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Influence of Natural Soil Fabric on the Cyclic Resistance of Low and High Plasticity Silts

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ABSTRACT

This paper presents the results from a study of the role of soil fabric on the cyclic response of silty soil samples retrieved from two different sites from a series of sites investigated as a part of a larger study: one along the Willamette River (Site B) and one along the Columbia River (Site D). The soils investigated in this study were retrieved from Site B and exhibited an average $PI = 13$, and from Site D which were characterized with an average $PI = 28$. The cyclic response of the soils was evaluated by performing several constant-volume, stress-controlled, cyclic direct simple shear tests (CDSS) with varying cyclic stress ratios, *CSR*s, on natural, intact specimens and their reconstituted counterparts. Despite the lower void ratios of the reconstituted specimens, the cyclic resistance of the intact specimens for Sites B and D at 15 loading cycles were 19% and 37% greater than their reconstituted counterparts, respectively. For the given loading conditions, the rate of excess pore pressure development, single amplitude shear strain (γ) accumulation, and shear stiffness degradation in reconstituted specimens were greater than the natural intact specimens, emphasizing the role of soil fabric, as confirmed by the lower shear wave velocity (V_s) of reconstituted specimens compared to their intact counterparts.

Introduction

Earthquake-induced liquefaction and cyclic softening-induced ground failures present a major challenge to society at large. Over the last several decades, significant progress has been made to understand the cyclic response of sands and clays; however, uncertainty on the cyclic response of transitional silty soil remains. Although numerous laboratory studies on reconstituted soil specimens have been performed to aid the understanding of general trends in cyclic response of transitional soils, these efforts have not captured the role of soil fabric, stress history, aging, cementation, preshaking history, mineralogy, and anisotropy, which contribute

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to the complexity of liquefaction or cyclic mobility of silty soil [1-5]. Limited laboratory studies on intact specimens of silt, e.g. [4-6], provide a basis to establish the dynamic responses of transitional soils and calibrate dynamic constitutive models. Laboratory cyclic tests of intact transitional soils continues to represent the best practice to identify the factors contributing to their cyclic response. This study presents comparison of cyclic responses of intact and reconstituted silt from two different tests sites to elucidate fundamental similarities and differences in their response.

Experimental Program and Testing Procedure

The two test sites, B and D, of a series of sites investigated as part of a larger study [6,7], are situated in Oregon along the Willamette and Columbia Rivers, respectively. Both sites are vulnerable to potential future seismic hazards, and in particular, a Cascadia Subduction Zone earthquake event with moment magnitude, $M_w \geq 9$. A series of mud-rotary borings were drilled for the retrieval of intact thin-walled Shelby tubes samples. Intact specimens were prepared from soil samples extruded from the top of tube in the same direction as movement of the soil during sampling to prevent any shear reversal-induced disturbance [8]. Cylindrical specimens with 20 mm height and 72 mm diameter were subjected to cyclic direct simple shear (CDSS) loading. All soil specimens were consolidated to *in-situ* vertical effective stress, σ'_{v0}, using the recompression method under zero lateral strain prior to cyclic testing. Various stress-controlled cyclic tests were performed on intact specimens of the silt and their reconstituted counterparts. Reconstituted samples were prepared from intact thin-walled tube samples using slurry deposition technique outlined by [9]. The soil slurry was consolidated in 72 mm diameter cylinders to the preconsolidation pressure, σ'_p, estimated from consolidation tests conducted on intact specimens.

Material Characteristics

The soil samples from Site B were lightly overconsolidated ($1.4 \leq OCR \leq 1.7$) low-plasticity silts (ML) with average water content $w_n = 39\%$, average $PI = 13$, and a fines content $FC = 86\%$. Site D soil samples were lightly overconsolidated ($1.6 \leq OCR \leq 2.2$) high-plasticity silts (MH) with average $w_n = 75\%$, $PI = 28$, and $FC = 100\%$. Using typical liquefaction screening criteria, the soil from Site B is susceptible to moderately susceptible to liquefaction [8], although they are identified to behave fundamentally as clay-like soils [10]. On the other hand, the Site D specimens are deemed insusceptible to liquefaction under the "sand-like" paradigm [8, 10] and may be susceptible to cyclic softening in accordance with clay-like behavior and the liquefaction susceptibility criterion proposed by [10].

Experimental Results

Figure 1 compares the $CSR - \gamma$ hysteresis loops and the development of γ and excess pore pressure ratio, r_u, with number of loading cycles, N, of an intact specimen from Site D (Figs. 1a - 1c) with its reconstituted counterpart (Figs. 1d - 1f) subjected to the CDSS tests with $CSR = 0.27$. Generally, both intact and reconstituted specimens exhibit a similar cyclic response in terms of wide hysteresis loops (i.e., clay-like response) without a transient zero shear stiffness during reloading along with a cyclic mobility-type response associated with gradual accumulation of γ and r_u with N. Despite the observed similarities, there are significant differences in the cyclic response of the intact and reconstituted specimens. For example, at $CSR = 0.27$ and for any given N, the reconstituted specimen generates larger γ and broader hysteresis loops (i.e., higher dissipated energy, rapid degradation of shear stiffness), exhibits larger contractive behavior, and develops γ and r_u at a faster rate compared to the intact specimen, to result in fewer cycles for the to reach $\gamma = 3\%$ ($N = 2.3$) compared to its intact counterpart ($N = 45.8$). Similarly, the $CSR - \gamma$ hysteresis and accumulation of γ and r_u with N for the intact and reconstituted specimens from Site B are shown in Figs. 1g - 1l. The intact and reconstituted specimens exhibit similar cyclic response in terms of narrow hysteresis loops with transient zero shear stiffness upon reloading. The rate of γ and r_u accumulation with N is higher in the reconstituted specimen compared to its intact counterpart, indicating a lower cyclic resistance compared to its intact counterpart.

Figure 2 presents the variation of the CSR with N required to reach $\gamma = 3\%$ for CDSS tests conducted on reconstituted specimens from Sites B and D and their intact counterparts. The results indicate that the intact specimens from Sites B ($e_c = 0.94$) and D ($e_c = 2.20$) and exhibit appreciably higher cyclic resistance ratios, CRR, compared to the reconstituted specimens despite the lower void ratios of the reconstituted specimens (Site B: $e_c = 0.84$, Site D: $e_c = 1.14$;). Although the reconstituted and intact specimens have identical mineralogy, grain size distribution, stress history, the observed differences in their behavior cannot be explained by common state parameters (e.g., e_c and σ'_{v0}); however, the differences in their response may originate from the differences in depositional environment and aging effects. This highlights the significance of soil fabric on cyclic response, as confirmed by the higher shear wave velocity of intact specimens (Site B: $V_s = 168\,m/s$, Site D: $V_s = 122\,m/s$,) compared to their reconstituted counterparts (Site B: $V_s = 159\,m/s$, Site D: $V_s = 107\,m/s$).

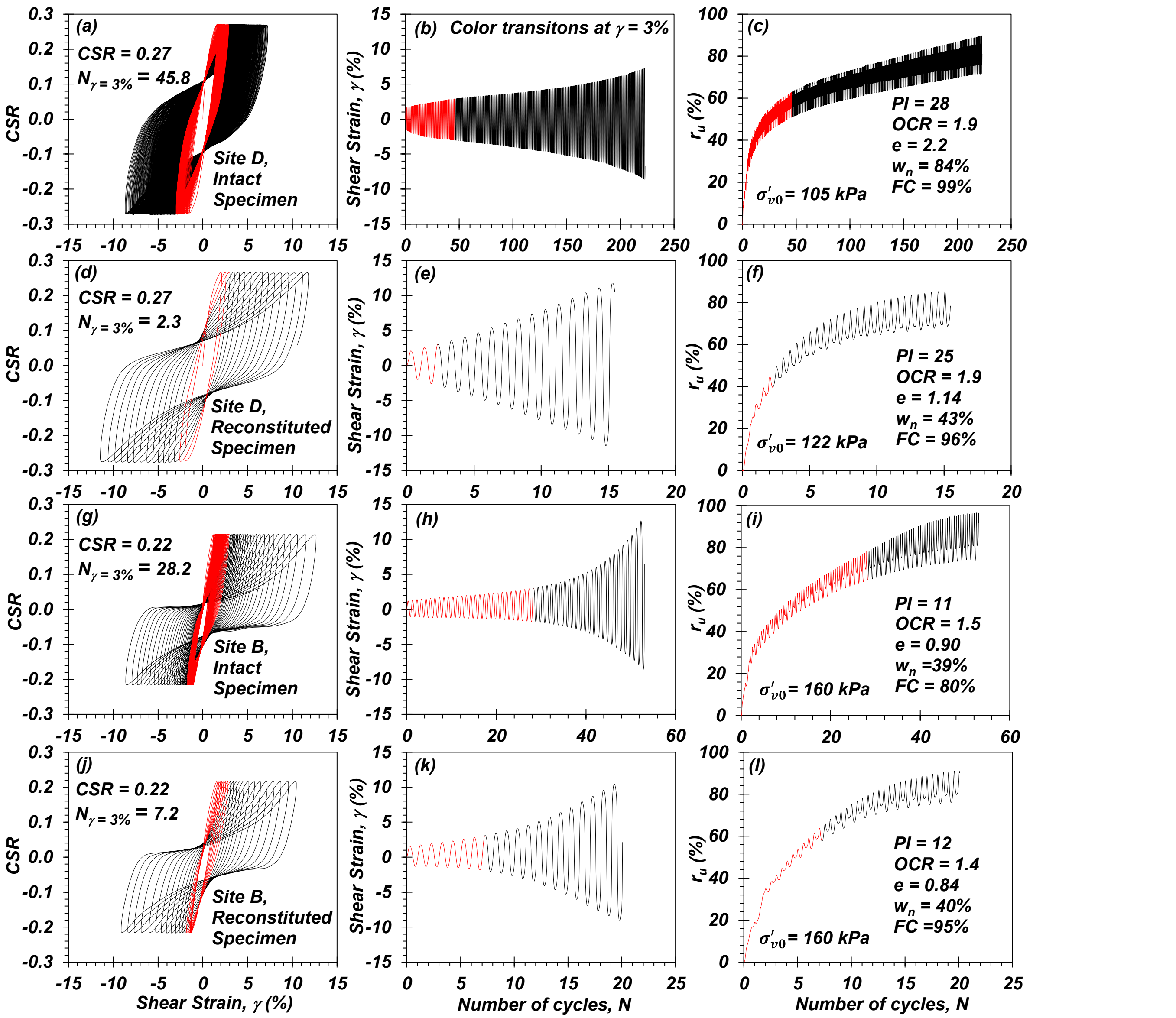

Figure 1. Comparison of cyclic response of intact and reconstituted specimens B and D indicating: $CSR - \gamma$ hysteresis (left column), accumulation of shear strain with number of cycles (middle column), and generation of excess pore pressure with number of cycles (right column).

Conclusions

This study presents comparison of cyclic response of intact and reconstituted silt from two sites located along Columbia and Willamette rivers. Both intact and reconstituted specimens exhibited the cyclic mobility behavior in the form of incremental accumulation of shear strain, excess pore pressure generation, and degradation of shear stiffness without abrupt strength loss as cyclic loading progressed. Despite the lower void ratio, the reconstituted specimens exhibit lower cyclic resistance, as deduced from the higher rate of pore pressure generation, stiffness degradation, and strain accumulation compared to their intact counterparts. This observation highlights the beneficial role of natural soil fabric and aging on the cyclic resistance of intact soils that are not present in reconstituted specimens. The results of this study indicate that the commonly used state parameters (e.g., void ratio and vertical effective consolidation stress) may not be sufficient to explain the existing difference between intact specimens and their reconstituted counterparts.

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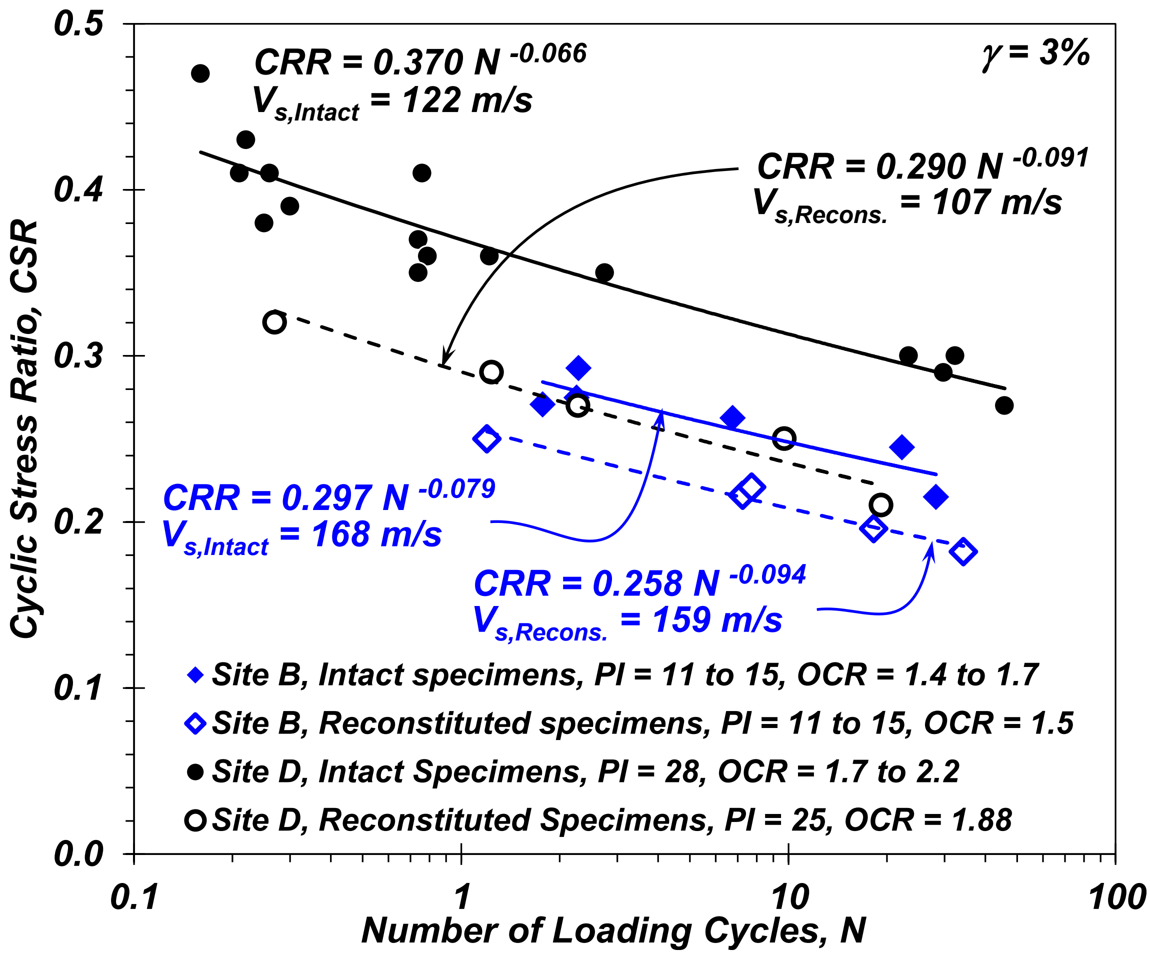

Figure 2. Comparison of variation of cyclic stress ratio, *CSR*, with number of loading cycles, *N*, for $\gamma = 3\%$ derived from constant-volume, stress-controlled, cyclic tests conducted on natural, intact and reconstituted specimens of Sites B and D.

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