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# The Influence of In-situ Effective Stress on Sample Quality for Intermediate Soils

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ABSTRACT: The role of overburden stress on sample quality for synthetic mixtures of silica silt and kaolin clay across a range of plasticity and silt content was investigated using oedometer tests. Existing clay-based sample quality criteria ($\Delta e/e_0$ and SQD) were developed from datasets obtained on samples of plastic clays obtained from 5 to 25 m depth, which indicate a trend of decrease in sample quality with depth. Measurements from oedometer specimens subjected to various simulated levels of overburden stress are used to quantify the sensitivity of current sample disturbance criteria to overburden stress. Low overburden stress specimens (i.e. shallow depths) undergo little total stress relief, requiring less volumetric recompression to in-situ stress, which results in an apparent higher sample quality regardless of the disturbance level. High overburden stress specimens (i.e. deep depths) undergo greater total stress relief during the sampling and specimen preparation process, which often results in a higher level of disturbance. The laboratory results show that SQD and $\Delta e/e_0$ are overburden stress level dependent for the PI 4 and 6 intermediate soil mixtures tested.

## 1 INTRODUCTION

Characterization of in-situ soil behavior requires soil sampling and laboratory testing where in-situ testing cannot be reliably performed. Sampling of clay soils is widespread in practice and has resulted in the development of sample quality criteria to assess the effectiveness of sampling techniques in obtaining undisturbed samples for laboratory testing. In sandy soils, where permeability is greater and suction is less effective at preserving the soil specimen, in-situ testing techniques are the preferred approach. Soils between plastic clays and clean sands, termed intermediate soils herein, can often be sampled using clay-based techniques, but the quality of the sample obtained as well as the applicability of the sample quality indices is not well understood.

Laboratory testing of soil specimens requires quantification of sample quality to assess the effectiveness of test results in representing in-situ soil properties. Empirically developed quality indices, based mostly on marine clays, are used in practice to evaluate the quality of specimens obtained by sampling. In practice these methods are often applied to soils that lie outside of the empirical database, with an implicit assumption that they are applicable. However, the broader applicability of these methods for intermediate soils is poorly understood.

This paper presents results from a continuing study investigating the behavior of intermediate soils (i.e. silty clays, clayey silts) when subjected to different levels of sample disturbance. Synthetic silt-kaolin specimens, which span a range of plasticity, are subjected to various stress paths that represent different levels of disturbance. The effect of simulated in-situ overburden stress level on the stress-strain responses during sampling and recompression is investigated using constant rate of strain consolidation tests, and the effectiveness of clay based sample quality criteria to capture this response is investigated.

## 2 CURRENT PRACTICE EVALUATING SAMPLE QUALITY

Sampling techniques typically used in practice are robust for clayey soils. The low permeability and high suction of clayey soils assists in maintaining the in-situ effective stresses during the drilling, sampling, and handling process, resulting in intact specimens that largely retain their in-situ stress-strain behavior.

Sampling of cohesionless soils is possible via ground freezing techniques, but is often cost prohibitive to implement on typical projects. Engineers are left with the choice between in-situ tests, sampling and laboratory testing, or a combination of the two to obtain soil properties at the site.

Sample quality criteria is used in practice to evaluate the effectiveness of sampling techniques in obtaining soil samples that will produce representative engineering properties when tested in the laboratory.

## 2.1 *Overview of Clay Criteria*

Efforts to obtain high quality samples of clay soils occur in geotechnical practice, particularly on larger scale projects. Reliable and practical sampling equipment and procedures to obtain high quality samples have developed over the last several decades. The tube sampler is the most common in practice, though use of a thin walled fixed piston sampler provides a practical high quality alternative to the tube sampler (Tanaka et al. 1996), while the Sherbrooke block sampler (Lacasse et al. 1985) is considered the highest quality sampler developed (and mostly limited to research projects).

The primary metrics used to indicate sample quality are $\varepsilon_{vol}$ and $\Delta e/e_0$, which were developed by the Norwegian Geotechnical Institute (NGI) in the late 1970s and early 1990s, respectively (Andresen and Kolstad 1979, Lunne et al. 1997, Lunne et al 2006). Measuring recompression strain to in-situ stress levels during 1D (odometer) or triaxial consolidation tests is used to indicate changes in specimen effective stress and destructuring during the drilling, sampling, and handling procedures. Terzaghi et al. (1996) defined the Specimen Quality Designation (SQD) as a rating index for the value of volumetric strain, $\varepsilon_{vol}$, necessary to re-establish the in-situ effective stress. In a similar manner, $\Delta e/e_0$ tracks changes in void space during recompression to in-situ effective stress, normalized by the initial void ratio.

These methods to evaluate sample quality are empirically derived based on comparisons between how different quality samplers induce sample disturbance. The database used to derive the recommendations in Table 1 consists primarily of marine clays with PI values of 6-43, OCR values of 1-4, obtained from depths of 5-25m, and are moderate to highly sensitive (measured from fall cone tests, Lunne et al. 2006).

## 2.2 *Influence of Overburden Stress*

The influence of overburden stress, or the magnitude of stress relief that occurs when a soil is removed from its in situ stress condition and prepared for laboratory testing, is not explicitly accounted for in the clay-based sample quality metrics, since samples were obtained from a limited depth range (5-25m). Some attempt was made, however, to account for trends in over consolidation ratio (OCR).

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

| 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) defined $\Delta e/e_0$ threshold values for sample quality for OCR ranges of 1-2 and 2-4 specimens to account for the greater stiffness and strength of higher OCR soils (Table 1). However, no correction was developed to account for increased strain during laboratory recompression to the in-situ state for samples with high overburden stresses. Trends in $\Delta e/e_0$ with depth from the Lunne et al. (1997) dataset for three different sampling techniques presented in Figure 1 shows that $\Delta e/e_0$ increases with sampling depth, or overburden stress.

Though not sampling the same soils as Lunne et al., Tanaka et al. (2002) obtained samples of marine clay from depths up to 400 m for design of a port facility in Japan. They initially hypothesized that there

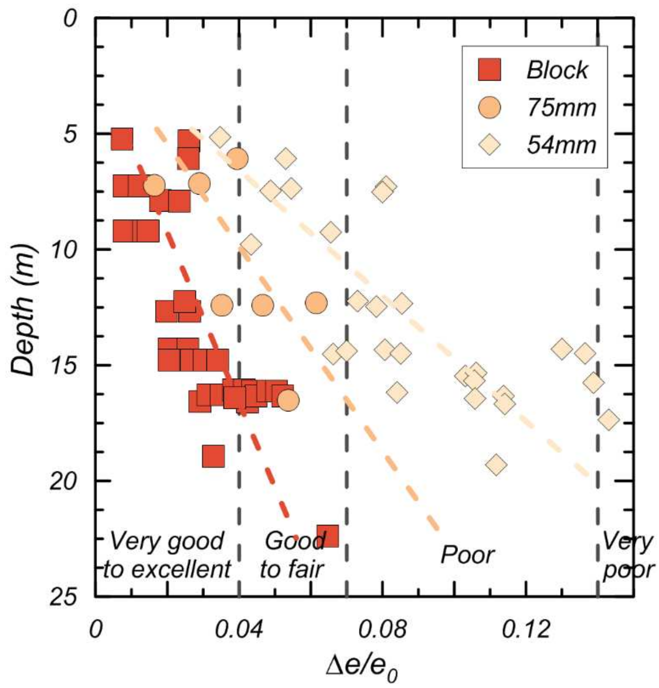


Figure 1 – Sample quality for different sampling methods: Sherbrooke Block, 75mm piston, and 54mm piston samplers. Dashed lines are added to indicate trend with depth (overburden stress) for each sampling method. Note that each sampling method was performed on three different clay soils.

would be a degradation of sample quality with increasing sampling depth due to the significant increase in recompression strains necessary to reestablish in-situ stresses as well as the increased stress relief from these significant depths. Their observations indicate that the sample quality of these soils is independent of sampling depth (Tanaka et al. 2002).

## 2.3 *Application to Intermediate Soils*

The clay-based sample disturbance criteria may not be applicable to intermediate soils even if they can be successfully sampled. The transition from a conventional clayey soil to a more sand-like material typically corresponds to an increase in the soil permeability, resulting in loss of the ability to maintain suction and constant volume during the sampling process. These changes affect the sample's ability to maintain in-situ effective stress and state, resulting in a laboratory specimen that is dissimilar to its in-situ counterpart. In addition, the decrease in clay fraction and/or fines content (and the corresponding increase in silt and/or sand content) results in increasing soil stiffness as silica particles have a higher material stiffness than the overall clay fabric, which has significant effect on measured stiffness during recompression in the laboratory. Fundamental differences in drainage, particle scale, soil fabric and sampling stress paths highlight some of the difficulties in applying clay-based criteria to intermediate soils.

Krage et al. (2015) demonstrated that clay based sample criteria do not track with the sample disturbance level for soils with a PI less than about 10. Further, the clay-based indices incorrectly indicated that the sample quality increased as the PI value decreased for a given level of disturbance; this could mislead engineers to interpret samples to be of higher quality than they actually are. The study compared a suite of mixtures across a range of plasticity subjected to differing levels of simulated sample disturbance. Heavily disturbed tests, obtained via a freezing and thawing cycle, show trends of increasing sample quality with decreasing PI (Figure 2) despite similar levels of extreme disturbance. Freezing and thawing of a non-plastic silica silt resulted in complete degradation of soil fabric, though recompression strains indicate a very good to excellent sample quality ($\Delta e/e_0 < 0.04$) that cannot be corroborated via laboratory observations of the mixture. This research highlighted the need for an improved sample quality metric for soils that accounts for effects of material stiffness and overburden stress.

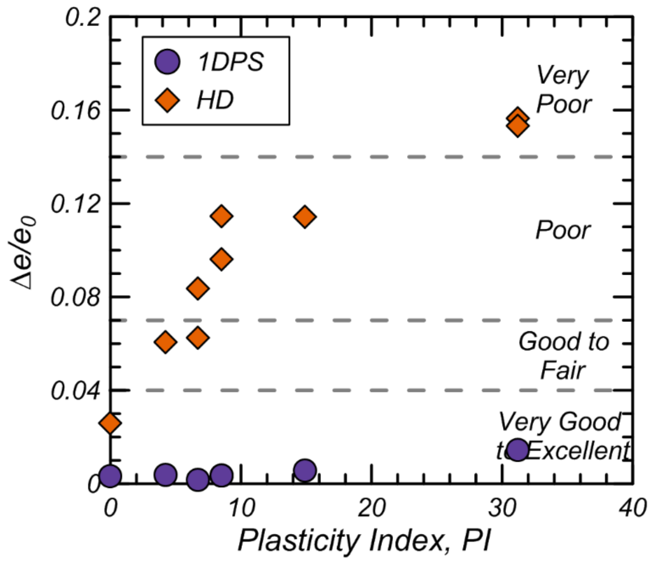


Figure 2. Results from a study using synthetic intermediate soil mixtures indicate a strong trend of increasing sample quality with decreasing PI for heavily disturbed mixtures.

## 3 MATERIALS AND METHODS FOR STUDY WITH SYNTHETIC INTERMEDIATE SOILS

Synthetic intermediate soil mixtures were prepared in the laboratory using varying proportions of silica silt (US-Sil-Co-Sil 250) and kaolin clay (Old Hickory, No. 1 Glaze) (Figure 3, e.g. 80S20K indicates 80% silica silt and 20% kaolin clay by mass). Each soil mixture was obtained by mixing dry soils and deionized water to hydrate at 1.5-2 times liquid limit of the mixture for a minimum of 24 hours. Following dry mixing and hydration, the slurry was mixed with a 1390 rpm mixing blade under vacuum pressures exceeding 68 kPa to thoroughly mix, de-air, and promote saturation of the initially dry soil particles prior to slurry deposition into 71.1 mm (2.8 inch) diameter oedometer cells for initial consolidation. Rotation was allowed as needed to prevent par-

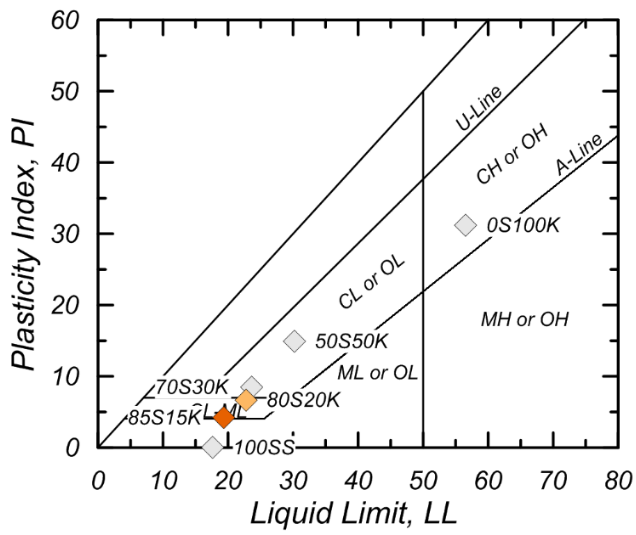


Figure 3. Atterberg limits for the synthetic intermediate soils where colored symbols indicate mixtures used in this study and gray symbols indicate mixtures used in Krage et al. (2015).

ticle segregation during deposition. This approached enabled preparation of replicable specimens with a consistent deposition method across the range of soil mixtures presented in Figure 3 (PI ranging from 0 to 31). Artificial specimens were prepared in the laboratory to capture behavioral trends in a controlled environment, therefore the structure inherent to natural intermediate soils is not captured in this study.

The processes used to induce two levels of disturbance, from an ideal best case "perfect sample" to a highly disturbed sample, were developed to examine the effects of sample disturbance on consolidation behavior. The development of each type of disturbance and the loading conditions necessary to establish consistent mechanical loading stress history between these cases are presented in the following section. The three distinct phases were: (1) initial preloading to establish stress history for simulating depositional processes, (2) inducing disturbance to each specimen to simulate disturbance during drilling, sampling, and handling, and (3) re-consolidating the specimen to evaluate recompression trends as performed in the laboratory.

### 3.1 *1D Perfect Sample*

1D perfect sampling (1DPS) was defined as the removal of deviatoric stress for an oedometer specimen to obtain $K_0$ of 1 ($\sigma'_v=\sigma'_h$). Under internal isotropic effective stresses, the 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 $\sigma'_{h0}$ (per Jamiolkowski et al. 1985). The amount of unloading necessary to achieve $K_0$ of 1 was estimated using Equation 1 (Mesri and Hyatt 1993).

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

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

The 1DPS, in principle, is the best possible condition the sample could experience and therefore provides the baseline "perfect" sample quality in this study. The vertical total stress was not further relieved beyond what was necessary to obtain $K_0$=1 such that existing effective stresses remained constant. Removal of total stress would inevitably disturb the specimen, changing the actual stress conditions within the specimen (due to handling, exposure to moisture/air, etc.).

### 3.2 *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 establish the desired $\sigma'_p$, simulated in-situ stress $\sigma'_{v0}$, and estimated $K_0$ of 1 stress (as discussed in the following section). At this point, the HD specimens were immediately unloaded to zero vertical stress and extruded from the 71.1 mm oedometer cell. To create the HD condition, the unconfined specimen was then placed in a freezer for a minimum of 24 hours at -12ºC, 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 tested following the remainder of the loading schedule for each in-situ stress level. This procedure was used to breakdown the structure of the specimen through the expansion of saturated void space during freezing.

### 3.3 *Loading Conditions*

Though the loading path is unique for each simulated in-situ stress, the stages of loading are consistent across all simulated in-situ stress levels (Table 2). Loading of the specimen is achieved using the following steps.

(1) Specimens were first loaded from slurry deposition to approximately 50% of the target $\sigma'_p$ (Table 2) by incrementally doubling the load (load increment ratio of 1) in a 71.1 mm diameter oedometer cell. This process eliminated excess water from the slurry and established material stiffness. 1DPS specimens were then trimmed into a 63.5 mm oedometer cell *prior* to CRS loading to establish simulated in-situ stress history while HD specimens are trimmed *after* establishing simulated in-situ stress history and induced disturbance. This ensures the 1DPS specimen will not be further removed from the oedometer cell, ensuring the specimen maintains perfect sampling conditions previously discussed. Additionally, trimming the HD specimen following application of stress history and disturbance simulates the trimming process of the typical field sample.

(2) In order to simulate the desired in-situ stress history, specimens were loaded via constant rate of strain consolidation (CRS) to establish the desired $\sigma'_p$ (Table 2), then unloaded to desired simulated "in-situ" stress, $\sigma'_{v0}$. Specimens were further unloaded to vertical stress corresponding to estimated

Table 2. Loading stress derived from in-situ effective stress

| $\sigma'_{v0}$ (kPa) | OCR | $\sigma'_p$ (kPa) | $\sigma'_{v,unload}$ (kPa) | $\sigma'_{v,reload}$ (kPa) | $\sigma'_{final}$ (kPa) |
|---|---|---|---|---|---|
| 20 | 1.8 | 36 | 90 | 23 | 2500 |
| 110 | 1.8 | 200 | 500 | 128 | 2500 |
| 250 | 1.8 | 450 | 1125 | 292 | 2500 |
| 500 | 1.8 | 900 | 2250 | 583 | 2500 |

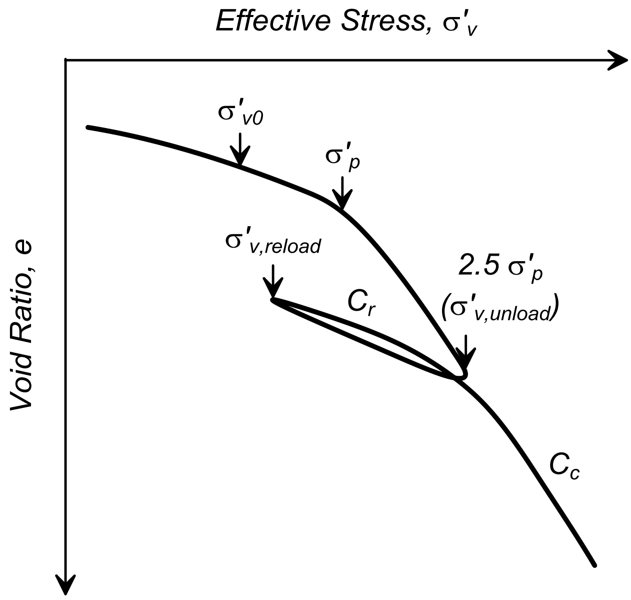

Figure 4. Conceptual loading path for phase 3 loading.

$K_0$=1 conditions using Equation 1 (OCR of approximately 4). Up until this point the stress history for 1DPS and HD specimens are identical. While the loading conditions will remain identical for both levels of simulated sampling, significant disturbance is induced to the HD specimen via a freezing and thawing cycle where the specimen was removed from the ring, sealed, frozen, thawed, and retrimmed into a 63 mm oedometer cell.

(3) Following induced disturbance for the HD sample (whereas no unloading removal of total stress beyond $\sigma'_{v,K0=1}$ for 1DPS), specimens are reloaded following the conceptual stress path in Figure 4. First, they were loaded to 2.5 times the corresponding $\sigma'_p$ (=$\sigma'_{v,unload}$) followed by unloading at this stress level to $K_0$ of 1 (=$\sigma'_{v,reload}$), then reloaded to 2500 kPa (capacity of the consolidation device).

## 4 RESULTS OF EXPERIMENTAL STUDY

The consolidation response of specimens shows varying amounts of recompression strain for different $\sigma'_{v0}$. Figure 5 shows the response of one mixture to four in-situ stresses for both 1DPS and HD cases. There are systematic trends in the observed consolidation behavior for both 1DPS and HD specimens. 1DPS specimens have a well-defined yield stress ($\sigma'_p$) and virgin compression line while HD specimens exhibit a less defined response with no apparent yield stress. The trend is consistent across a range of in-situ stress levels for 1DPS and HD specimens. Additionally, specimens initially loaded to higher $\sigma'_{v0}$ require more recompression strain to reestablish $\sigma'_{v0}$ for both 1DPS and HD specimens. Albeit the 1DPS specimens only require less than 1% strain to reestablish $\sigma'_{v0}$, while HD specimens

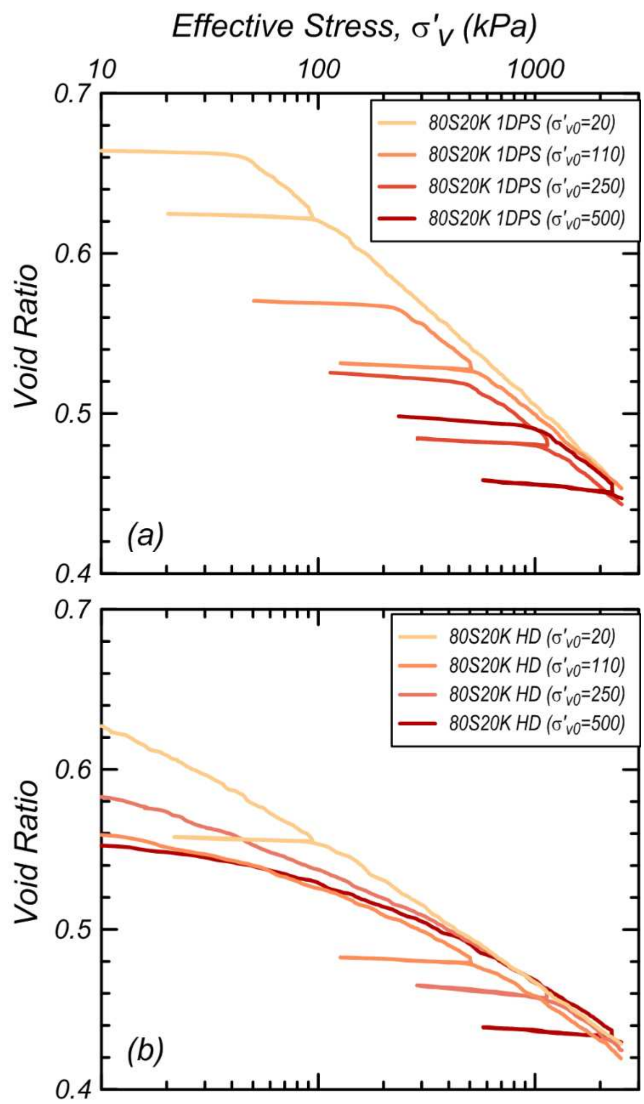

Figure 5. Plots of void ratio versus effective stress for (a) 1DPS and (b) HD loading of 80S20K for 4 simulated in-situ stress levels.

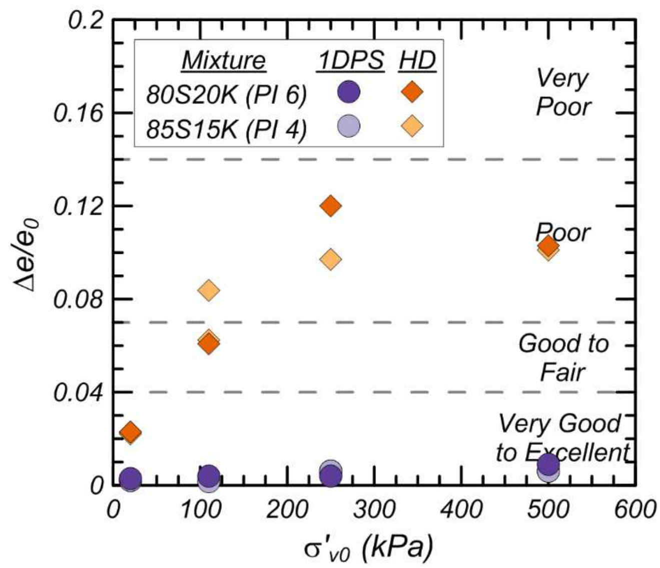

Figure 6. $\Delta e/e_0$ sample quality rating for 1DPS and HD specimens for 4 different simulated in-situ stress levels and two different mixtures: 80S20K (PI 7) and 85S15K (PI 4).

require 1-4% strain. Further scrutiny of the compression curves reveals a small increase in the unload-reload stiffness from low to high $\sigma'_{v0}$ for both levels of disturbance.

There is a strong trend of decreasing sample quality with increasing simulated in-situ effective stress for HD mixtures. Figure 6 shows that all 1DPS specimens are of very good to excellent sample quality, while HD specimens range from very good to excellent to poor sample quality. These observations are inconsistent with level of disturbance induced to each specimen. HD specimens with low $\sigma'_{v0}$ undergo less recompression strain (or $\Delta e$) to reestablish $\sigma'_{v0}$, while specimens with high $\sigma'_{v0}$ undergo more recompression strain to reestablish $\sigma'_{v0}$. This reflects the greater overall stress relief of the high $\sigma'_{v0}$ specimens during the simulated disturbance procedure.

The magnitude of quality rating ($\Delta e/e_0$) of the PI 4 (85S15K) and PI 7 (80S20K) mixtures shown in Figure 6 appears to be consistent for a given $\sigma'_{v0}$. This observation is consistent with the observations from Krage et al. (2015) where decreasing PI resulted in an improved quality rating for a given simulated in-situ effective stress.

These observations further highlight the limitations of clay-based sample quality indices for tracking sample quality in intermediate soils with different simulated in-situ effective stress. Further research is necessary to successfully account for trends with $\sigma'_{v0}$ identified in this paper.

## 5 CONCLUSIONS

This paper examined the adequacy of existing clay-based sample quality criteria for evaluating the influence of in-situ overburden effective stress on synthetic intermediate soil mixtures. The effects of sampling depth on sample quality are not well quantified within current clay-based quality criteria with samples obtained from 5-25 meters and depth effects not discussed in detail.

In this study, synthetic intermediate soil specimens subjected to 1D perfect sampling have a clearly defined yield stress ($\sigma'_p$) and produce a well-defined virgin compression line, while highly disturbed specimens exhibit a less defined response with no apparent yield stress. These trends are consistent across a range of simulated in-situ stress levels for the 1DPS and HD specimens.

There is an apparent trend of decreasing quality rating ($\Delta e/e_0$) with increasing simulated in-situ effective stress for the HD samples. Current recompression based quality rating methods do not account for this observed trend. Shallow samples are likely to undergo less recompression strain (or $\Delta e$) while deep samples are more likely to undergo greater recompression strain to in-situ stresses.

## 6 ACKNOWLEDGMENTS

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