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Quality assurance for cyclic direct simple shear tests for evaluating liquefaction triggering characteristics of cohesionless soils

Assurance de la qualité des essais cycliques de cisaillement direct simple pour l'évaluation de l'initiation de la liquéfaction des sols sans cohésion

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ABSTRACT: Undrained or constant volume direct simple shear (CDSS) tests are commonly used to evaluate the liquefaction triggering characteristics of cohesionless soils. However, while the American Society for Testing of Materials (ASTM) has developed standards for monotonic direct simple shear testing, they have not developed a standard for CDSS. As a result, herein the authors review their test database and assign "grades" *A-D* to different aspects of the tests, e.g.: accumulated shear strain and imposed shear stress on the specimen during the consolidation phase, and maximum axial strain that occurs during the cyclic phase of constant volume CDSS testing. Additional grades are also assigned to the tests based on unusual behaviors in the stress paths. Acceptance criteria based on the cumulative test scores are then proposed for "high" quality tests. The slope of the relationship between cyclic stress ratio (CSR) and number of cycles to liquefaction (N_L) is influenced by the exclusion of tests using the acceptance criteria, even though the excluded tests were of sufficient quality to have been included in most published studies.

RÉSUMÉ: Les essais de cisaillement direct simple à volume constant ou non drainé (CDSS) sont couramment utilisés pour évaluer les caractéristiques d'initiation de la liquéfaction des sols sans cohésion. La société américaine pour les essais de matériaux (ASTM) a élaboré une norme pour les essais de cisaillement direct simple monotones, mais il n'y a pas de norme similaire pour les CDSS. En conséquence, les auteurs examinent ici leurs bases de données de tests qu'ils ont compilée et leur attribuent des «notes» *A-D* selon certains critères : la contrainte de cisaillement accumulée et la contrainte de cisaillement imposée sur le spécimen lors de la phase de consolidation, et la contrainte axiale maximale survenant pendant la phase cyclique du test CDSS à volume constant. Les tests sont également filtrés en fonction de comportements inhabituels dans les *stress-paths*. La pente de la relation entre le rapport de contrainte cyclique (CSR) et le nombre de cycles à la liquéfaction (N_L) est altérée du fait de l'exclusion de données d'essais ayant reçu des «notes» inférieures. La note *D* serait généralement considérée comme étant de qualité suffisante pour être incluse dans la plupart des études.

Keywords: cyclic direct simple shear; liquefaction; constant volume; active control; passive control

1 INTRODUCTION

One of the purposes of cyclic testing of soils is to develop liquefaction resistance curves for a given relative density (D_r). These curves can reveal several important characteristics of soils. For example, the relationship between cyclic stress ratio (*CSR*) and number of cycles to liquefaction (N_L) allows estimates of soil-specific resistance to liquefaction (i.e., cyclic resistance ratio, *CRR*). In addition, the b-value (i.e. the negative slope of a line defining the relationship between *CSR* vs N_L data in log-log space) can be used in the simplified liquefaction evaluation framework to account for duration effects via the magnitude scaling factor, *MSF*, relationship.

There are several types of cyclic testing methods, including cyclic triaxial (CTRX), cyclic direct simple shear (CDSS), and cyclic torsional simple shear (CTS) tests. Simple shear is commonly accepted as the shear mode of deformation most closely associated with response of soil deposits under earthquake loading, and thus CDSS is a popular choice for liquefaction studies. However, there is no ASTM standard for CDSS tests under cyclic loading, though there is a standard for direct simple shear (DSS) tests under monotonic loading (ASTM D6528-17). Without this guidance, those who perform CDSS tests are left to their own means to judge the quality of their tests. The objective of this paper is to identify several factors that can affect the quality of CDSS tests but that are also often overlooked. Using a grading scheme to assign quality scores to the tests, this study explores the influence of imposing acceptance criteria for inclusion/exclusion of CDSS test data on the b-value of the resulting liquefaction resistance curves.

2 BACKGROUND

The desirable boundary conditions for CDSS tests to represent loading in the field are constant vertical total stress, zero lateral strains, and zero axial strains (Boulanger 1990). To achieve these boundary conditions, there are three general kinds of CDSS tests used in practice (El Mohtar et al. 2018): undrained, constant vertical stress (CS) tests, constant volume (CV) tests using passive control (PC) to limit volumetric deformations, and CV tests using active control (AC) to limit volumetric deformations.

CS tests are performed on saturated samples of soil and the drainage lines are closed during shearing to allow excess pore water pressures to generate. This test typically requires more effort than CV type tests due to the necessary steps of back-pressure saturating the sample to flush out air. It can also be time-consuming to allow the soil to consolidate, particularly if the sample contains a significant amount of fines. In these CS tests, the closed drainage valves enforce constant volume conditions during shearing.

In CV tests, constant volume conditions are enforced using either PC (e.g., mechanical) or AC (e.g., feedback loop) conditions. Because constant volume conditions are enforced, the samples do not need to be saturated and pore pressures do not need to be measured. In such tests, the change in vertical stress during the cyclic loading phase is approximately equal to the pore pressures that would have developed in a saturated soil sample in the same conditions (Finn and Vaid 1977; Finn et al. 1979; Dyvik et al. 1987). CV-CDSS tests using PC maintain constant volume with a physical locking mechanism that minimizes vertical deformations. In contrast, CV-CDSS tests using AC maintain constant volume via a feedback loop between a vertical LVDT and the vertical actuator to adjust the vertical load such that the vertical deformations are minimized. CV tests can be performed relatively quickly because there is no need for back-pressure saturation of the soil.

Some studies have shown that CS tests result in greater liquefaction resistances relative to comparable CV tests (Finn and Vaid 1977; Finn et al. 1979; El Mohtar et al. 2018), while others suggest that CV tests are more accurate (e.g. Finn et al. 1979). Although both CV and CS tests are still used frequently in research and practice, the authors predominantly use CV-CDSS tests, and thus the remainder of this paper will focus on quality assurance of these tests. The following sections outline some of the issues that commonly arise in CV-CDSS tests, potential causes for these issues, and some suggested methods for minimizing these issues. These issues have been discovered through experimentation with CV-CDSS methods, personal communications with other experienced researchers, and a review of the literature. Note: all figures in this paper represent CV-CDSS tests on air-pluviated samples of Monterey 0/30 sand.

2.1 Issues in CV-CDSS Tests

The main phases of a CV-CDSS test are ramp-up, consolidation, and cyclic loading. During ramp-up, the vertical stress on the soil sample is increased from a nominal seating load to the desired initial vertical effective stress, σ'_{v0}. This σ'_{v0} is maintained throughout the consolidation phase until axial deformations stabilize. During cyclic loading, constant volume is maintained using AC or PC conditions and the soil is subjected to predetermined shear stresses (τ) or shear strains (γ). In stress-controlled tests with sinusoidal loading, the *CSR* is calculated as the amplitude of the sinusoidal loading (τ_{max}) divided by σ'_{v0}. Hereafter, the issues that have been observed in CV-CDSS under both AC and PC conditions are detailed, and then the issues unique to AC and PC conditions are discussed.

2.1.1 Shear Strain during Consolidation

The imperfect alignment of the vertical components of the testing apparatus and the soil specimen can lead to induced γ in the specimen during consolidation before cyclic testing begins. Unfortunately, it can be difficult to detect imperfect vertical alignment until the sample has already consolidated and γ has developed. For example, Figure 1 shows the increase in γ during the ramp-up phase and the consolidation phase just before cyclic loading begins. Note that γ reaches more than 0.05%. The accumulation of γ prior to the cyclic phase can potentially affect the liquefaction resistance of the soil sample and thus is an issue that should be considered in assessing the quality of CV-CDSS test data.

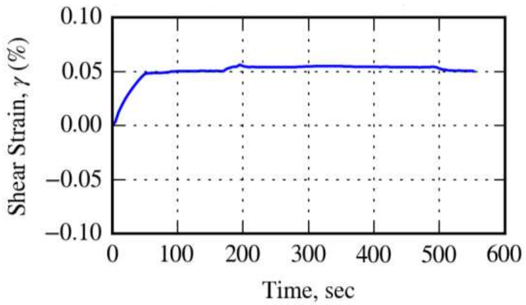

Figure 1. Shear strain during the ramp-up and consolidation phases of a PC CV-CDSS test (D_r = 58%, σ'_{v0} = 100 kPa).

2.1.2 Shear Stress during Consolidation

In addition to induced γ, the imperfect alignment of the vertical components of the testing apparatus and the soil specimen can induce τ in the soil specimen prior to the cyclic loading phase. This accumulation of stress can be detected by recording and plotting the shear stress in the sample during the ramp-up and consolidation phases. Figure 2 shows the increase in τ during the ramp-up and consolidation phases, which at one point reaches approximately -2.8 kPa. As with γ, the changes in τ prior to cyclic loading can potentially affect the soil's resistance to liquefaction and should be considered when assessing the quality of CV-CDSS tests.

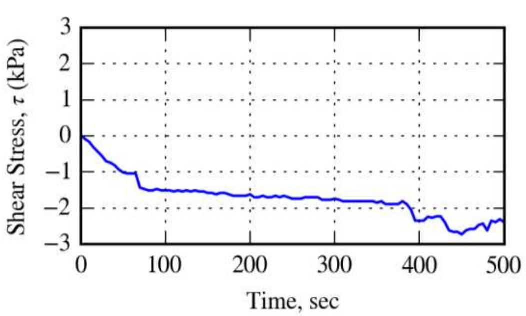

Figure 2. Shear stress during the ramp-up and consolidation phases of a PC CV-CDSS test (D_r = 23%, σ'_{v0} = 100 kPa).

2.1.3 Volume Change during Cyclic Loading

It is difficult to maintain constant volume in conditions when equivalent excess pore pressures are high and there are system compliance issues (Boulanger 1990). There is no ASTM standard to recommend a maximum level of acceptable volume change in cyclic testing, but for monotonic DSS testing, the maximum acceptable axial strain (ε) is 0.05% (assuming the lateral confinement of the sample maintains zero radial deformation). Results from CV-CDSS tests as part of this study suggest that ε in excess of 0.05% can develop during the cyclic phase of supposed "constant volume" CDSS testing. This development of unwanted axial strain has been observed by several researchers who have performed CV-CDSS tests using various test apparatuses (Drs. Yaurel Guadalupe-Torres, Jack Germaine, Rune Dyvik, Carmine Polito, personal comm. 2018). The potential reasons for this volume change depend on whether AC or PC is employed, and thus are discussed separately. However, the following points apply generally.

El Mohtar et al. (2018) showed that minor axial deformations (ε much less than 0.05%) in CV-CDSS tests can influence the liquefaction resistance of the soil. Similarly, in monotonic CV-DSS tests, $\varepsilon = 0.05\%$ affects the measured vertical effective stress (σ'_v) and τ at failure, particularly for stiff soils (Dyvik and Suzuki 2018). The magnitude of ε could be related to the stiffness of the testing apparatus, particularly when testing dense sands which require a stiffer testing apparatus (Dyvik, personal comm. 2018).

2.2 Issues in CV-CDSS Tests with PC

To maintain constant volume using PC in both monotonic DSS and CV-CDSS tests, a mechanism on the vertical piston is locked after consolidation is completed to minimize axial deformations of the sample during monotonic or cyclic loading. In monotonic DSS testing, the success of the PC system in maintaining constant volume depends on the stiffness of the equipment (Dyvik and Suzuki 2018). Similar principles apply in CV-CDSS tests.

Deformations measured at the position of the vertical actuator (i.e. outside of the locking mechanism) may appear to be close to zero. However, if another LVDT is installed near the top of the soil sample, this LVDT will likely record much larger deformations than those measured at the level of the vertical actuator. Figure 3 shows such a discrepancy in ε calculated from deformations recorded at the actuator level and at the soil level (i.e. internal LVDT). Though the deformations measured near the actuator indicate $\varepsilon \approx 0$, the deformations from the internal LVDT indicate that the recommended 0.05% is exceeded after about 5 cycles of loading. The value of ε calculated from the internal LVDT is more representative of the actual ε in the soil sample and is thus a better indication of whether or not constant volume conditions were maintained.

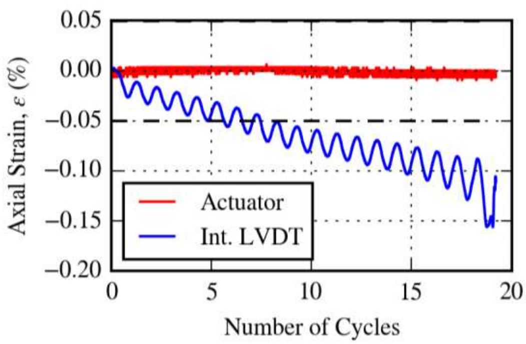

Figure 3. Comparison of axial strain at two locations in the testing apparatus during the cyclic phase of a PC CV-CDSS (D_r = 19%, σ'_{v0} = 250 kPa).

One of the likely reasons for the large ε at the level of the soil sample is that the components of the testing apparatus between the locking mechanism and the top of the soil sample are not stiff enough and/or have connections that add to the overall compliance of the apparatus. If the soil is contractive, then during cyclic loading the stress acting on the top platen will decrease and the force in the vertical components between the locking mechanism and the soil will relax, which could lead to an overall lengthening, thus causing ε in the sample (Dyvik and Suzuki 2018). If these components were sufficiently stiff and opportunities for compliance were reduced, then ε could be minimized.

There are several odd behaviors in the stress paths from CV-CDSS tests using PC that have been observed. For example, some stress paths converge to a non-zero σ'_v, as shown in Figure 4. In this case, it could be due to issues with calibrating the internal vertical load cell (located between the locking mechanism and the soil sample). Also, some stress paths have non-zero lower-bound limits on the vertical effective stress during portions of the cyclic loading, manifesting as a vertical line at low σ'_v as shown in Figure 5. This could be caused by a combination of inadequate PID values and some compliance in the components of the testing apparatus between the locking mechanism and the top of the soil sample.

It is also possible for tests using PC to have stress paths that indicate irregular generation of equivalent excess pore water pressures, manifesting in irregular spacing between cycles in the stress path, prior to the initiation of liquefaction in the soil. Figure 6 shows an example of such irregular spacing in a stress path and the respective normal displacement recorded at the level of the vertical actuator (outside the locking mechanism). As shown in this figure, the irregular spacing is closely correlated with the displacement of the actuator, which is still in contact with the vertical piston. During cyclic loading, the controls software requires that the vertical actuator maintain constant displacement, which means that it may increase or decrease the applied normal stress to maintain its position. It is generally assumed that the locking mechanism below the actuator prevents the actuator from affecting σ'_v in the soil. However, as shown here, if the actuator is in contact with the piston during cyclic loading, the actuator can influence σ'_v.

2.3 Issues in CV-CDSS Tests with AC

Though greatly reduced using AC compared to using PC to maintain constant volume, ε can still develop during cyclic loading in CV-CDSS tests. In monotonic DSS testing, the success of the AC system in maintaining constant volume depends on the capabilities of the equipment used, including the load delivery system and data collection (Dyvik and Suzuki 2018). The same principle is likely even more critical in CV-CDSS testing.

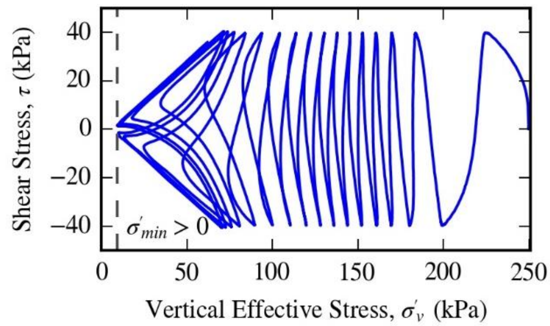

Figure 4.Stress path converging at a non-zero value of vertical effective stress (PC CV-CDSS test, D_r = 70%).

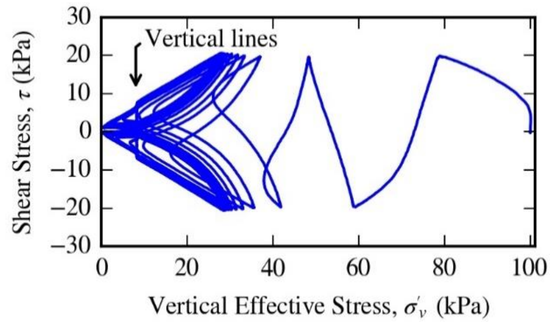

Figure 5. Stress path with vertical lines at low vertical effective stress (PC CV-CDSS test, D_r = 85%).

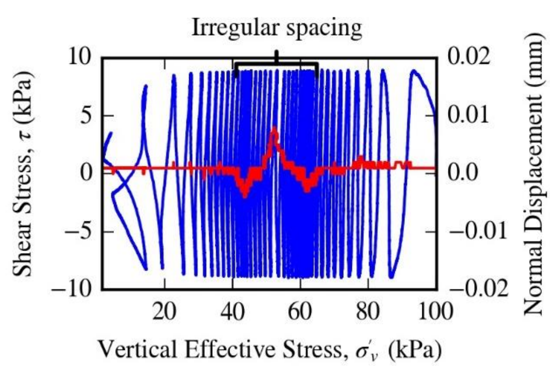

Figure 6. Stress path (in blue) with irregular spacing and normal displacement of the vertical actuator (in red) during a PC CV-CDSS test (D_r = 20%).

Often the initial ε is minimal when AC is used, but once γ is large, ε can exceed the recommended limit of 0.05% (Dyvik, personal comm. 2018). Figure 7 shows ε during the cyclic loading phase of a CV-CDSS test using AC. Note that ε is well within +/- 0.05% (Int. LVDT) until the last few cycles of the test when it momentarily exceeds this threshold. If ε exceeds 0.05% after liquefaction has initiated, it has little to no effect on the value of N_L, and the test may still be considered high quality. However, if ε exceeds 0.05% before liquefaction initiates, then it should be taken into account when judging the quality of the test.

CV-CDSS tests using AC typically do not result in the same odd stress paths observed in tests using PC, but they do have their own unique issue: some tests performed using AC exhibited a biased stress path in which the cycles were more pointed toward one direction (e.g., positive shear) and more rounded in the opposite direction (e.g., negative shear). Figure 8 shows an example of a biased stress path from a CV-CDSS test performed using AC. This bias is not noticeable in PC tests. The exact cause is still unknown, but it may be related to rocking or lag in the system's feedback loop or a combination of both. "Rocking" is caused by an imbalance of forces inherent to CDSS tests (Vucetic and Lacasse 1984), where the horizontal faces of the top and bottom platens confining the soil specimen can tilt or rock. This motion can affect constant volume conditions and affect stress paths (Cappellaro et al. 2018).

The final issue with AC in CV-CDSS tests is the potential for misshapen τ vs. γ hysteresis loops. This may not greatly affect N_L, but it could affect the computed dissipated energy per unit volume of soil (i.e., the cumulative area enclosed in τ vs. γ hysteresis loops, Green 2001). The cause of misshapen hysteresis loops is not yet known, but it is likely linked to the vertical actuator pushing or pulling on the vertical piston to maintain constant volume. A possible solution could be performing the cyclic loading at a slower rate.

3 METHODS

The issues with PC and AC tests outlined in the previous section were each given grading schemes to help distinguish between higher quality CV-CDSS tests and lower quality tests. The grade assignments and associated points are outlined in Table 1. The quality acceptance criteria for tests are based on the total number of points for the test. However, a grade of *D* for any aspect of a test results in the overall disqualification of the test.

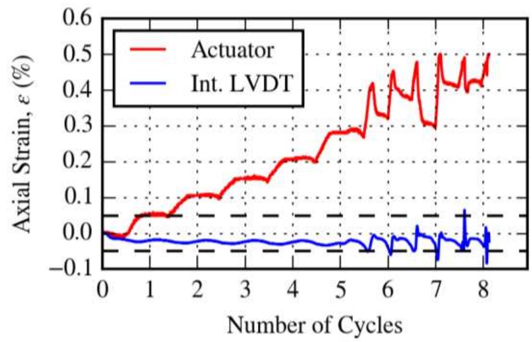

Figure 7. Comparison of axial strain at two locations in the testing apparatus during the cyclic phase of an AC CV-CDSS test (D_r = 67%, σ'_{v0} = 250 kPa).

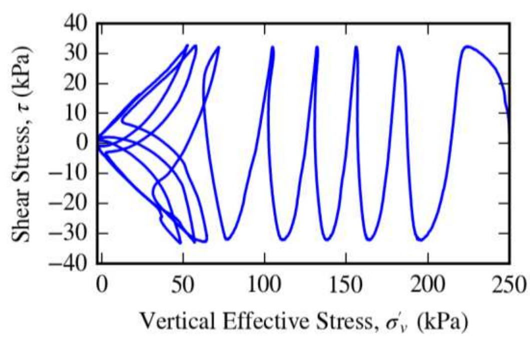

Figure 8. Biased stress path (PC CV-CDSS test, D_r = 67%).

After assigning these grades to the PC CV-CDSS tests in the database, it was observed that soil samples with D_r = 25% were able to achieve higher scores (maximum possible is 10, minimum possible is less than -1) more easily than samples with D_r = 60% or 80%. Thus, the minimum total scores for the acceptance criteria were adjusted based on D_r: 8.5, 8.0, and 6.5 for D_r = 25%, 60%, and 80%, respectively. It was also determined that any test with irregular spacing or a bias toward $+\tau$ or $-\tau$ should be removed due to the unmeasurable effects of these phenomena on the liquefaction resistance of the soil; thus these aspects of testing are not listed in Table 1. Vertical lines in the stress paths were allowed because these occurred approximately at the moment of liquefaction initiation or thereafter.

Table 1. Grading Criteria for PC CV-CDSS Tests

Criterion	A-D	Score
<u>γ during ramp-up, consolidation</u>		
$\gamma \leq 0.05\%$	*A*	+3
$\gamma \leq 0.10\%$	*B*	+2
$\gamma \leq 0.20\%$	*C*	+1
$\gamma > 0.20\%$	*D*	-
<u>τ during ramp-up, consolidation</u>		
$\tau \leq 1.0$ kPa	*A*	+3
$\tau \leq 2.0$ kPa	*B*	+2
$\tau \leq 3.0$ kPa	*C*	+1
$\tau > 3.0$ kPa	*D*	-
<u>ε during cyclic phase (c.p.)</u>		
$\varepsilon \leq 0.05\%$ for 80% of the c.p. or until $r_u = 0.75$	*A*	+3
$\varepsilon \leq 0.05\%$ for 60% of the c.p.	*A-*	+2.5
$\varepsilon \leq 0.05\%$ for 40% of the c.p.	*B+*	+2
$\varepsilon \leq 0.10\%$ for 100% of the c.p. or until $r_u = 0.75$	*B*	+1.5
$\varepsilon \leq 0.10\%$ for 75% of the c.p.	*B-*	+1
$\varepsilon \leq 0.10\%$ for 50% of the c.p.	*C*	+0.5
$\varepsilon > 0.10\%$ within 50% of the c.p.	*D*	-
<u>SP1 (vertical line in stress path)</u>		
There is a vertical line	True	-1
	False	+1
<u>Stress path convergence</u>		
Converges to $\sigma'_v = \sigma'_{min} > 0$	True	$-10 \times (\sigma'_{min}/\sigma'_{v0})$
	False	0

4 RESULTS AND DISCUSSION

If all the PC tests are used (i.e., ignoring the acceptance criteria), the *CSR* vs. N_L plots are shown in Figure 9a. If only the tests meeting the acceptance criteria are considered, then the *CSR* vs. N_L plots are shown in Figure 9b. However, due to the differences in the respective number of tests in the two datasets, a direct comparison of b-values from the CSR vs. N_L curves shown in Figures 9a and 9b cannot be made.

To account for the differences in the sizes of the datasets, *N* random PC CV-CDSS tests were sampled from the entire dataset for a given D_r and the *b*-values of the regressed data determined, over J iterations. To avoid selecting clustered CV-CDSS tests, half of the *N* samples were selected from the N_L < 15 cycles range and half were selected from the $N_L \geq 15$ range. If *N* was odd, then the number selected from the $N_L \geq 15$ range was one more than the number selected from the N_L < 15 range.

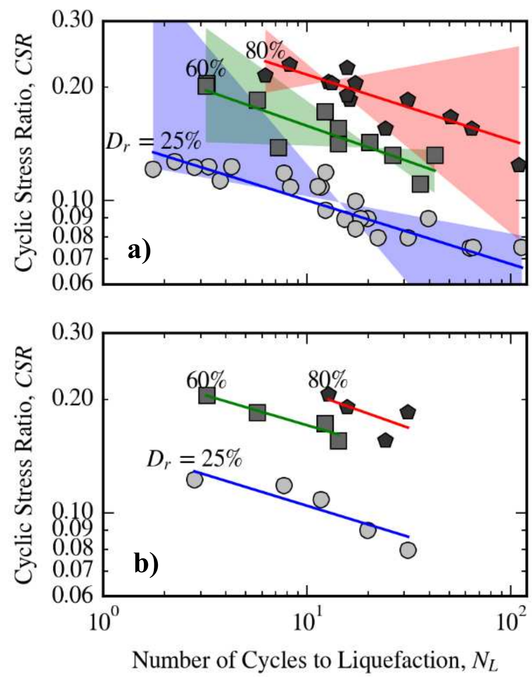

Figure 9. Liquefaction resistance curves (liquefaction defined as single-amplitude γ = 3.5%, σ'$_{v0}$ = 100 kPa) for a) all PC CV-CDSS tests, and b) PC CV-CDSS tests that passed the acceptance criteria.

The mean *b*-values obtained for the randomly sampled tests from the entire dataset are 0.171, 0.190, and 0.172 for D_r = 25%, 60%, and 80%, respectively. In comparison, the *b*-values for the regressed data meeting the acceptance criteria (i.e., Figure 9b) are 0.166, 0.159, and 0.192 for D_r = 25%, 60%, and 80%, respectively. In general, the use of acceptance criteria alters *b*-values and reduces the overall scatter around the regressed relationships between *CSR* and N_L.

5 CONCLUSIONS

There are several factors that are often overlooked that may affect the quality of CV-CDSS tests, including accumulated shear stress or strain during ramp-up and consolidation, excessive axial strain during cyclic loading, and unexpected behaviors in the stress path indicating some underlying issue with the test setup. This paper outlines these issues and proposes quality grades corresponding to each factor. Acceptance criteria are proposed based on the cumulative score for a test. If only test data that meets the acceptance criteria are considered, the *b*-values are influenced and the overall scatter around the regressed relationship between *CSR* and N_L is reduced.

6 ACKNOWLEDGEMENTS

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