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Applicability of Clay-Based Sample Disturbance Criteria to Intermediate Soils

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ABSTRACT

Extensive research on sampling methods and sample disturbance has been performed for clays, resulting in widely accepted practices that can enable reliable soil characterization via laboratory testing. However, for clean sands it is known that conventional sampling methods produce highly disturbed samples that can result in unrepresentative laboratory measurements; in-situ based characterization of sands is generally the preferred approach. For intermediate soils – clayey sands, clayey silts, silty clays, etc. with low plasticity – there exists little data or guidance for determining whether obtaining high quality laboratory samples is possible.

This paper presents the results of a study aimed to evaluate the applicability of current clay-based sample disturbance criteria for a range of synthetic intermediate soils (mixtures of silica silt and kaolin clay) with varying levels of plasticity using constant rate of strain consolidation tests. The specimens were subjected to different levels of sample disturbance and the effect on the measured soil response was evaluated by clay-based volumetric sample disturbance measures (e.g. $\Delta e/e_0$ and *SQD*). Results show decreasing $\Delta e/e_0$ as plasticity decreases for heavily disturbed specimens despite similar level of disturbance, indicating an apparent (and potentially misleading) increase in sample quality for heavily disturbed, low plasticity specimens using the $\Delta e/e_0$ criteria. Normalization of $\Delta e/e_0$ by the compression index (C_c) or the recompression index (C_r) are considered as alternate indicators of sample quality that may be independent of the soil's plasticity.

Introduction

The characterization of soil behavior often requires in-situ and laboratory tests where the relative merits of each depend on the type of soil being tested. Sand-like soils cannot be sampled using conventional sampling techniques; more weight is given to in-situ based soil characterization methods. Clay-like soils tend to be more cohesive and samples obtainable using conventional methods are ideal for high quality laboratory tests. It is for these reasons that extensive testing on sampling methods, sample disturbance, and sample quality metrics has been performed for clay soils, resulting in widely accepted practices and guidance for reliable soil characterization. Soils that are neither sand-like nor clay-like (i.e. intermediate soils) often exhibit unique behavior that may make characterization using traditional field and laboratory techniques difficult.

This paper presents the results of a study aimed to evaluate the applicability of current clay-based sample quality criteria for a range of synthetic intermediate soils (mixtures of silica silt

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and kaolin clay) with varying levels of plasticity (*PI*) using constant rate of strain consolidation tests. The range of soils used to develop clay-based criteria are presented and the mechanics of sampling disturbance on intermediate soils is discussed.

Overview of Clay-based Criteria

High quality samples are obtainable in clay soils since the sampling process is typically undrained due to low soil permeability, resulting in no volume change during the sampling process and enables the soil to maintain suction stress. If no volume change occurs, then the global void ratio and water content remain at in-situ conditions immediately prior to sampling.

For perfect sampling conditions (Ladd and Lambe 1963; Hight 2003) the drilling process removes the deviator stress and after sampling the soil is subjected to an isotropic effective stress close to the in-situ horizontal effective stress (σ'_{h0}; Jamiolkowski et al. 1985). Upon laboratory reconsolidation, minimal strains are necessary to re-establish in-situ stress conditions, thus creating the perfect sample. However the sampling, handling, and specimen preparation process may induce shearing that decreases the suction working to maintain in-situ sampling effective stresses, increasing the level of disturbance. Additionally, induced shearing can cause destructuring, which can be even more damaging. Increased recompression strains would occur during reconsolidation to in-situ stresses as a result of shear induced changes to the mean effective stress.

The magnitude of reconsolidation strains is used as an indicator of sample disturbance by capturing the degradation of mean effective stress during sampling, handling, and specimen preparation (Andresen and Kolstad 1979, Terzaghi et al. 1996, Lunne et al. 1997, 2006). The current clay-based sample quality criteria presented in Table 1 were derived from comparisons between samples obtained using different sampling methods that reflect differences in sampling quality.

Table 1. Quantification of sample disturbance based on specimen volume change during laboratory reconsolidation to σ'_{v0}.

Specimen Quality Designation (SQD) (Terzaghi et al. 1996)		$\Delta e/e_0$ Criteria (Lunne et al. 1997)		
Volumetric Strain (%)	SQD	OCR = 1 – 2 $\Delta e/e_0$	OCR = 2 – 4 $\Delta e/e_0$	Rating*
< 1	A	< 0.04	< 0.03	Very good to excellent
1 – 2	B	0.04 – 0.07	0.03 – 0.05	Good to fair
2 – 4	C	0.07 – 0.14	0.05 – 0.10	Poor
4 – 8	D	> 0.14	> 0.10	Very poor
> 8	E			

* Refers to use of samples for measurement of mechanical properties.

Lunne et al. (1997) note that Δe is the change in pore volume during laboratory reconsolidation (from the initial specimen state to in-situ stress) normalized by the initial pore volume (initial specimen state). They suggest that use of the updated $\Delta e/e_0$ is more representative of sample quality than ε_{vol}. Changes in pore space represent further degradation in mean effective stress if the initial pore volume is lower, which is not captured using ε_{vol}.

The database used to derive $\Delta e/e_0$ criteria is presented in Figure 1 and soils consist primarily of marine clays with *PI* of 6-43, *OCR* 1-4, depth from 5-25 m, and are moderate to highly sensitive (measured from fall cone tests, Lunne et al. 2006). As a result, implementation of the criteria (Table 1) should only be applied within the ranges presented in Figure 1.

$\Delta e/e_0$ sample quality bins shown in Figure 1c are not just a function of sampler quality, but is also a function of sample depth, or overburden stress. The three dashed lines approximate trends of sample quality from block, 74 mm, and 54 mm samplers (lines added by current authors), indicating a convergence of sample qualities at shallow depths. Since Δe is evaluated from the initial specimen state to the in-situ stress, samples obtained from shallow depths (i.e. low overburden stress) require less recompression strain, independent of disturbance. However, as overburden stress increases, the total stress relief during sampling increases, resulting in decreasing sample quality for nearly all sampling methods at greater depths (not considering effects of aging and cementation). This indicates that existing methods may not adequately consider the stress range across which Δe should be determined upon reconsolidation.

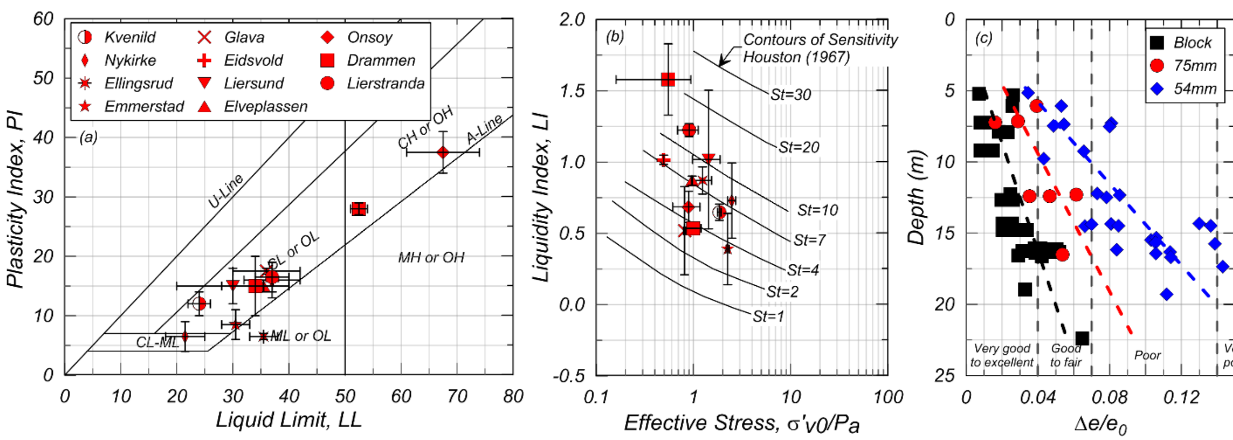

Figure 1 – Range of soils used to derive sample quality for clay-based soils (data from Lunne et al. 2006). Sample quality for different sampling methods: Sherbrooke Block, 74 mm piston, and 54 mm piston samplers. Dashed lines in (c) are added to indicate trend with depth (overburden stress) for each sampling method.

Applicability to Intermediate Soils

It is typically assumed that clay-like soils behave undrained (due to low permeability) while sand-like soils are fully drained during shear. Higher permeability, larger grain size, and limited cohesion reduces the ability to maintain in-situ structure during sampling, handing, and preparation (Hight 2003). As a result, quasi-undrained to drained conditions can exist during drilling, sampling, and/or specimen preparation (least likely during the sampling process itself).

Intermediate soils also span across distinct particle-scale differences between sand-like and clay-like soils. Clay-like behavior is dominated by the compressibility of clay minerals, soil fabric, and pore chemistry, while sand-like behavior is governed primarily by particle mineralogy, stiffness, and packing (i.e. relative density). Further, clay-like soil can exhibit significant compressibility due to large initial void ratios and compressible fabric while sand-like soils have a stiffer response due to lower initial void ratios and direct contact between stiff sand grains.

While the sampling stress path for intermediate soils are unknown (due to unknown drainage behavior) and unique, the lower bound path for intermediate soils can be understood considering the behavior of loose sand. Sand-like soils are drained during sampling and specimen preparation process, resulting in volume change (contractive or dilative depending on in-situ state) and no effective confinement applied by matrix suction. As a result it is nearly impossible to obtain sand samples that represent in-situ behavior without using ground freezing techniques (often cost prohibitive). Due to the high mineralogical stiffness of sand grains (mostly silica), $\Delta e/e_0$ measured upon specimen reconsolidation will always be small regardless of the level of sample disturbance.

There is a clear need for an improved sample quality metric that captures the effects of sample quality across a range of soil types (high *PI* clays to low *PI* intermediate soils) and is independent of the overburden stress. To begin studying this issue, a trial experimental study was performed on synthetic intermediate soil specimens subjected to varying levels of simulated sample disturbance.

Experimental Study with Synthetic Intermediate Soils

Soil mixtures with a range of *PI*, permeability, compressibility, and strength were prepared using varying proportions of silica silt (US-Sil-Co-Sil 250) and kaolin clay (Old Hickory, No. 1 Glaze) (Figure 2, e.g. 70S30K indicates 70% silica silt and 30% kaolin clay by mass). The mixtures were prepared in a controlled laboratory environment, mixed by percent dry mass and allowed to hydrate with deionized water at 1.5-2 times liquid limit. After hydrating for a minimum of 24 hours, soils were mixed with a 1390 rpm mixing blade under vacuum pressure (exceeding 68 kPa) to thoroughly mix, de-air, and promote saturation of the initially dry soil particles. These mixtures were then deposited as a slurry into 71.1 mm (2.8 inch) diameter oedometer cells for initial consolidation. Rotation was allowed as needed to prevent particle segregation during deposition. This approached enabled preparation of replicable specimens with a consistent deposition method across the range of soil mixtures presented in Figure 2 (*PI*s ranging from 0 to 31).

A suite of processes to induce various levels of disturbance, from a “perfect” sample to a highly disturbed sample, was developed to examine the effects of sample disturbance on consolidation behavior. The two bounding cases are presented herein; an ideal best case “perfect sample” and a highly disturbed sample.

1D Perfect Sample

1D perfect sampling (1DPS) was defined as the removal of deviatoric stress within an oedometer to obtain K_0 of 1 ($\sigma'_v=\sigma'_h$). At effective stresses for K_0 equal to 1, removal of total stress results in an equal and opposite application of an isotropic suction stress that maintains effective stresses estimated to be equal to σ'_{h0} (per Jamiolkowski et al. 1985). The amount of unloading necessary to achieve K_0 of 1 is estimated using Equation 1.

$$K_{0,OC} = (1 - \sin\varphi'_{cv})OCR^{\sin\varphi'_{cv}} \quad (1)$$

where *OCR* was controlled with consolidation loading and φ'_{cv} was either obtained using monotonic direct simple shear (DSS) tests or estimated using DSS results from similar mixtures.

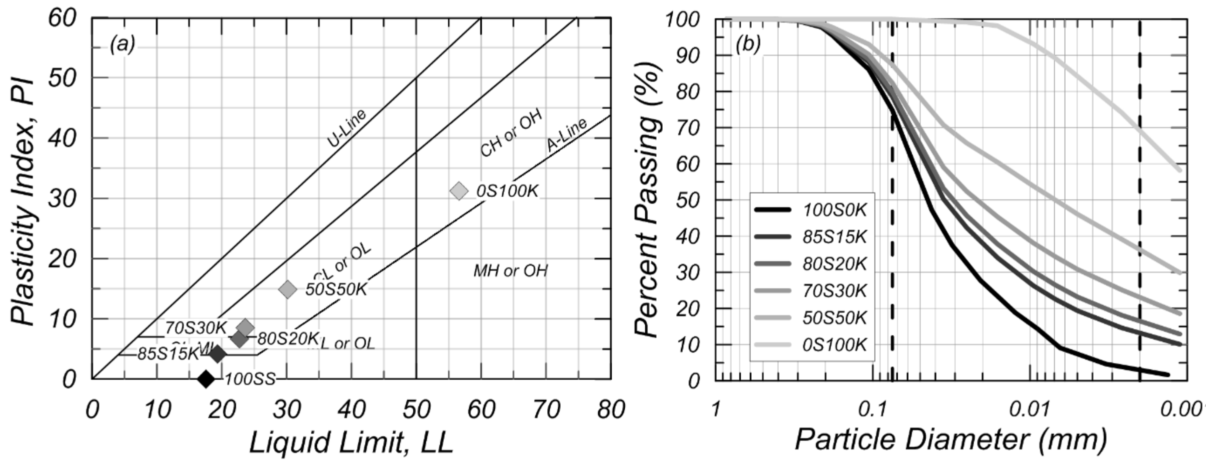

Figure 2. Properties of synthetic mixtures used in the experimental study.

1DPS is achieved using the following steps. Specimens were first loaded from slurry deposition to approximately 100 kPa using a LIR of 1 in a 71.1 mm diameter oedometer cell. Specimens were then extruded and trimmed into a 63.5 mm diameter oedometer ring. The specimen was then loaded to 200 kPa to establish σ'_p and then unloaded to establish a representative “in-situ” stress of 111 kPa (*OCR* = 1.8). Specimens were then further unloaded to vertical stresses corresponding to K_0 of 1 conditions as discussed above. The specimen was then re-loaded to 500 kPa (2.5 σ'_p). An unload-reload loop was performed at this stress level, unloading vertical stress to K_0 of 1 corresponding to the new σ'_{max}, then reloading to 2500 kPa.

Once K_0 of 1 conditions were initially established, the vertical total stress was not further relieved, maintaining the existing effective stresses. Removal of total stress would disturb the specimen, changing the actual stress conditions within the sample (due to handling, exposure to moisture/air, etc.). The 1DPS, in principle, is the best possible condition the sample could experience and therefore provides the baseline “perfect” sample quality in this study.

Highly Disturbed Sample

Highly disturbed (HD) conditions were established using the following procedure. Specimens were first loaded from slurry deposition in the same manner as 1DPS. Specimens were then removed from the IL oedometer (in the same 71.1 mm ring) and CRS loaded to 200 kPa to establish σ'_p. Samples were then unloaded to establish a representative “in-situ” stress of 111 kPa (*OCR* = 1.8). Specimens were then further unloaded to vertical stresses corresponding to K_0 of 1 conditions. At this point, the highly disturbed specimens were immediately removed from vertical stress and extruded from the 71.1 mm oedometer cell. To create the HD condition, the specimen was then placed in a freezer for a minimum of 24 hours, allowed to thaw in a constant temperature, constant humidity chamber for a minimum of 24 hours, and then trimmed into a 63.5 mm oedometer cell. The specimen was then CRS loaded to 2.5 times the σ'_p (500 kPa). An unload-reload loop was performed at this stress level, unloading to K_0 of 1 conditions corresponding to the new preconsolidation stress, then reloading to 2500 kPa.

Results of Experimental Study

The results of a suite of consolidation tests performed on these mixtures is shown in Figure 3. Compressibility is shown to increase with increasing clay content as shown by comparing 1DPS curves. Recompression strains (Δe) necessary to establish σ'_{v0} (111 kPa) tend to increase for all mixtures with disturbance. The unload-reload loop performed at 2.5 σ'_p appears to be independent of sample disturbance. Note that for all cases the sample quality obtained using 1DPS loading is $\Delta e/e_0$ of very good to excellent, while HD, frozen tests range from $\Delta e/e_0$ of very good to excellent to very poor (Figure 4a).

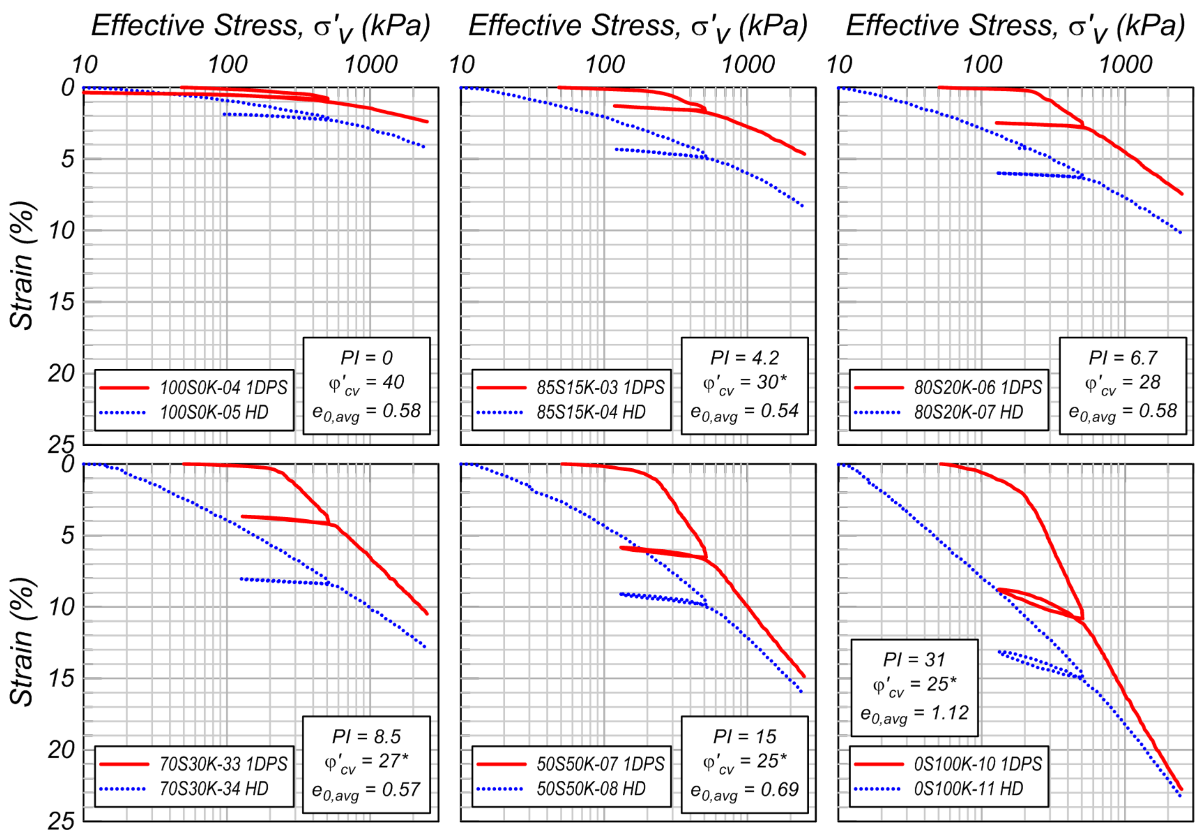

Figure 3. Consolidation curves for 6 mixtures with varying levels of *PI* and φ'_{cv} for both 1DPS and highly disturbed specimens (strain response is shown for comparison between tests; * denotes φ'_{cv} estimated from DSS tests).

There is a clear relationship between $\Delta e/e_0$ and *PI* for highly disturbed (HD) soils (Figure 4a). Highly disturbed mixtures with *PI* less than 4 have $\Delta e/e_0$ very good to excellent and good to fair sample quality even though the specimen was subjected to significant levels of disturbance. It is evident that the clay-based $\Delta e/e_0$ criteria should be modified to be applicable for intermediate soils or alternative indicators of sample quality for intermediate soils need to be developed.

Given that the recompression and compression indices of the mixtures systematically increase with increasing *PI* (or % kaolin), normalization of the $\Delta e/e_0$ data may prove a useful parameter to include in the quantification of sample quality. The first scheme presented is normalization of initial recompression stiffness ($\Delta e/e_0$ from seating to in-situ stress; 10-111 kPa) by the compression index ($C_c = \Delta e/log\Delta\sigma'_v$; measured from 2.5 σ'_p to 5 σ'_p). The second proposed scheme is normalization of $\Delta e/e_0$ by the recompression index ($C_r = \Delta e/log\Delta\sigma'_v$; measured from unload σ'_v to σ'_v corresponding to *OCR*=1.8 during reload). Both methods attempt to account for differences in mineralogy and stiffness for a variety of soils. Use of $\Delta e/e_0/C_c$ is convenient, since no unload-reload loop is necessary. However, Figure 4 shows that C_c is influenced by the level of disturbance with percent difference in C_c between 1DPS and HD specimens between -52% and 30% (most clear for 0S100K). C_r is not influenced by sample disturbance when unloading is performed at 2.5 σ'_p and therefore $\Delta e/e_0/C_r$ is proposed as an additional normalization scheme. These results show that normalizing $\Delta e/e_0$ by C_c or C_r accounts for differences in sample mineralogy, eliminating the trend of increasing sample quality with decreasing *PI* for highly disturbed specimens. Neither normalization method currently considers the stress range over which to evaluate Δe and as such does not capture effects of *OCR* and σ'_{v0} on recompression $\Delta e/e_0$.

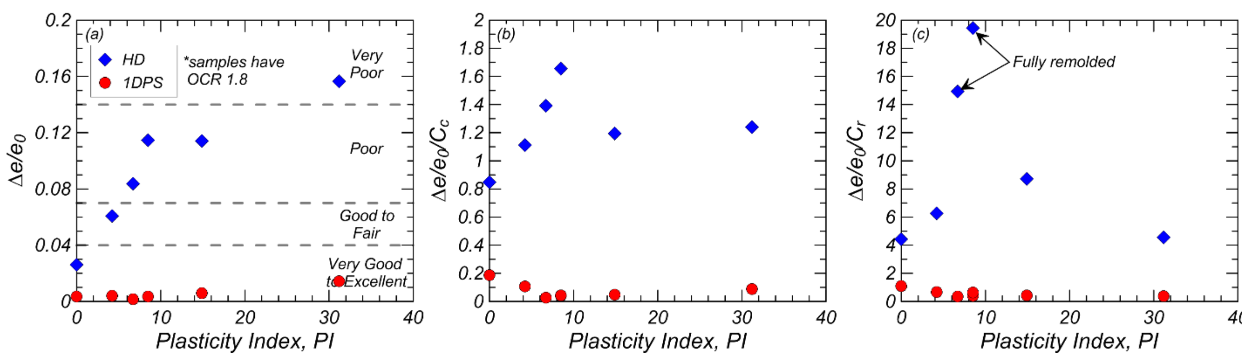

Figure 4. Comparison of sample quality for synthetic intermediate soils using: (a) existing clay-based criteria, (b) normalizing $\Delta e/e_0$ by C_c and (c) normalizing $\Delta e/e_0$ by C_r. Some HD specimens (*PI* of 7 and 8) were more severely disturbed than others.

Conclusions

An overview of the range and applicability of clay-based sample quality criteria was presented. An experimental study using synthetic intermediate soils was performed to highlight limitations of clay-based sample quality criteria; an alternative normalization was presented to reflect the range of intermediate soil properties. The conclusions are as follows:

1. It is important to understand limitations of the clay-based criteria. Use of $\Delta e/e_0$ criteria is suitable to apply in soils that are moderate to highly sensitive and plot along the A-line.

Little information exists for low *PI* soils.

2. Intermediate soils tend to be partially drained or fully drained during sampling, thus leading to potential volume change during sampling. Lower *PI* materials are influenced by more silt content and tend to have increased φ'_{cv} and decreased compressibility. This makes measurement of recompression stiffness (Δe) less sensitive to sample disturbance and more dependent on compressibility of the material.
3. Sample quality using existing clay based criteria fails to accurately capture the effects of significant disturbance for the low *PI* soils tested in this research. The highly disturbed, via freezing, low *PI* samples had a range of samples qualities from very good to excellent, good, and poor, while undisturbed tests on the same mixtures produces only very good to excellent quality.
4. Normalization of the clay based $\Delta e/e_0$ sample quality value using a property that is sensitive to soil composition, is routinely measured in a consolidation test and that is not subject to sample disturbance may prove useful. In this study both $\Delta e/e_0/C_c$ (with C_c measured from 2.5-5 σ'_p) and $\Delta e/e_0/C_r$ (measured from an unload-reload loop performed at 2.5 σ'_p) seem to eliminate the trend of increasing sample quality with decreasing *PI* for the intermediate soil mixtures studied in this research.

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