Effect of Prior Strain History on Cyclic Strength and CPT Penetration Resistance of Silica Silt

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ABSTRACT

The effect of prior strain history on cyclic strength and cone penetration test (CPT) tip resistance of non-plastic silica silt is evaluated. A series of undrained cyclic direct simple shear (DSS) tests on slurry deposited specimens are performed to characterize cyclic strength. Cyclic strengths are evaluated for maximum shear strains of 1% and 3% in 15 cycles. Drained CPT tip resistances are estimated from simulated cavity expansion limit pressures. Cylindrical cavity expansion simulations are performed in the finite difference program FLAC (Itasca 2014) using a modified version of the MIT-S1 elasto-plastic constitutive model (Pestana et al. 2002, Jaeger et al. 2012). The evolution of cyclic strength and simulated CPT tip resistance during a series of cyclic loading and reconsolidation stages is presented. The developed relationships between cyclic strength and CPT tip resistance are shown to track the curvature of corresponding semi-empirical $q_{c1N_{cs}}$-CRR triggering curves. Dependence of the presented relationships on failure criterion (maximum shear strain) is shown to be qualitatively consistent with the literature.

INTRODUCTION

Recurrent liquefaction of soil deposits has been well-documented; liquefaction of previously liquefied sites has recently been observed in Japan and New Zealand (Wakamatsu 2012, Maurer et al. 2014). A fundamental understanding of the effect of prior earthquake induced cyclic loading on both cyclic strength and in situ penetration resistance is necessary to make informed interpretations of case history data and forward predictions of liquefaction potential. The effect of prior earthquake loading on non-plastic soils is thought to be dependent on: (1) destruction of structure and aging effects during liquefaction, (2) change in density from post cyclic reconsolidation, (3) post-liquefaction aging and (4) induced anisotropy/structure (Olson et al 2001, Oda et al 2001). Seed et al. (1977) observed increased resistance to liquefaction after a series of small shaking events (generating excess pore pressure ratios less than 30%) in 1-g shaking table tests on sand. They attributed this strength increase to changes in particle structure which decreased the contractive tendency of
the sand (while the relative density remained practically unchanged). Oda et al. (2001) observed a reduction in cyclic strength in a series of triaxial tests on Toyoura sand when pre-sheared cyclically or monotonically despite increased relative density. They suggested the observed strength decrease was a result of induced anisotropy of a column like structure. Ha et al. (2011) observed an initial reduction followed by an increase in liquefaction resistance in a series of 1-g shaking table tests on five Korean sands. Mesri et al. (1990) found CPT tip resistance to increase with both density and time dependent secondary compression due to increases in stiffness and horizontal effective stress. These observations suggest that cyclic strength and penetration resistance may increase or decrease with strain history produced by earthquake induced cyclic loading and ensuing reconsolidation.

It is implicitly assumed the effect of prior strain history is accounted for in CPT-based triggering correlations. In forward applications these correlations are assumed applicable regardless of strain history. However, experimental observations (such as those by Seed et al. 1997 and Oda et al. 2001) have shown cyclic strength and cone penetration resistance to be strain history dependent. While case history observations rely on surface expressions to define liquefaction (e.g. sand boils, lateral spreading), the choice of failure criterion to define cyclic strength is important to the interpretation of experimental observations. Idriss and Boulanger (2008) used experimental results for irregular cyclic simple shear testing on Fuji river sand by

![Figure 1. CPT-based triggering correlation of Boulanger and Idriss (2014) with contours of maximum shear strain based on Ishihara and Yoshimine (1992).](image-url)
Ishihara and Yoshimine (1992) to plot their liquefaction triggering curve with contours of maximum shear strain, $\gamma_{\text{max}}$. These relationships are replotted in Figure 1 for the updated Boulanger and Idriss (2014) CPT-based triggering curve. The sensitivity of cyclic strength to maximum shear strain increases with increasing tip resistance.

This study examines the effect of prior strain history on the cyclic strength and CPT tip resistance of normally consolidated, slurry deposited, non-plastic silica silt (SIL-CO-SIL 250 silica flour). Cyclic strengths were measured by a series of undrained cyclic direct simple shear (DSS) tests and post-cyclic reconsolidation stages. CPT tip resistance was estimated from cylindrical cavity expansion simulation using the MIT-S1 elasto-plastic constitutive model (Pestana and Whittle 1999, Pestana et al. 2002, Jaeger et al. 2012). Results are presented for $\gamma_{\text{max}} = 1\%$ and $3\%$ (single amplitude) in 15 cycles. Cyclic strength and CPT tip resistance are shown to increase with recurring cyclic loading and reconsolidation stages. The resulting correlation between cyclic strength and CPT tip resistance is below the case-history based triggering correlation by Boulanger and Idriss (2014), but it exhibits parallel trends and a dependence on failure criterion (maximum shear strain) which is consistent with those expected based on the relationships by Ishihara and Yoshimine (1992).

**METHODOLOGY**

The effect of prior strain history on the relationship between cyclic strength and penetration resistance is conceptually illustrated in Figure 2. A soil element within a liquefiable layer (Figure 2a) is shaken by three hypothetical earthquake events. Prior to shaking, the element exists at state A in the void ratio-vertical effective stress space shown in Figure 2b. Earthquake induced cyclic loading (EQ#1) liquefies the soil element as depicted by the leftward path from state A. Post shaking reconsolidation densifies the soil element to state B assuming unimpeded pore pressure dissipation in the soil profile. A second earthquake loading (EQ#2) re-liquefies the soil element resulting in reconsolidation to state C. A third earthquake loading (EQ#3) liquefies the soil element once again. The effect of the described loading history (cycles of earthquake induced cyclic loading followed by reconsolidation) on both the cyclic strength and penetration resistance of states A, B, and C is illustrated in Figure 2c.

The effect of prior strain history as conceptually described above is explored herein by: (1) cyclic DSS tests to measure the evolution of cyclic strength with strain history, and (2) cavity expansion simulation allowing for changes in density from multiple cyclic loading and reconsolidation stages to estimate CPT tip resistances.

**MONOTONIC AND CYCLIC DSS TESTING**

Undrained monotonic and cyclic DSS tests were performed on normally consolidated, slurry deposited specimens of non-plastic silica silt. Results of monotonic tests at three overburden stresses (vertical effective consolidation stress,
The results of the cyclic undrained simple shear tests with multiple liquefaction and reconsolidation stages are summarized in Figure 4. From an initial slurry deposited, normally consolidated state, A1, the specimen is subjected to multiple liquefaction and reconsolidation stages. States A1-A4, B1-B2, and C1-C2 are subjected to a cyclic stress ratio (CSR) of 0.13, 0.21, and 0.42 respectively. Cyclic shearing was stopped at 3% shear strain (single amplitude) at each stage. Following cyclic loading, the
A specimen was re-centered ($\gamma = 0\%$) and allowed to reconsolidate back to the initial vertical effective consolidation stress ($\sigma'_{vc} = 100$ kPa). This analysis focused on evaluating the cyclic strengths for a criteria of $\gamma_{max} = 3\%$ in N = 15 cycles. States A1, A3, B2, and C2 were used to estimate cyclic strengths because they reached 3% shear strain in close to 15 cycles. For example, A3 reached 3% shear strain in 11.5 cycles, from which the strength at 15 cycles is estimated based on the estimated slope of the cyclic strength versus number of loading cycles curve. Significant densification from post-cyclic reconsolidation was observed, with post-cyclic reconsolidation strains ranging from about 0.7% to 1.5% across the eight tests presented.

Stress strain responses and stress paths for states A1, A3, B2, and C2 are presented in Figure 5. Strain accumulates more slowly during test A3 than during test A1 once the normalized vertical effective stress decreases below about 0.2. This is attributed to the increased dilative tendency of A3 which developed from two additional cyclic loading and reconsolidation stages. Tests B2 and C2 exhibit a significant reduction in vertical effective stress (pore pressure generation) during the first quarter cycle of loading followed by gradual strain accumulation. As the specimen densifies from cycles of cyclic loading and reconsolidation it becomes more dilative at small values of normalized vertical effective stress but retains similar behavior during earlier cycles of loading for a given CSR. Greater differences in the cyclic strength determined for $\gamma_{max} = 1\%$ and $3\%$ are therefore obtained as the specimen densifies. For example, test A1 reaches 1% and 3% shear strain in almost the same number of cycles, while test D2 reaches 1% shear strain during the first quarter cycle and 3% shear strain after 13 cycles. This behavior is in qualitative agreement with Ishihara and Yoshimine’s (1992) observations. Post-cyclic reconsolidation paths are plotted alongside the cyclic shearing paths in red; the small amount of shear strain developed during reconsolidation is attributed to enforcement of zero shear stress on the horizontal plane.

**Figure 3. Experimental and simulated monotonic DSS paths for the silica silt.**
CAVITY EXPANSION SIMULATION

Drained cone penetration tip resistance was estimated by cylindrical cavity expansion simulation using MIT-S1 in the commercial finite difference program FLAC (Itasca 2014). Cavity expansion limit pressures are converted to CPT tip resistances by projecting the cavity limit pressure onto the cone face following Leblanc and Randolph (2008). Cavity expansion simulations only consider the effect of density changes measured during post-cyclic reconsolidation.

Results of calibration of the MIT-S1 constitutive model are illustrated in Figure 3 above. Calibration of MIT-S1 to the slurry deposited silica silt is based on an experimental program designed to capture the primary behaviors affecting CPT tip resistance. Other behaviors are constrained by well-established empirical relations (Price et al. 2015). Experimental and simulated paths for undrained monotonic DSS tests exhibit dilative tendencies at large shear strains for the three different overburden stresses tested.

The conversion of cavity expansion pressures to equivalent cone penetration resistance follows Leblanc and Randolph (2008). Cavity expansion is modeled using a 100 zone axisymmetric model in FLAC. Cavity expansion limit pressures are computed as described in Price et al. (2015) and Jaeger et al (2012). Cavity expansion limit pressures are assumed to act radially on the entire cone face as the minor principal stress. An interface friction angle between the cone face and surrounding soil is assumed to be the triaxial compression critical state friction angle of the soil.

Figure 4. A cyclic DSS test with multiple liquefaction and reconsolidation stages; liquefied conditions are plotted at \( \sigma'_{v} = 1.5 \) kPa for convenience.
Figure 5. Cyclic DSS test results for A1, A3, B2 and D2.
The vertical effective stress acting on the cone is assumed to be the major principal stress and can be solved for given the cone geometry, critical state friction angle, and cavity expansion limit pressure.

RESULTS

Cyclic strengths from the cyclic DSS tests are plotted vs the CPT tip resistances simulated by cavity expansion for $\gamma_{\text{max}} = 1\%$ and $3\%$ in 15 cycles in Figure 6. Results from four tests (A1, A3, B2, and D2) are plotted corresponding to cyclic loading conditions where the silica silt specimen developed $3\%$ shear strain in close to 15 cycles. The CSR was then adjusted to an equivalent CSR for $N = 15$ using the slope of CSR-N curves from tests on virgin, normally consolidated silica silt specimens and $\gamma_{\text{max}} = 3\%$ (Price et al. 2015). Results for $\gamma_{\text{max}} = 1\%$ in 15 cycles from four tests (A1, A4, B2, and D2) are also plotted. Adjustment of these cyclic strengths to $N = 15$ cycles used the slope of the CSR-N curves for virgin specimens with $\gamma_{\text{max}} = 1\%$.

The derived results are compared to the case history-based liquefaction triggering correlation by Boulanger and Idriss (2014) for a fines content (FC) equal to that of the silica silt (FC = 76%) (Figure 6). Contours of maximum shear strain based on the experimental test results by Ishihara and Yoshimine (1992) and the empirical

Figure 6. Cyclic strength vs. drained cone tip resistance simulated by cavity expansion for $\gamma_{\text{max}} = 1\%$ or $3\%$ in 15 cycles
correlation by Boulanger and Idriss (2014) are shown for $\gamma_{\text{max}} = 1\%$ and $3\%$. The developed relationships lie to the right of their case history-based counterparts; however, their curvature and dependence on maximum shear strain follows the empirical trends. The developed curves are closer to the case history-based curves for a fines content of $35\%$.

The differences between the developed and empirical curves may be due to several sources of uncertainties that are currently under investigation. The conversion from a drained cavity expansion limit pressure to an equivalent cone penetration resistance is suspected as a primary source of uncertainty influencing the presented relationships. Implementation of a numerical solution for the axisymmetric cone penetration problem is in progress and may reduce the uncertainty associated with indirect simulation of cone penetration by cavity expansion. In addition to implementation of the full penetration problem, continued DSS lab testing and centrifuge validation are currently ongoing (e.g. Darby et al. 2016).

CONCLUSIONS

The effect of prior strain history on cyclic strength and CPT penetration resistance of slurry deposited, non-plastic silica silt was evaluated. The evolution of cyclic strengths was measured through a series of undrained cyclic DSS tests and post-cyclic reconsolidation stages. Cyclic strengths were evaluated for $\gamma_{\text{max}}= 1\%$ and $3\%$ in $15$ cycles. The progression of CPT penetration resistance was estimated from cylindrical cavity expansion simulations using the MIT-S1 constitutive model. Simulations only considered the change in density occurring during post-cyclic reconsolidation.

The developed relationships between cyclic strength and penetration resistance possess similar curvature to their case history-based counterparts. The dependence on maximum shear strain is in qualitative agreement with experimental data presented by Ishihara and Yoshimine (1992). The preliminary results are promising and encourage further application of the present approach to investigate the effect of prior strain history on CPT-based liquefaction triggering correlations.

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