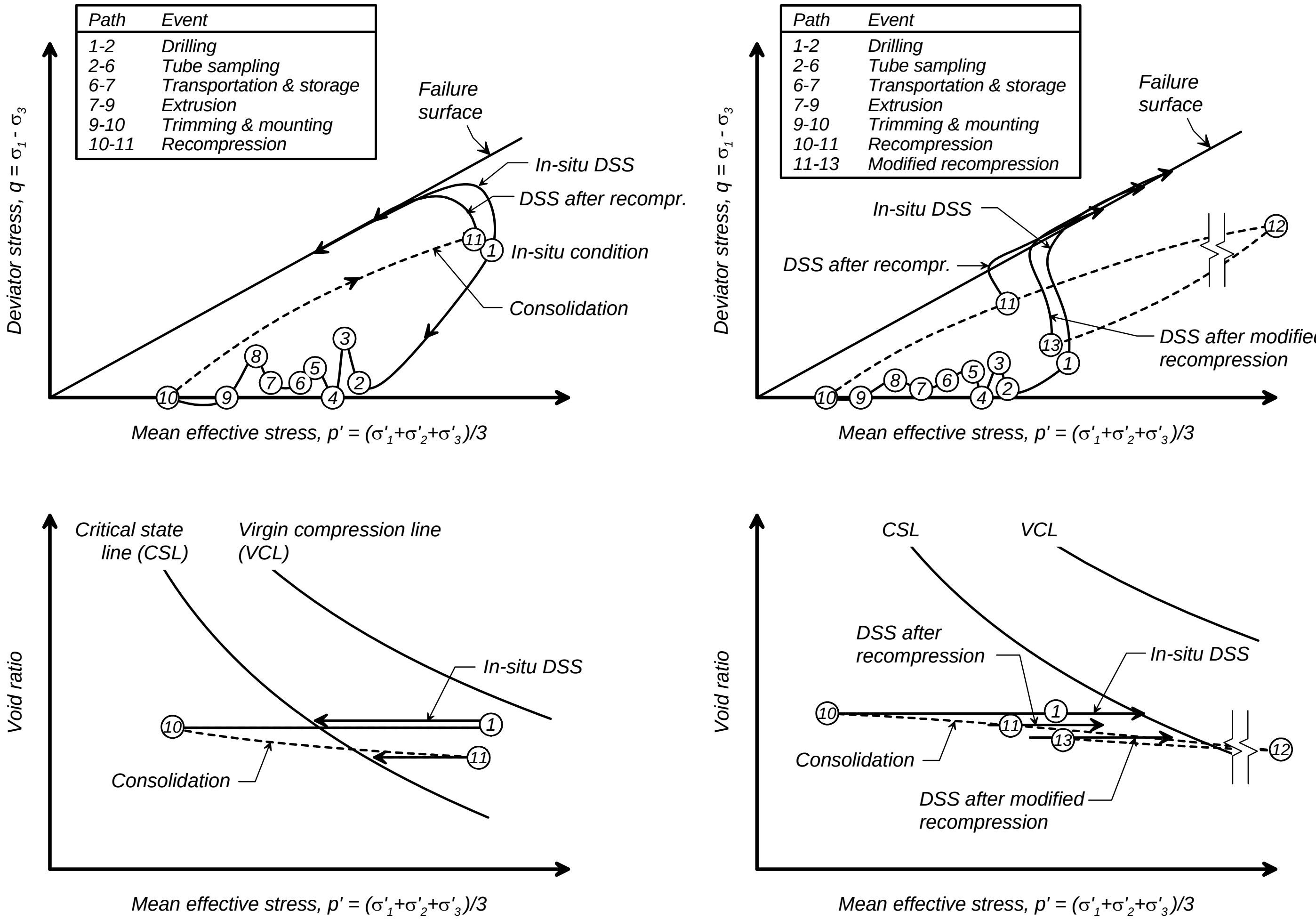


Fig. 2. Comparison of the CAUC triaxial test responses of Eidsvold silty clay specimen obtained by Sherbrook and piston samplers (after Karlsrud et al. 1996).

consolidation. The large recompression consolidation strains that developed in the piston specimen reduced its void ratio sufficiently for the material to change from a contractive to dilative response at large shear strains during undrained shearing. Lunne et al. (1997) summarized the differences in these responses by noting that the behavior at small stresses and strains was dominated by the original clay structure, whereas the behavior at larger strains was dominated by the specimen's void ratio. They further noted that the difference in sample quality between block and piston specimens is most pronounced for sensitive, low-plasticity clays and is less pronounced for medium-plasticity clays (PI>30). Note that the two cases illustrated in Figs. 1 and 2 support the current practice of using tube sample diameters of at least 76 mm.

The effects of sample disturbance are schematically illustrated in Fig. 3 (modified and expanded after Ladd and DeGroot 2003) showing the stress path and void ratio (e) versus mean effective stress (p') path that a clay may experience during sampling and testing according to the Recompression technique. The schematic paths for nearly normally consolidated clay shown in Fig. 3(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 and laboratory direct simple shear (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 – 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_o) 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.

A similar schematic for over-consolidated clay is shown in Fig. 3(b) to illustrate the testing procedure wherein a DSS specimen may be preloaded close to its in-situ preconsolidation stress (Ladd and DeGroot 2003, Lunne et al. 2006). This testing procedure, referred to as the Modified Recompression technique herein, is illustrated by the path through points 11, 12, and 13 in Figure 3(b) and is used to re-establish a reasonable K_o condition in the DSS device. For example, Ladd and DeGroot (2003) recommended preloading DSS specimens to 80% of the estimated in-situ preconsolidation stress, and then unloading them to the in-situ vertical effective stress (σ'_{vo}) prior to undrained shearing. In comparison, recompression of an over-consolidated specimen to the σ'_{vo} alone [point 11 in Fig. 3(b)] will generally produce lateral stresses (i.e., K_o) 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 behavior, but requires that the in-situ preconsolidation stress can be estimated or bounded with a reasonable degree of confidence.



(a) Normally consolidated or lightly overconsolidated clay

(b) Overconsolidated clay with OCR ≈ 3-4

Fig. 3. Schematic of stress paths during sampling and undrained monotonic DSS testing of clay (modified and expanded after Ladd and DeGroot 2003).

The degree of sample disturbance may be estimated from the volumetric strain (ε_v) that develops during reconsolidation to the σ'_{vo} using the sample quality designation (SQD) method proposed by Terzaghi et al. (1996) and the change in void ratio relative to initial void ratio ($\Delta e/e_o$) method proposed by Lunne et al. (1997). The SQD method defines sample quality from A (best) to E (worst) based on the magnitude of ε_v that occurs during reconsolidation to σ'_{vo}. Lunne et al. (1997) uses $\Delta e/e_o$ (instead of ε_v) and the over-consolidation ratio (OCR) to rate sample quality from excellent to very poor. They use $\Delta e/e_o$ rather than $\varepsilon_v = \Delta e/(1+e_o)$ because the same amount of ε_v is expected to cause a greater amount of disturbance as the initial void ratio decreases. Further, they consider the soil's OCR because the same magnitude of ε_v is expected to cause greater disturbance as the OCR increases.

The use of SHANSEP testing procedures can be used to minimize the effects of sample disturbance for more ordinary clays, such as non-cemented, low-sensitivity, sedimentary clays, as summarized in Ladd and DeGroot (2003). In this approach, samples are consolidated at stresses that bring them to a normally consolidated condition in the laboratory, and then mechanically unloaded to select values of OCR prior to undrained shearing. For many ordinary clays, the undrained stress-strain response normalizes with respect to the consolidation stress and OCR, which can then be used to estimate strengths for a broad range of in-situ stress and stress-history conditions.

Sands

Sample disturbance has been shown to have a potentially significant effect on the monotonic and cyclic undrained response of sands, unless recourse is made to use of frozen sampling techniques. Strains imposed on sands during conventional tube sampling procedures can be sufficient to destroy or erase the effects that prior strain history, over-

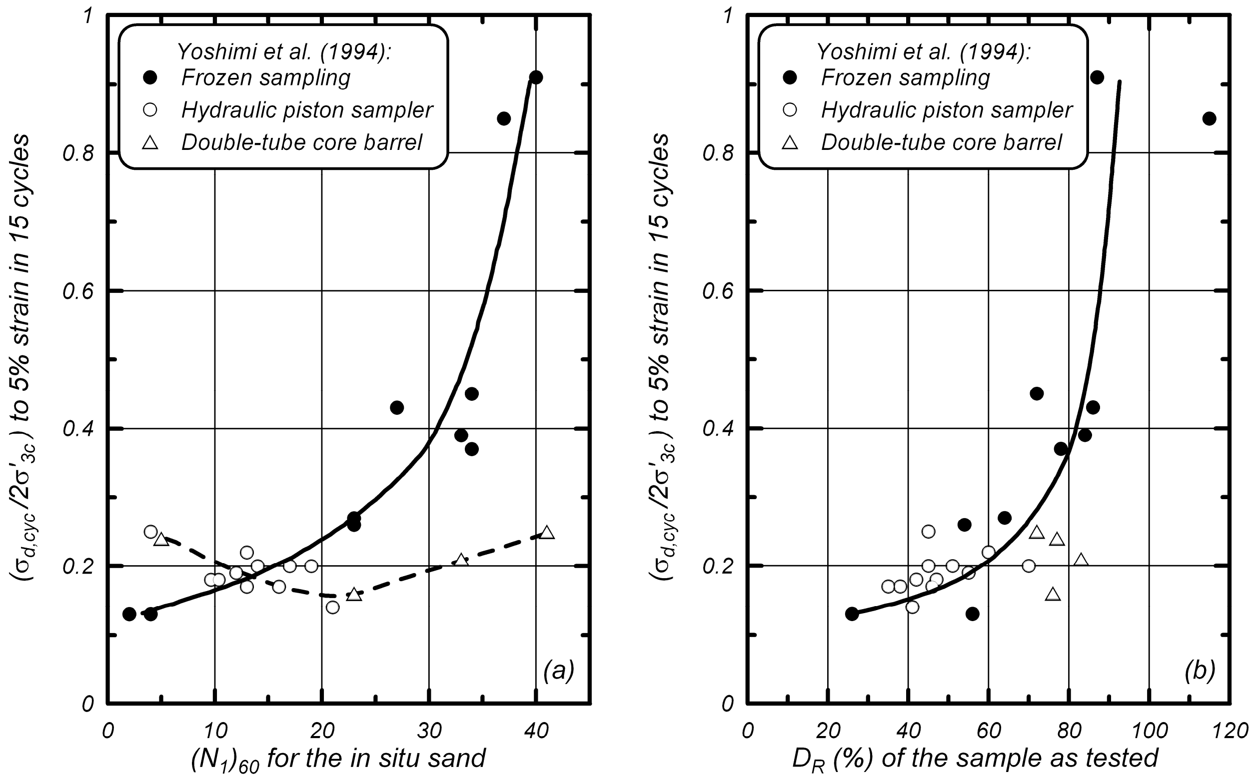


Fig. 4. Comparison of undrained cyclic triaxial strengths of sand samples obtained by frozen sampling and conventional tube sampling techniques (after Yoshimi et al. 1994; redrawn in Idriss and Boulanger 2008).

consolidation, cementation, or aging can have on sand behavior. This is well illustrated by the cyclic strength data of sand samples obtained from two different tube samplers and by frozen sand sampling techniques as presented by Yoshimi et al. (1994) and shown in Fig. 4. The frozen sample results show the expected trend of cyclic strengths increasing with increasing relative density or penetration resistance, whereas all the conventional tube sample results showed cyclic strengths of about 0.2 regardless of the in-situ relative density of the sand. Tube sampling caused the loose sands to densify (contract) and the dense sands to loosen (dilate), such that the as-tested densities varied less than the in-situ densities. The combined effects of density (volumetric) changes and fabric disruption caused by tube sampling renders disturbed samples and unreliable test results, as the cyclic strength of loose sands may be overestimated and the cyclic strength of dense sands strongly underestimated. Results such as these are the primary reason why the in-situ cyclic strength of sand is most commonly evaluated using penetration test-based liquefaction correlations.

The effects of conventional tube sampling on the response of saturated sand to undrained monotonic loading is schematically illustrated in Fig. 5, which can be compared to the schematic presented previously for clay (Fig. 3). The free-draining nature of sand enables the effective stress in a specimen to drop to very low values during the various stages of sampling through specimen mounting, and the stresses and strains imposed during these paths can cause yielding of the specimen. In addition, the specimen's void ratio can change significantly during the various phases of sampling and specimen preparation. Small changes in void ratio can have a large effect on monotonic undrained critical state (or steady state) shear strengths (e.g., Castro 1975), and also contribute to the changes in cyclic strengths as a result of disruption in of the sand fabric.

While the actual stress and volumetric changes soils undergo during the sampling and specimen preparation process are inevitability varied, many measures can be taken to improve the quality of and confidence in laboratory tests results. Details regarding sampling tube preparation, sealing, transport, storage, and cutting as well as specimen extrusion, trimming, and mounting can all influence the measured soil behavior. It is important to recognize that many of these details can decrease or increase the measured monotonic or cyclic strengths as well as change the volumetric behavior (being contractive or dilative). Procedures have been proposed (Poulos et al. 1985) and used successfully (Castro et al. 1992) to correct measured values of undrained steady state strengths of sands for void ratio changes that have occurred during the sampling and specimen preparation processes, but no procedures have been developed to correct measured values of undrained cyclic strengths for the effects of such void ratio

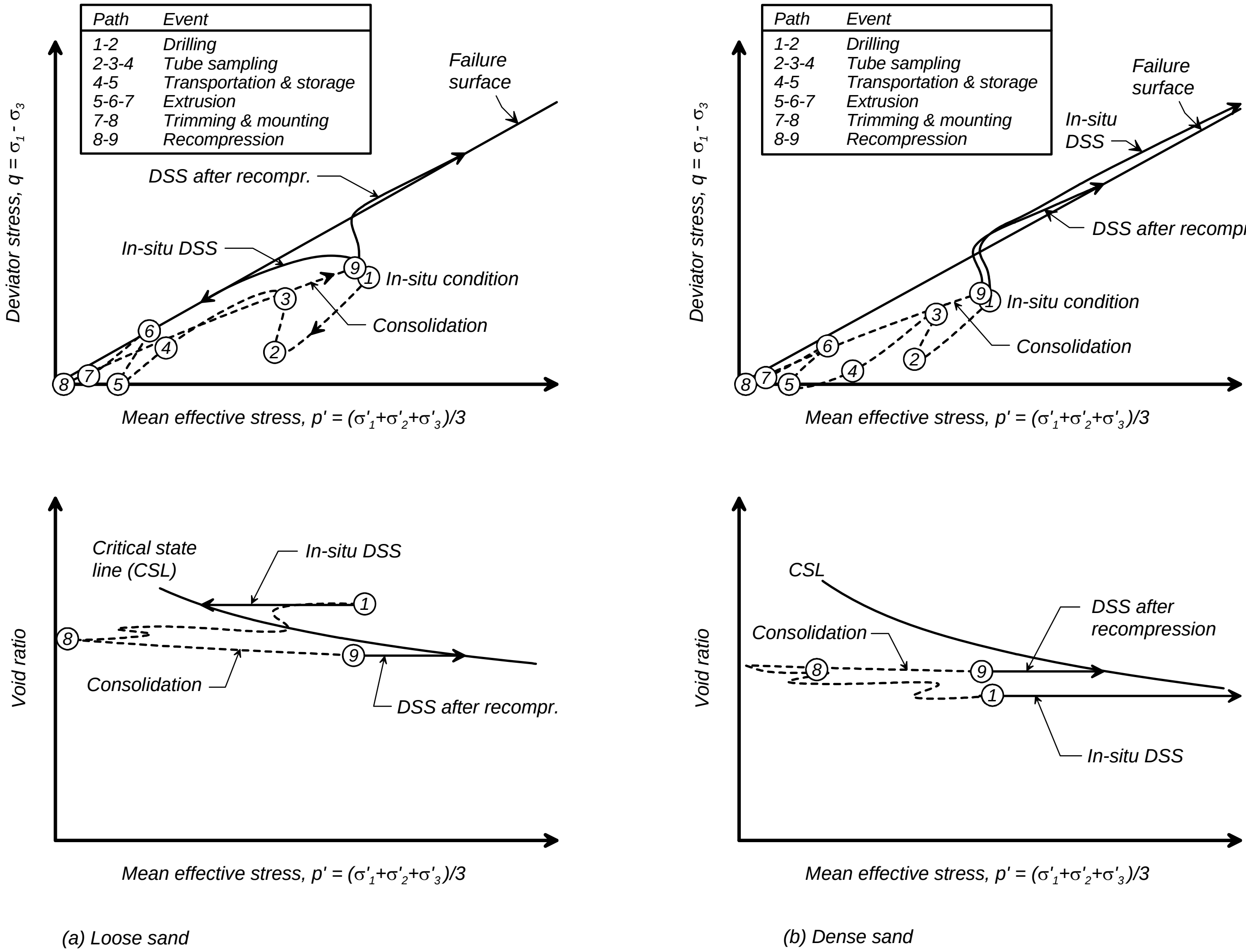


Fig. 5. Schematic of stress-paths during sampling and undrained monotonic DSS testing of sand.

changes. Guidance and recommendations regarding the details of sampling and specimen preparation are beyond the scope herein, but will be addressed in a future paper.

INTERMEDIATE SOILS TESTING PROCEDURES

Intermediate soils, for the purpose of this paper, are considered to be those soils that are intermediate to clays and sands in their index characteristics and engineering behavior. This includes silty and clayey sands, sandy silts, sandy clays, and very low plasticity silts and clayey silts. There is a shortage of in-situ, experimental, and case history data for the range of intermediate soils encountered in situ, and therefore it is often unclear how best to evaluate their susceptibility to earthquake-induced shear strains and strength loss. In practice, the question is often reduced to deciding whether or not a program of conventional tube sampling and laboratory testing can be used to assess their engineering properties or if the effects of sample disturbance are too severe and the soil properties should be estimated using various penetration tests or other in-situ test based correlations.

A test protocol for assessing the susceptibility of a soil to the effects of sample disturbance was developed as part of a recent testing program for tube samples of intermediate soils from a site in California. The idea was to develop a testing protocol wherein companion samples could be subjected to different stress histories to assess the soil's sensitivity to some component of the sampling and specimen preparation process. The challenge is evaluating the relative importance the effect of sample disturbance has on test results when the only specimens available for laboratory testing are from conventional tube sampling techniques with some unknown degree of disturbance.

The protocol adopted included four different specimen preparation techniques as schematically illustrated in Fig. 6

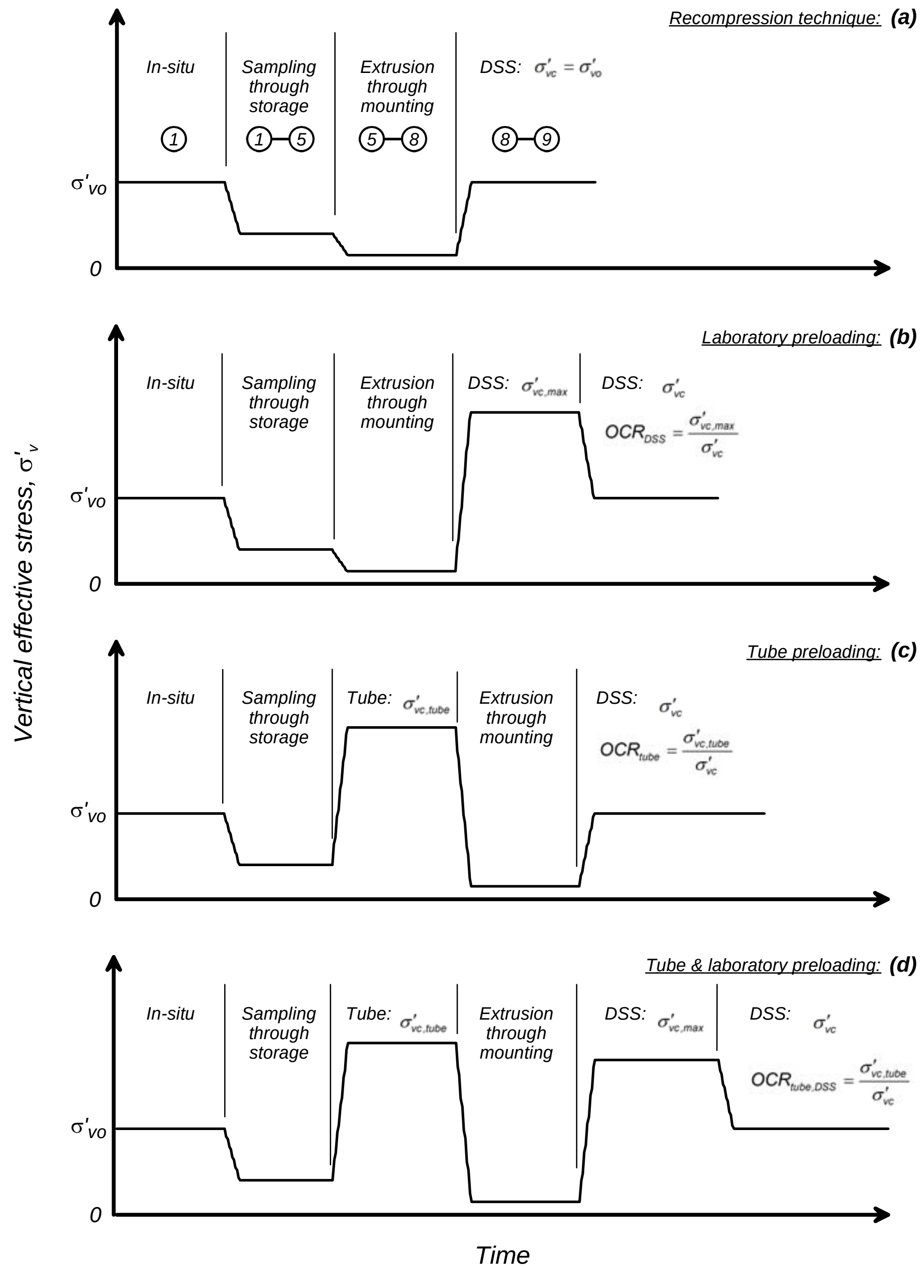


Fig. 6. Schematic of the four specimen preparation techniques used to evaluate susceptibility of samples to disturbance from the extrusion through mounting process.

which present the variation in vertical stress on test specimens over time. The baseline specimen preparation technique was the NGI's "Recompression technique" (Fig. 6a) in which the vertical effective consolidation stress applied to the specimen in the laboratory (σ'_{vc}) is equal to the estimated in-situ value (σ'_{vo}). The σ'_v acting on the specimen at the intermediate stages of sampling, storage, extrusion, and mounting is expected to be less than σ'_{vo} for typical soils and handling procedures.

The second specimen preparation technique, "laboratory preloading," (Fig. 6b) involved consolidating the specimen in the laboratory test device (DSS for this schematic) to a $\sigma'_{vc,max}$ that exceeds the in-situ stress (σ'_{vo}), and then unloading the specimen to a desired σ'_{vc}; the schematic shows the unloading stress as equal to the in-situ stress, but other unloading stresses may be used to produce other degrees of OCR. This sequence produces a specimen with a “DSS over-consolidation ratio” of

$$OCR_{DSS} = \frac{\sigma'_{VC,max}}{\sigma'_{VC}} \quad (1)$$

with the OCR_{DSS} being equal to the specimen's true OCR only if the value of $\sigma'_{vc,max}$ exceeds the in-situ preconsolidation stress (or yield stress, as discussed by Ladd and DeGroot 2003). In certain cases, the value of $\sigma'_{vc,max}$ may not equal or exceed the in-situ preconsolidation stress, and these will be discussed after the four techniques illustrated in Fig. 6 have been described.

The third specimen preparation technique, "tube preloading," (Fig. 6c) involved applying a consolidation stress to the sample while it was still inside the sampling tube. To apply this loading, an approximately 50-mm-long section was cut from the sampling tube, and then placed in a consolidation device. The sample was then consolidated to a stress ($\sigma'_{v,t}$) that was greater than the in-situ value. The sample was then removed from the consolidation device, extruded from the sample tube, trimmed, and mounted in the DSS device for consolidation to a σ'_{vc} equal to the estimated σ'_{vo} value. This sequence produces a specimen with a "tube over-consolidation ratio" of

$$OCR_{tube} = \frac{\sigma'_{V,t}}{\sigma'_{VC}} \quad (2)$$

Note that the OCR_{tube} will also be the sample's OCR if the value of $\sigma'_{v,t}$ exceeds the in-situ preconsolidation stress (or yield stress).

The difference in specimens prepared with the same OCR_{DSS} (Fig. 6b) and OCR_{tube} (Fig. 6c) is whether the extrusion-though-mounting steps occur before or after the application of the maximum consolidation stress. Disturbance caused by the extrusion, trimming, and mounting (E-T-M) process may be expected to affect the degree to which the benefits of prior over-consolidation are retained by the soil specimen. In addition, the reconsolidation step in the DSS device may not re-establish the lateral stress conditions that would have existed in situ for the same degree of over-consolidation (as previously discussed in relation to the use of the Modified Recompression technique and shown in Fig. 3). Thus, the differences in stress-strain response for specimens prepared to the same OCR_{DSS} and OCR_{tube} would provide an indication of how significant the effects of disturbance from extrusion through mounting and lateral stress conditions are for that particular soil type and test condition.

The fourth specimen preparation technique, "tube and laboratory preloading," (Fig. 6d) involved applying a tube preloading followed by a modified recompression loading of the specimen in the DSS device. The modified recompression loading in the DSS device may only go up to 70-80% of the maximum vertical preload stress applied to the sample while in the tube and conducted in the same manner that the Modified Recompression technique is used for conventional over-consolidated clay specimens. This specimen preparation technique was used as a check on whether the combination of both a tube and laboratory preload produced any differences in response from those for specimens prepared with the same OCR_{DSS} only. The "tube and laboratory preloading" OCR is defined using the tube preloading stress as,

$$OCR_{tube,DSS} = \frac{\sigma'_{V,t}}{\sigma'_{VC}} \quad (3)$$

with the implicit understanding that the laboratory preload stress will be about 80% of the tube preload stress.

The ability to define any of the above measures of OCR requires that the preconsolidation stress be known, or at least bounded, with some reasonable degree of accuracy. If the in-situ preconsolidation stress is not well defined, then the preloading stresses applied in the laboratory need to exceed the upper range of possible in-situ preconsolidation stresses for the specimen's preconsolidation stress and OCR to be well defined in the laboratory. It may not be desirable to bring certain soils to such a normally consolidated state in the laboratory if the stresses are likely to cause a breakdown or disruption of the soil fabric, such as in the case of lightly cemented or sensitive soils. If the preconsolidation stress for such a soil is not well defined, then the different measures of OCR may also not be well defined. In such cases, the preloading stresses described in Fig. 6 may instead be referred to as "consolidation ratios," with the OCR notation in Eqs. 1, 2, and 3 being replaced with CR_{DSS}, CR_{tube}, and $CR_{tube,DSS}$, respectively.

These four specimen preparation techniques were used as part of testing programs on two different soils, as described in the following sections.

POTRERO CANYON STRATUM A

Samples of soft silty clay were obtained from Stratum A at a site in Potrero Canyon in Los Angeles County (Dahl et al. 2010). The soil profile consists of 12 m of recent Holocene alluvium overlying older dense silty sand and firm lean clay (Bennett et al. 1998) and underlain by siltstone and claystone. The recent alluvium consists of 1-m of desiccated clay and silt overlying Stratum A soils which consist of 3.1- to 3.4-m of very soft clay (CL) to very loose silt (ML) and occasionally as fat clay and elastic silt (CH and MH) per Unified Soil Classification System (USCS). Stratum A soils have a fines content of 93% or greater, a clay content (defined as <0.002mm) generally between 26 and 34%, a natural water content between 29% and 33%, a liquid limit (LL) between 36 and 47 (average of 41%), and a plasticity index (PI) between 12 and 24 (average of 18). A summary of the index parameters for Stratum A is listed in Table 1. The groundwater table varies between 2.1 m to 5.6 m depth.

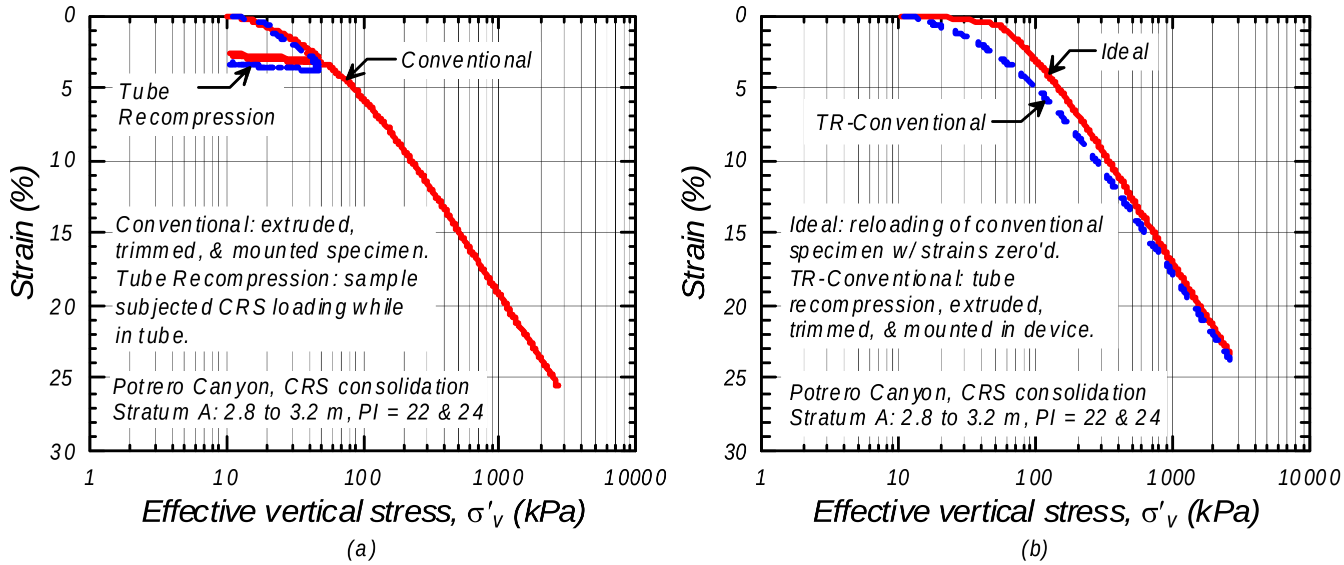


Fig. 7. CRS consolidation test results for samples of Stratum A from Potrero Canyon.

Table 1. Index characteristics of soil samples

Site	Fines Content (%)	Moisture Content (%)	Liquid Limit (%)	Plasticity Index (%)
Potrero Canyon	≥ 93	29-33 ave = 31	36-47 ave = 41	12-24 ave = 18
Perris Dam	41-48	12-14 ave = 13	20-27 ave = 24	4-13 ave = 9

Tube samples were obtained using an Osterberg piston sampler at two locations: (1) below a 7.6-m-thick test fill at depths 1.25 m to 3.44 m below original ground surface (i.e., 8.8 m to 11.1 m below the fill surface), and (2) at depths of 2.8 m to 3.2 m below the ground surface approximately 90 m outside the test fill. Tubes were transported in foam lined boxes to the laboratory, and select tubes were x-rayed and transported to the University of California, Davis, where they were stored in a climate controlled/humidifier room until testing. Samples used for testing were selected after review of x-ray images and were extruded from the tubes in the same direction as they were sampled in field. Details of the tube cutting and specimen preparation are described in Dahl et al. (2008). Specimens were trimmed from their initial 71-mm diameter to a 64-mm diameter and 25-mm height for consolidation testing and to a 66-mm diameter and 18-mm height for direct simple shear (DSS) testing.

CRS Consolidation

The results of constant-rate-of-strain (CRS) consolidation tests on samples prepared using techniques similar to those illustrated in Fig. 6a and 6b are compared in Fig. 7. The consolidation curve labeled "conventional" is for a specimen prepared and consolidated in a conventional manner. The specimen was extruded, trimmed, and mounted (E-T-M) in the consolidation frame, submerged in a water bath, subjected to a seating load (~3 kPa) overnight, and then loaded at a strain rate of approximately 1.0%/hr. Initial recompression loading to the σ'_{vo} of 46 kPa, which was held constant for 60 min, resulted in a ε_v of 2.7%. This corresponds to a SQD of C according to the criteria proposed by Terzaghi et al. (1996), and a $\Delta e/e_0$ = 0.054 which corresponds to a sample quality of "good to fair" according to the criteria proposed by Lunne et al. (1997). The unloading-reloading cycle resulted in a recompression index, C_r, of 0.013 for this specimen, which is smaller than the values (0.030 to 0.054) obtained for four other samples from this stratum.

The consolidation curve labeled "tube recompression" in Fig. 7a is for a sample that was consolidated in the tube (i.e., a 5-cm length of the tube) to a stress $\sigma'_{v,t}$ equal to the in-situ stress, and then unloaded. The volumetric strain upon recompression to the in-situ stress (also held constant for 60 min) was about 3.3%, which results in the same sample quality designations as for the conventional consolidation test result. The compressibility and recompression index are also similar to that for the conventional consolidation test result.

The "tube recompression" sample was then unloaded, extruded, trimmed, and mounted in a conventional consolidation ring, and the subsequent consolidation loading response is labeled as “TR-Conventional specimen” in Fig. 7b. Also shown for comparison in Fig. 7b is a consolidation curve labeled “ideal,” which is simply the reloading portion of the “conventional” test result from Fig. 7a with the initial height (zero strain) defined at the end of the unloading cycle. The “ideal” response would have a recompression volumetric

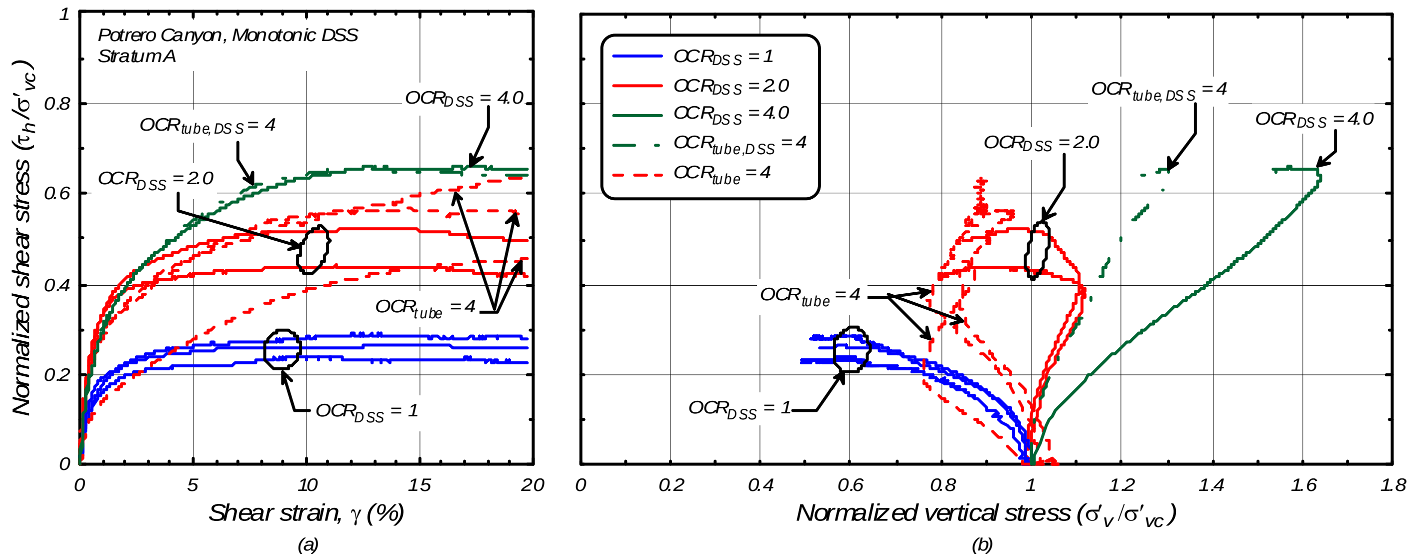


Fig. 8. Normalized monotonic undrained DSS responses for Potrero Canyon Stratum A specimens prepared using different sample preparation histories.

strain of about 0.6%, which would correspond to an SQD of A or sample quality rating of very good to excellent. The TR-Conventional specimen developed a recompression volumetric strain of about 2.5%, which is less than the recompression volumetric strains for the two tests presented in Fig. 7a (3.3-3.7%) but more than the "ideal" recompression strain.

The virgin compression index, C_c, for the conventional and tube recompression specimens are 0.26 and 0.29, respectively, which are consistent with other test results for this stratum (range of 0.22 to 0.33).

The estimated preconsolidation stresses, σ'_p, for both specimens shown in Fig. 7 range from 60 to 70 kPa. These specimen were obtained outside the fill area and have an estimated in-situ vertical effective stress, σ'_{vo}, about 46 kPa indicating a slightly over-consolidated state which may be expected for a recent alluvium deposit subjected to seasonal groundwater table changes and natural ageing.

Monotonic Undrained DSS tests

Monotonic undrained DSS tests were performed with a GEOTAC DigiShear apparatus using a latex membrane around the specimen that is confined to zero lateral strain by sixteen 1.6-mm-thick stacked rings. Undrained shearing was performed under constant-volume conditions with full free specimen drainage. Changes in vertical stress ($\Delta\sigma'_v$) that occur to maintain the constant height requirement is 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.

Ten monotonic undrained DSS tests were performed on specimens prepared to OCRs from 1.0 to 4.0 using variations on the sample preparation procedures illustrated in Fig. 6. The test results are presented in terms of normalized shear stress (τ/σ'_{vc}) versus shear strain (γ) and normalized shear stress versus normalized effective vertical stress (τ/σ'_{vc} versus σ'_v/σ'_{vc}) in Fig. 8.

The solid lines in Fig. 8 correspond to six specimens subjected to "laboratory preloading" (Fig. 6b) in the DSS device to OCR_{DSS} values of 1.0, 2.0, and 4.0. For these specimens, the OCR_{DSS} is equal to the OCR because the maximum consolidation stresses exceeded the estimated in-situ preconsolidation stresses. Specifically, one set of specimens were consolidated to $\sigma'_{vc} = 1.2\cdot\sigma'_{vo}$ (212 to 240 kPa) and to $\sigma'_{vc} = 2.4\cdot\sigma'_{vo}$ (440 to 480 kPa) then unloaded to $\sigma'_{vc} = 1.2\cdot\sigma'_{vo}$ (220 to 240 kPa) for an OCR_{DSS} = 1.0 and 2.0, respectively. An additional specimen was consolidated to $\sigma'_{vc} = 4\cdot\sigma'_{vo}$ (192 kPa) and then unloaded to $\sigma'_{vc} = \sigma'_{vo}$ (48 kPa) for an OCR_{DSS} = 4.0. The specimens exhibited ductile responses with nearly constant shear resistances for shear strains ranging from 5% to 20% for the OCR_{DSS} = 1.0 and 2.0 specimens and from 10% to 20% for the OCR_{DSS} = 4.0 specimen. The normalized undrained shear strengths (s_u/σ'_{vc}) ranged from 0.24 to 0.29, 0.43 to 0.53, and 0.65 for OCR_{DSS} = 1.0, 2.0, and 4.0 specimens, respectively. These strengths can be expressed in the form (Ladd and Foott 1974)

$$\frac{s_u}{\sigma'_{vc}} = S \cdot OCR^m \tag{4}$$

where S is the value of (s_u/σ'_{vc}) for OCR_{DSS} = 1.0, and m is the slope of the (s_u/σ'_{vc}) versus OCR relationship on a log-log plot. Fitting this relationship to the data at γ = 15% results in

S = 0.27 and m = 0.68 which are within the range of values for S but low for the range of values for m that Ladd (1991) summarized for ordinary sedimentary clays with shells.

Four additional tests, shown as dashed lines in Fig. 8, were performed on samples subjected to "tube preloading" (Fig. 6c) or "tube and laboratory preloading" (Fig. 6d). These specimens were first consolidated in the sample tubes (i.e., a 5-cm length of the tube) to $\sigma'_{v,t} = 4 \cdot \sigma'_{vo}$, and then extruded, trimmed, and mounted in the DSS device and tested either of two ways. The tube-and-laboratory-preloaded specimen with $OCR_{tube,DSS}$ = 4.0 was consolidated in the DSS device to $\sigma'_{vc,max} = 0.8(4 \cdot \sigma'_{vo})$ and then unloaded to $\sigma'_{vc} = \sigma'_{vo}$ (e.g., analogous to the modified recompression loading approach). This tube-and-laboratory-preloaded specimen exhibited a stress-strain behavior and $s_u/\sigma'_{vc} = 0.65$ that was very similar to that of the conventional OCR_{DSS} = 4 specimen. The other three specimens were consolidated in the DSS device to $\sigma'_{vc} = \sigma'_{vo}$ and thus had only experienced tube preloading with OCR_{tube} = 4.0 (e.g., Fig. 6c). These tube-preloaded specimens exhibited a slight strain-hardening response after they transitioned from incrementally contractive to incrementally dilative behavior at a shear strain of 2-3.5%, and they eventually developed shear resistance ratios of $\tau_h/\sigma'_{vc} = 0.44$, 0.56, and 0.59 at γ=15%. The shear resistances of the tube-preloaded specimens (OCR_{tube} = 4) were 9-32% lower than those for the laboratory-preloaded specimens (OCR_{DSS} = 4) or the tube-and-laboratory-preloaded specimens ($OCR_{tube,DSS}$ = 4), but still significantly greater than those for the normally consolidated (OCR_{DSS} = 1) specimens.

The effects that sample preparation stress history had on monotonic undrained DSS responses, as shown in Fig. 8, are attributed to the effects of disturbance during the E-T-M process and the role of initial K_o conditions. The tube-preloaded specimens clearly retained some memory of their consolidation stress history since their strengths are significantly greater than the normally consolidated specimens (which were tested at about the same final consolidation stress). The recompression of the tube-preloaded specimens would, however, be expected to produce a lower K_o condition than would have developed in the laboratory-preloaded specimen or the tube-and-laboratory-preloaded specimen; e.g., as previously illustrated in Fig. 3 and noted by Lunne et al. (2006) in reference to DSS testing of over-consolidated clay samples. The lower initial K_o condition for the tube-preloaded specimens would explain why they exhibited greater yielding (lower stiffness) at small strains during DSS shearing than the laboratory-preloaded specimen. At large strains, the tube-preloaded specimens never reach the same shear resistance as the laboratory-preloaded specimen, which may be due to the combined effects of the lower initial K_o condition (either through more lateral compliance as the lateral stress changes during shear, or by the effects of having enabled yielding of the soil to occur sooner) and disturbance to the soil fabric during the E-T-M process.

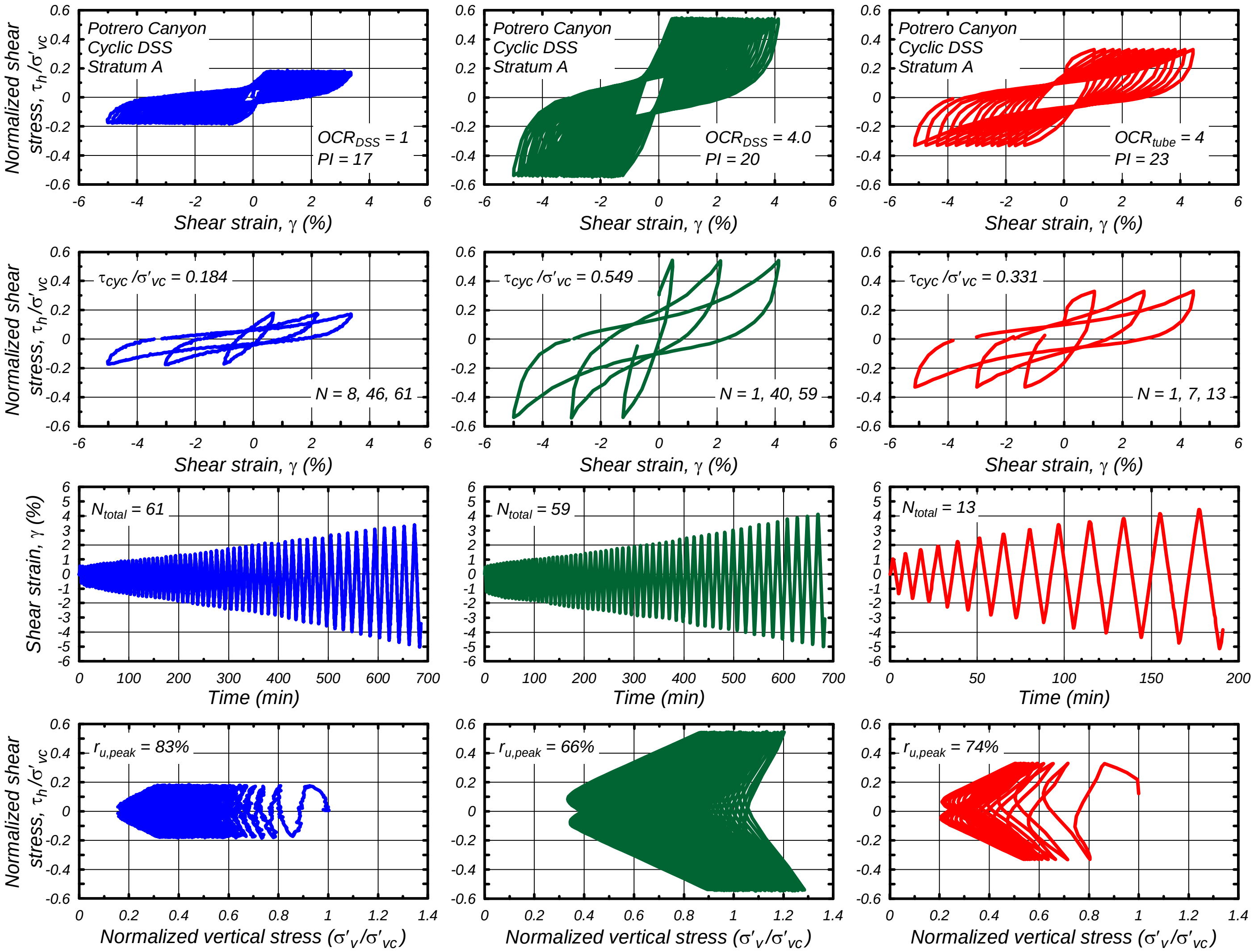
Cyclic Undrained DSS tests

Eight cyclic undrained DSS tests were performed on specimens prepared using the same sample preparation procedures and consolidation stresses described for the monotonic undrained DSS tests. Cyclic loading at uniform stress amplitudes was produced under strain-controlled loading at a strain rate of 50%/hr. The frequency of the resulting stress time series varied during each test depending on the specimen's shear resistance and imposed stress amplitude, but generally ranged from 0.0004 Hz to 0.0055 Hz for individual stress cycles. Cyclic loading was continued until at least 5% single-amplitude shear strain was reached.

Cyclic loading responses are shown in Fig. 9 for three different specimens: (a) a specimen that was laboratory-preloaded to a normally consolidated, OCR_{DSS} = 1, condition, (b) a specimen that was laboratory-preloaded to OCR_{DSS} = 4.0 and (c) a specimen that was tube-preloaded to OCR_{tube} = 4. These three specimens had PIs of 17, 20, and 23, respectively, and were subjected to τ_{cyc}/σ'_{vc} = 0.184, 0.549, and 0.331, respectively. All three specimens developed high excess pore pressure ratios and a progressive accumulation of shear strains, which may be described as cyclic softening or cyclic mobility behavior. Of the three specimens, the OCR_{DSS} = 1 specimen had the lowest cyclic resistance and developed the largest maximum excess pore pressure ratio ($r_u = \Delta u/\sigma'_{vc}$) of 0.83 (taken at 5% shear strain). The OCR_{DSS} = 4 specimen had the highest cyclic resistance and developed the lowest r_u of 0.66. The OCR_{tube} = 4 specimen had a cyclic resistance that was intermediate to the other two specimens, and developed a r_u of 0.74 that was also intermediate.

The combinations of cyclic shear stress ratio (τ_{cyc}/σ'_{vc}) and number of uniform stress cycles (N) causing peak single-amplitude shear strains of 3% are summarized in Fig. 10 for all specimens. The results for the laboratory-preloaded specimens with OCR_{DSS} = 1, 2.0, and 4.0 show a strong influence of OCR on cyclic strength; for example, the cyclic resistance ratio (CRR = τ_{cyc}/σ'_{vc}) to γ = 3% in 10 uniform loading cycles increases from about 0.20 at OCR_{DSS} = 1, to 0.35 at OCR_{DSS} = 2.0, to 0.63 at OCR_{DSS} = 4.0. This increase in CRR is similar to the previously described increase in s_u for the same increase in OCR for monotonic undrained DSS test results. Alternatively, the cyclic strengths can be expressed as a cyclic strength ratio (τ_{cyc}/s_u), which for γ = 3% in 10 uniform loading cycles would produce ratios of about 0.74, 0.80, and 0.90 for the OCR_{DSS} = 1, 2.0, and 4.0 specimens, respectively. These cyclic strength ratios are within the range of values reported for various clays and plastic silts (e.g., Boulanger and Idriss 2007).

Cyclic strengths for three tube-preloaded (OCR_{tube} = 4) specimens and two tube-and-laboratory-preloaded ($OCR_{tube,DSS}$ = 4) specimens are also presented in Fig. 10. The three tube-preloaded specimens had cyclic strengths that were about 40-45% smaller than obtained for laboratory-preloaded OCR_{DSS} = 4 specimens and were coincidentally comparable to the cyclic



(a) OCR_{DSS} = 1 (b) OCR_{DSS} = 4 (c) OCR_{tube} = 4

Fig. 9. Typical stress-strain and effective stress paths for Potrero Canyon Stratum A specimens during cyclic undrained DSS testing.

strengths obtained for laboratory-preloaded OCR_{DSS} = 2 specimens. The two tube-and-laboratory-preloaded specimens had cyclic strengths that were comparable to those obtained with laboratory-preloaded specimens at the same OCR_{DSS} = 4.

The differences in cyclic strengths for laboratory-preloaded and tube-preloaded specimens at the same OCR_{DSS}, as shown in Fig. 10, are slightly greater than the differences in their corresponding monotonic undrained shear strengths (Fig. 8). These differences are also attributed to the combined effects of disturbance during the E-T-M process and the role of initial K_o conditions.

PERRIS DAM

Samples of medium dense clayey sand were obtained from the shallow alluvial foundation soils near the downstream toe of Perris Dam in California. The 3500-m long embankment dam is founded on alluvium consisting of silty and clayey sand to sandy silt with local zones of cementation. The alluvium varies from 6 m to 88 m in thickness, and is underlain by granitic bedrock. Seismic reevaluation of the dam identified potentially liquefiable soils per SPT and CPT liquefaction correlations in the upper 9 m of alluvium (referred to as Shallow alluvium). The samples of Shallow alluvium tested in this study were obtained between depths of 7.2 and 10.4 m and classify as clayey sand (SC) to silty, clayey sand (SC-SM) per the USCS with fines contents of about 41 to 48% and clay-size

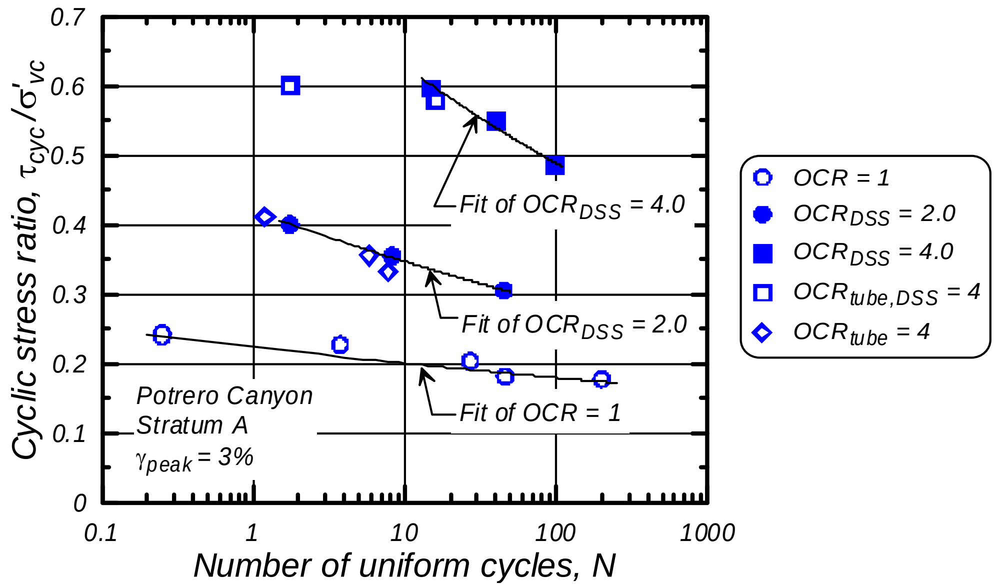


Fig. 10. Cyclic stress ratio versus number of uniform loading cycles to cause a peak shear strain of 3% on Potrero Canyon Stratum A specimens prepared to different OCR and OCR_{tube}.

contents of 2 to 14% (defined as <0.002 mm). Typically, the natural water content was between 12 and 14%, the liquid limit (LL) between 20 and 27 (average of 24), and the plasticity index (PI) between 4 and 13 (average of 9). A summary of soil index characteristics is listed in Table 1. For this same depth interval, representative CPT tip resistances, q_t, were 2.6 to 10.0 MPa and representative SPT blow counts, N_{60}, were 14 to 40. Groundwater prior to the dam construction (completed in 1973) was encountered at depths greater than 100 ft in the valley center to depths of 30 ft along the valley edges. Groundwater since reservoir filling is about 5 ft below ground surface.

High quality tube samples were obtained between 7.2 and 10.4 m depth using primarily a 27-inch Pitcher barrel sampler and when feasible by push sampling using thin-walled sample tubes that were modified to have a cutting edge with a 0.5% clearance ratio (i.e., the difference between the inside diameter and cutting edge diameter, divided by the inside diameter) to minimize sampling disturbance (Clayton et al. 1998). Tubes were sealed with expandable o-rings inserts at each end and transported in foam-lined boxes to a soils laboratory for storage in a temperature controlled room. Select tubes were x-rayed and brought to UCD where they were stored in a climate controlled/humidifier room until testing. Tube sections used for testing were selected after review of x-ray images and samples were extruded in the same direction as obtained in the field. Specimen preparation and trimming were performed in the same manner as used for the Potrero Canyon study (i.e., samples trimmed from the initial 71 mm diameter to 64 mm diameter and 25 mm height for consolidation testing and to 66 mm diameter and 18 mm height for DSS testing).

CRS Consolidation

Results of CRS consolidation tests on samples prepared using techniques similar to those illustrated in Fig. 6a and 6b are compared in Fig. 11. Testing procedures and notation are the same as described in the Potrero Canyon study. Initial recompression loading of the "conventional" specimens to the σ'_{vo} of 119 kPa, which was held constant for 60 min, resulted in a ε_v = 1.5%, which corresponds to a SQD = B (Terzaghi et al. 1996), and a $\Delta e/e_0$ = 0.050, which corresponds to a "good to fair" rating assuming an OCR less than 2.0 (Lunne et al. 1997). The unloading-reloading cycle resulted in a C_r = 0.006 for this specimen, which is consistent with values (0.004 to 0.009) obtained for four other specimens from this stratum.

Recompression loading of the "tube recompression" sample shown in Fig. 11a to σ'_{vo} of 119 kPa (also held constant for 60 min) resulted in slightly higher volumetric strains of about 2.2% and $\Delta e/e_0$ of 0.071, corresponding to a SQD of C and a rating of "poor," respectively. The unloading portion of the curve gives a C_r of 0.009, which is within the values obtained for the conventional consolidation test result.

Consolidation curves for the TR-Conventional specimen and the "ideal" specimen (i.e., reloading portion of the "conventional" test result from Fig. 11a) are shown in Fig. 11b. The "ideal" response would have a recompression volumetric strain of about 0.7%, which would correspond to an SQD of A or sample quality rating of very good to excellent. The TR-Conventional specimen developed a recompression volumetric strain of about 1.1%, which is less than the recompression volumetric strains for the two tests presented in Fig. 11a (1.5-2.2%) but slightly more than the "ideal" recompression strain.

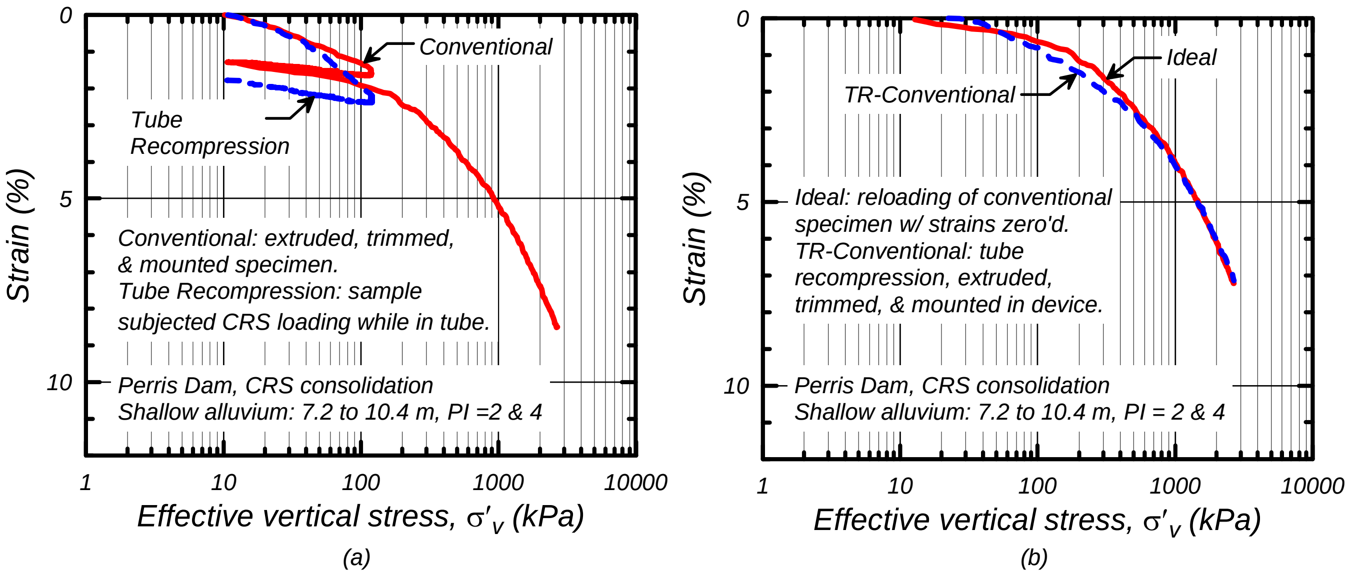


Fig. 11. CRS consolidation test results for samples of shallow alluvium from Perris Dam.

The virgin compression index for these specimens, based on the slope of the consolidation curves between stresses of 1,000 and 2,500 kPa, are about 0.100 and 0.106 for the tube recompression and conventional specimens, respectively. These values are consistent with other test results for this stratum (range of 0.099 to 0.137).

The preconsolidation stresses, σ'_p, for these specimens are difficult to determine from the rounded consolidation curves shown in Fig. 11 but can be roughly estimated to range from 180 to 450 kPa. Specimens have an estimated in-situ vertical effective stress, σ'_{vo}, of about 118 kPa indicating the in-situ over-consolidation ratios might range from OCR≈1.5 to OCR≈4. These values are within the expected range for a recent alluvium deposit subjected to a rise in the groundwater table due to reservoir filling (OCR≈2) and effects of natural ageing/cementation.

<u>Monotonic Undrained</u>

Seven monotonic undrained DSS tests were performed on specimens prepared to CR_{DSS} from 1.0 to 4.0 using variations on the sample preparation procedures illustrated in Fig. 6. The test results are presented 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}) in Fig. 12.

The solid lines in Fig. 12 correspond to five specimens that were laboratory-preloaded in the DSS device to CR_{DSS} of 1.0 and 4.0; Note that the CR_{DSS} may not be equal to the OCR because it is not certain if the maximum consolidation stress is greater than the "estimated" in-situ preconsolidation stress. Specifically, four specimens were consolidated to $\sigma'_{vc} = \cdot\sigma'_{vo}$ (103-130 kPa) and one specimen to $\sigma'_{vc} = 4\cdot\sigma'_{vo}$ (496 kPa) then unloaded to $\sigma'_{vc} = \sigma'_{vo}$ (124 kPa) for a $CR_{DSS} = 1$ and 4.0, respectively. Specimens with a $CR_{DSS} = 1$ exhibited a slight strain-hardening response after they transitioned from incrementally contractive to incrementally dilative (i.e., a phase transition) at shear strains between 2 to 4% with three specimens continuing to strain-harden to at least $\gamma = 10\%$. At $\gamma = 10\%$ these specimens had a τ_h/σ'_{vc} of 0.40, 0.48, and 0.53 with two specimens strain-hardening to a 0.53 and 0.61 at $\gamma = 15\%$. The fourth specimen response was more ductile with a near constant shear resistance of $\tau_h/\sigma'_{vc} = 0.49$ between $\gamma = 7\%$ and 13%. The $CR_{DSS} = 4$ specimen response was dilative upon shearing and strain-hardened throughout the test with τ_h/σ'_{vc} increasing from 1.28 to 1.37 between $\gamma = 10\%$ and 15%. The increase in undrained shear resistance with increasing CR_{DSS} is consistent with the trends observed for many clays and plastic silts, but it is difficult to express the results in terms of a stress-history normalization of undrained shear strengths (e.g., Eq. 4) due to the difficulties in defining undrained shear strengths from the strain-hardening responses of these soils and in defining the preconsolidation stresses.

Two additional tests, shown as dashed lines in Fig. 12, were performed using specimens tube-preloaded to a $CR_{tube} = 4$. These samples were then extruded, trimmed, and mounted in the DSS device and tested either of two ways. The tube-and-laboratory-preloaded specimen with $CR_{tube,DSS} = 4$ was consolidated in the DSS device to $\sigma'_{vc,max} = 0.8(4\cdot\sigma'_{vo})$ and then unloaded to $\sigma'_{vc} = \sigma'_{vo}$, which is analogous to a modified recompression approach after the tube preloading. This specimen exhibited a stress-strain behavior that was slightly softer initially but very similar to the laboratory-preloaded $CR_{DSS} = 4$ specimen (i.e., dilative response upon shearing) and eventually developed a τ_h/σ'_{vc} of 1.41 at $\gamma = 15\%$. The other

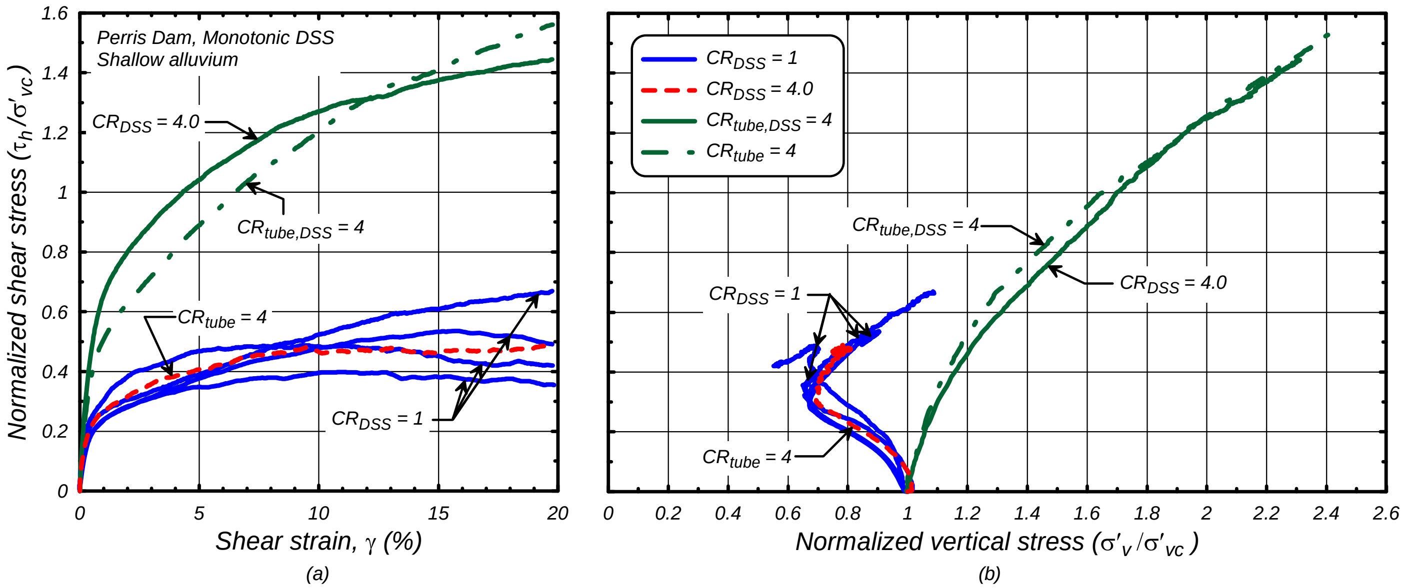


Fig. 12. Normalized monotonic undrained DSS responses for Perris Dam Shallow alluvium specimens prepared using different specimen preparation histories.

specimen was consolidated in the DSS device to $\sigma'_{vc} = \sigma'_{vo}$ such that it had only been tube-preloaded ($CR_{tube} = 4$; e.g., Fig. 6c). The response of the $CR_{tube} = 4$ specimen was similar to $CR_{DSS} = 1$ specimens in that it exhibited a slight strain-hardening response after transitioning from incrementally contractive to incrementally dilative behavior at $\gamma = 2.7\%$ and eventually developed a shear resistance ratio of $\tau_h/\sigma'_{vc} = 0.46$ at $\gamma = 15\%$. The shear resistance of the $CR_{tube} = 4$ specimen was 67% lower than those for the laboratory-preloaded $CR_{DSS} = 4$ specimen or the tube-and-laboratory-preloaded ($CR_{tube,DSS} = 4$) specimen, and within the range of values obtained for the conventional laboratory-preloaded $CR_{DSS} = 1$ specimens.

The effects that sample preparation history had on monotonic undrained DSS responses (Fig. 12) are attributed to the combined effects of disturbance during the E-T-M process and a low initial K_o condition in the DSS device. The $CR_{tube} = 4$ specimen did not appear to retain any significant memory of the consolidation stress history since its strength was similar to the conventional $CR_{DSS} = 1$ specimens (which were tested at about the same final consolidation stress). The combined effects of the disturbance during the E-T-M process and the lower initial K_o condition (as previously discussed and illustrated in Fig. 3) for the tube-preloaded specimen appear to have largely erased the benefits that preloading would normally have imparted to the soil.

<u>Cyclic Undrained</u>

Sixteen cyclic undrained DSS tests were performed on specimens prepared using the same sample preparation procedures and consolidation stresses as described for the monotonic undrained DSS tests, and one additional test was performed using a specimen that was laboratory-preloaded to $CR_{DSS} = 1$ at $\sigma'_{vc} = 4 \cdot \sigma'_{vo}$. Cyclic loading at uniform stress amplitudes was produced under strain-controlled loading at a strain rate of 50%/hr. The frequency of the resulting stress time series varied during each test depending on the specimen's shear resistance and imposed stress amplitude, but generally ranged from 0.0006 Hz to 0.0044 Hz for individual stress cycles. Cyclic loading was continued until at least 5% single-amplitude shear strain was reached.

Cyclic loading responses are shown in Fig. 13 for three different specimens: (a) a specimen laboratory-preloaded to a normally consolidated, $CR_{DSS} = 1$, condition, (b) a specimen laboratory-preloaded to $CR_{DSS} = 4.0$ and (c) a specimen tube-preloaded to $CR_{tube} = 4$. These specimens had PIs of 13, 16, and 13, respectively, and were subjected to $\tau_{cyc}/\sigma'_{vc} = 0.209$, 0.599 (after initially being subjected to 100 cycles at 0.225, 100 cycles at 0.319, and 178 cycles at 0.419), and 0.217, respectively. All three specimens developed high excess pore pressure ratios and a progressive accumulation of shear strains (i.e., cyclic softening or cyclic mobility behavior). Of the three specimens, the laboratory-preloaded $CR_{DSS} = 1$ specimen had the lowest cyclic resistance and developed the largest maximum excess pore pressure ratio ($r_u = \Delta u/\sigma'_{vc}$) of 0.93 (taken at 5% shear strain). The laboratory-preloaded $CR_{DSS} = 4$ specimen had the highest cyclic resistance and developed the lowest r_u of 0.65. The tube-preloaded $CR_{tube} = 4$ specimen had a cyclic resistance that was intermediate to the other two specimens in that the cyclic strength and generation of excess pore pressures, r_u of 0.91, was similar to the $CR_{DSS} = 1$ specimen, but with a slower incremental accumulation in shear strains like the $CR_{DSS} = 4$ specimen.

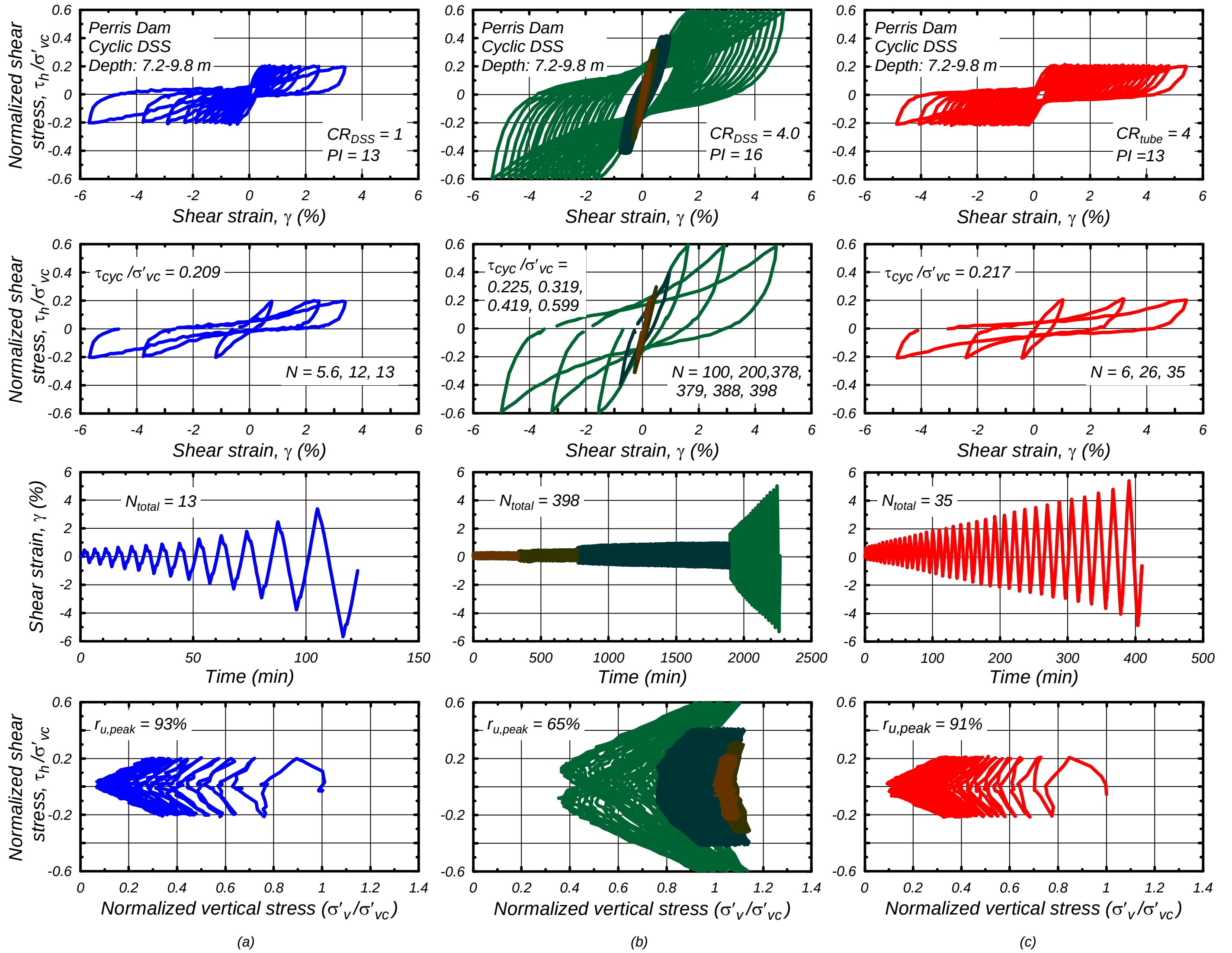


Fig. 13. Typical stress-strain and effective stress paths for Perris Dam Shallow alluvium specimens during cyclic undrained DSS loading: (a) CR_{DSS} = 1, (b) CR_{DSS} = 4.0, and (c) CR_{tube} = 4.0.

The combinations of cyclic shear stress ratio (τ_{cyc}/σ'_{vc}) and number of uniform stress cycles (N) causing peak single-amplitude shear strains of 3% are summarized in Fig. 14 for all specimens. The influence of CR on cyclic strength is shown in the results of the laboratory-preloaded CR_{DSS} = 1 and 4.0 specimens; for example, the cyclic resistance ratio (CRR = τ_{cyc}/σ'_{vc}) to γ = 3% in 10 uniform loading cycles increases from about 0.23 at CR_{DSS} = 1 to 0.62 at CR_{DSS} = 4.0. This increase in CRR is similar to the previously described increase in monotonic undrained shear resistance with CR_{DSS}.

Cyclic strengths for three tube-preloaded (CR_{tube} = 4) specimens and two tube-and-laboratory-preloaded ($CR_{tube,DSS}$ = 4) specimens are also presented in Fig. 14. The three tube-preloaded specimens had cyclic strengths that were about 50-60% smaller than obtained for laboratory-preloaded CR_{DSS} = 4 specimens and slightly greater (about 20-25% on average) than the cyclic strength results obtained for laboratory-preloaded CR_{DSS} = 1 specimens. The two tube-and-laboratory-preloaded specimens had cyclic strengths that were slightly lower (about 15%) than those obtained with laboratory-preloaded CR_{DSS} = 4 specimens.

The differences in cyclic strengths for tube-preloaded CR_{tube} = 4 specimens and laboratory-preloaded CR_{DSS} = 4 specimens, as shown in Fig. 14, are similar to the differences observed in their corresponding monotonic undrained shear strengths (Fig. 12). As before, these differences are attributed to the combined effects of disturbance during the E-T-M process and a low initial K_o condition in the DSS device.

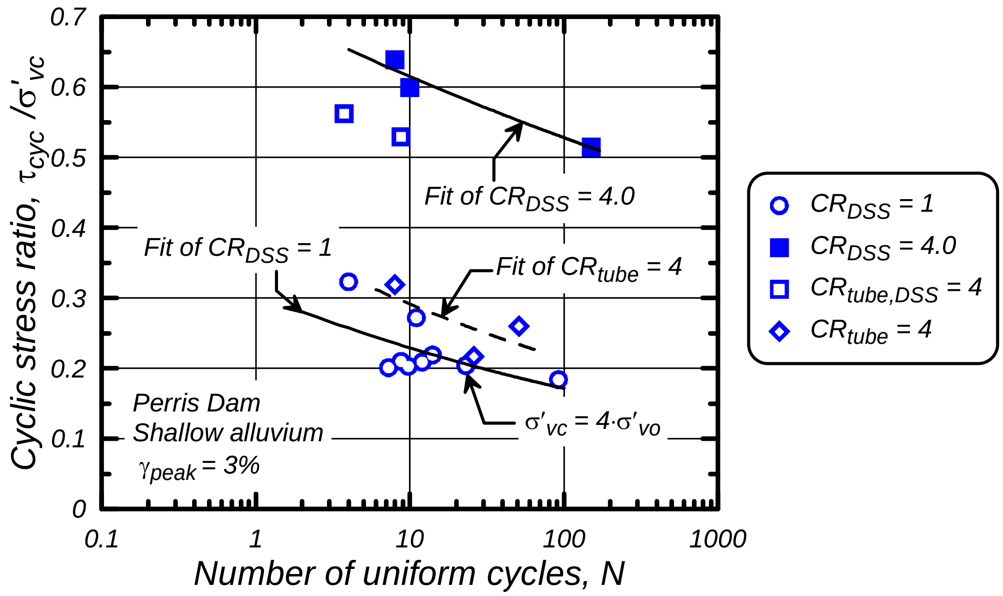


Fig. 14. Cyclic stress ratios versus number of uniform loading cycles to cause a peak shear strain of 3% on Perris Dam Shallow alluvium specimens prepared to different CR_{DSS} and CR_{tube}.

RELATIVE ROLES OF DISTURBANCE AND K_O

The relative impacts of E-T-M sample disturbance and low initial K_o conditions from recompression consolidation in DSS tests are difficult to evaluate for these different soil types, but some estimate of their effects on undrained cyclic strengths may be attempted for clean sands using previously established relationships. For example, Ishihara et al. (1977, 1985) performed cyclic torsional shear tests on normally consolidated clean sand with different K_o values and showed that the cyclic resistance ratio (CRR) was approximately proportional to mean effective consolidation stress, such that the CRR for anisotropically consolidated specimens could be approximately related to the CRR for isotropically consolidated specimens as,

$$CRR_{K_o \neq 1} = \left(\frac{1+2K_o}{3}\right) \cdot CRR_{K_o = 1} \qquad (5)$$

Over-consolidation of sand in one-dimensional compression improves the CRR through both an increase in K_o and a preloading of the sand fabric. The increase in K_o due to over-consolidation can be estimated as,

$$K_o = \left[1 - \sin\left(\phi'_{cv}\right)\right] \cdot OCR^{0.5} \qquad (6)$$

where ϕ'_{cv} is the constant volume friction angle. The additional benefits of over-consolidation were evaluated by Ishihara and Takatsu (1979) using cyclic torsional simple shear tests, in which the effects of K_o and OCR could be controlled independently. Their experimental results suggest that the additional increase in CRR is about proportional to the square root of OCR. This rate of increase is slightly greater than obtained from the cyclic triaxial tests of Ishihara et al. (1978) and about twice the rate obtained from the cyclic triaxial tests of Lee and Focht (1975). The benefits of over-consolidation have also been studied using simple shear devices, in which the effects of K_o and OCR cannot be controlled independently (Seed and Peacock 1971, Finn et al. 1971). The results of those studies suggest that the additional benefits of over-consolidation, beyond those attributable to increases in K_o, have ranged from 23-44% at an OCR of 4. Thus, the combined set of experimental results indicate that the additional benefits of over-consolidation can range from an increase in CRR of about 10-40% at an OCR of 2 to about 25-100% at an OCR of 4.

The above relationships can now be used to estimate the expected increase in CRR for a clean sand that was preloaded to an OCR_{DSS} = 4. The value of K_o would be expected to increase from about 0.5 to about 1.0 based on Eq. 6, which would cause the CRR to increase by a factor of 1.5 based on Eq. 5. The additional increase in CRR due to the preloading could range from a factor of 1.25 to 2.0, such that the overall effect of an OCR_{DSS} = 4 would be to increase the CRR by a factor of 1.9 to 3.0.

For clays, the effect of over-consolidation on cyclic strength in DSS tests can be estimated using Eq. 4 and the observation that cyclic strengths are approximately proportional to monotonic undrained strengths over a range of OCR. Thus, an OCR_{DSS} = 4 would be expected to increase both monotonic and cyclic undrained strengths by a factor of about 3.0, which is the same as the upper range of effects expected for clean sand. It is not clear however, how much of the strength increase in clays should be attributed to increases in K_o versus fabric preloading.

The experimental results for the clayey sand from Perris Dam (Fig. 14) show that the CRR increased by a factor of about 2.7 to 3.1 at a CR_{DSS} = 4. This increase in CRR is reasonably consistent with the upper range of increases observed for clean sands and with the expected increase for ordinary clays. If the experimental results for clean sands are considered as a guide, then this increase in CRR might be separated into a factor of about 1.5 due to the increase in K_o and a factor of about 2.0 due to the fabric preloading. This suggests that the CRR values for CR_{tube} = 4 specimens should have increased by a factor of almost 2.0 (assuming the K_o value after recompression in the DSS device is closer to the normally consolidated value) if the E-T-M process had not disturbed the soil fabric imparted by the preloading.

The preceding discussion provides a basis for evaluating the differences in CRR values that might be obtained from DSS tests using the CR_{tube} and CR_{DSS} sample preparation protocols. The CRR values obtained from the CR_{tube} specimens would not be expected to be the same as the CR_{DSS} specimens, since the CR_{tube} specimen will have a lower initial K_o condition in the DSS device. Nonetheless, the CR_{tube} specimen would be expected to show an increase in CRR (relative to those obtained by conventional recompression testing) due to the preloading effect. For example, the experimental results for the silty clay from Potrero Canyon Stratum A showed an increase in CRR due to tube preloading that was almost equal to what would be expected, whereas the results for the clayey sand from Perris Dam showed very little increase in CRR due to tube preloading. The extent to which that expected increase is not realized can be used as a measure of the susceptibility of the soil to the effects of disturbance during the E-T-M process.

Additional work is needed to expand the preceding discussion to include monotonic and cyclic undrained strengths from either DSS or triaxial tests across a range of soil types. An improved understanding of how disturbance and sample preparation protocols affect the behavior of different soil types under different loading conditions is needed for developing improved guidance on evaluating the seismic behavior of intermediate soils.

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 systematically explore and understand its behavior under different loading conditions. Information from such studies can help guide the selection of appropriate engineering procedures, including judging whether it would be more appropriate to estimate cyclic strengths using liquefaction correlations or whether the results of cyclic laboratory tests can be relied upon.

A test protocol 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 compressibility, 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.

Insight provided by the testing protocol was illustrated in results obtained for samples of a silty clay (CL) with PI = 12-24, in which conventional sampling and testing procedures were expected to work reasonably well, and for a clayey sand with 41-48% fines and PI = 4-13, in which the effects of sampling disturbance were a primary concern. The test results for the silty clay from Potrero Canyon Stratum A were illustrative of a soil that had well-defined in-situ preconsolidation stresses, exhibited stress-history normalized engineering properties, and retained a significant memory of the fabric preloading imposed by the tube preloading protocol. The test results for the clayey sand from Perris Dam showed that this soil retained very little memory of the fabric preloading imposed by the tube preloading protocol, which indicates that this soil is highly susceptible to disturbance during the extruding, trimming, and mounting process. These results suggest that the cyclic strengths from tube samples reconsolidated to their in-situ stress in the DSS device (i.e., following the recompression technique) would significantly underestimate the in-situ cyclic strengths, given that these soils are known to be slightly cemented, over-consolidated, and moderately dense in situ based on the available geologic and site characterization data.

The selection of appropriate consolidation procedures for samples of intermediate soils should consider the same factors that have been identified as important for clays and plastic silts. Preloading of DSS test specimens (e.g., a modified recompression approach) to re-establish a reasonable K_o condition can be extremely important for obtaining good estimates of in-situ strengths, although this requires confidence in, or reasonable bounds on, the estimated in-situ OCR as obtained from consolidation tests or geologic and historical information. SHANSEP-type procedures may prove useful for some intermediate soils, such as low-plasticity silts, if the results of the laboratory and in-situ testing support the use of a stress-history normalization framework. In such cases, the SHANSEP-type procedures have the additional advantage of reducing the impacts that sampling disturbance may have on the results. Recompression-type procedures may be preferable for sensitive, brittle, or cemented soils whose fabric may be disturbed by consolidation to stresses that exceed the in-situ values. For many intermediate soils, the choice of consolidation procedures may require trial tests to explore the quality of the tube samples, the relative merits of alternative consolidation procedures, and the susceptibility of the soil to sampling disturbance. The presented protocol for evaluating susceptibility to E-T-M disturbance is intended to assist in the latter task, and hence provide an additional means for judging the degree to which the laboratory measurements of cyclic strengths are expected to represent in-situ strengths.

Additional studies involving detailed laboratory and in-situ testing of intermediate soils are needed to further assess and develop the engineering procedures that can used to estimate their in-situ static and cyclic strengths.

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