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Cyclic Re-Liquefaction Behavior of a Sand

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Abstract. Despite extensive amount of research on cyclic response of sands, re-liquefaction behavior and cyclic liquefaction resistance of cohesionless soils under a repeated cyclic load have not received the same amount of attention. This is important as most soil deposits in high seismic areas have been subjected to repeated number of earthquakes. This paper presents series of laboratory cyclic simple shear tests on specimens of a local sand. Sand specimens are reconstituted at relative densities of 25%, 45%, and 65% and subjected to effective vertical stresses of 50, 100, 200, 400, and 600 kPa. Reconstituted samples are subjected to two consecutive cyclic loads and sand behavior and liquefaction resistance are examined and compared following both cyclic loads. Re-liquefaction is simulated by unloading the specimens after the first cyclic load and re-consolidating the specimen under the same initial vertical stress. A similar cyclic load is then re-applied on the sand specimen. The results show a moderate increase in relative density after re-consolidation, which is greater for loose sand specimens. However, a complicated change in cyclic liquefaction resistance is observed for loose and dense specimens which also varies with stress level. Despite the larger increase in relative density, the loose specimens exhibit a decrease in cyclic resistance following the first cyclic load. The reduction in cyclic resistance increases with decreasing effective stress (from 600 to 50 kPa). On the other hand, dense samples experience an increase in cyclic resistance, particularly at higher stress levels.

Keywords. Liquefaction, sand, cyclic simple shear, earthquake.

1. Introduction

Prior strain history and repeated shaking events can have a significant impact on liquefaction potential and cyclic strength of a saturated sand. Due to reconsolidation and densification following an earthquake shaking, one would expect that the re-liquefaction resistance of a soil would improve. In contrast, several cases of recurrent soil liquefaction have been reported for sites which had suffered liquefaction in the past [1-3]. For example, a relatively weaker aftershock (M_w = 7.1, PGA ≈ 0.1g) caused repeated liquefaction at the northwestern part of the Tohoku district in Japan which had already experienced liquefaction following a stronger magnitude 7.7 earthquake (PGA ≈ 0.28g) on May 26, 1983 [2] as well as in the 1964 Niigata earthquake [4]. Recent examples also include recurrent liquefaction of natural deposits in Christchurch, New Zealand during the 2010-11 Canterbury earthquake sequence [3, 5], and in artificial fills in the Tokyo area following the 2011 Tohoku earthquake [6]. Existing laboratory studies also show a rather complicated effect of pre-shaking and contradictory outcomes. Many investigators [7-11] have reported improved cyclic liquefaction resistance following small-amplitude

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monotonic or non-liquefying cyclic pre-shearing, and reconsolidation. Whereas, large pre-shearing (e.g, with $\gamma_{cyc} > 0.5\%$, or $r_u > 0.7$) and liquefaction have been observed to erase the effects of post-liquefaction densification and reduce the subsequent cyclic liquefaction resistance [7-10, 12-14].

Understanding the undrained response of sand deposits which may have been subjected to a prior earthquake or large aftershocks is critically important for assessing liquefaction susceptibility and estimating liquefaction-induced and post-liquefaction displacements. The purpose of this study is to re-evaluate the effect of a prior liquefaction occurrence on the liquefaction resistance and cyclic shearing behavior of sand samples. High-quality cyclic direct simple shear (CDSS) tests are conducted to replicate cyclic stresses under level ground conditions to simplify the study of liquefaction response, without the complex effects of an initial horizontal shear stress.

2. Experimental Procedure

2.1. Tested Material

A local sand from the Boler Mountain in London (Ontario, Canada) was used in this study. Natural Boler sand has a fines content of about 11%. For this study the fines were removed by sieving and washing through sieve #200, resulting in a clean sand with D_{50} = 0.24 mm, C_U = 1.75, and C_C = 1.38. A specific gravity (G_S) of 2.67, and maximum (e_{max}) and minimum (e_{min}) void ratios of respectively 0.845 and 0.525 were determined following ASTM D4254 and ASTM D4253 standard testing procedures. Using scanning electron microscopic images, X-Ray diffraction and acid dissolution analyses, Boler sand was found to be composed of about 90% to 85% quartz (SiO_2) and 10% to 15% carbonate ($CaCO_3$) and dolomite ($MgCa(CO_3)_2$) particles, with sub-angular to angular particle shapes.

2.2. Equipment

Constant-volume CDSS tests were carried out in this study using an advanced NGI-type simple shearing apparatus manufactured by Global Digital Systems (GDS) Instruments Ltd. (Hampshire, UK). In these tests, a cylindrical specimen is enclosed in an un-reinforced rubber membrane while being supported laterally by a stack of smooth (‘‘frictionless’’) circular close-fitted rings. The thin rings (each 1.1 mm thick) maintain a constant cross-sectional area while allowing uniform shear deformations. Normal and shear forces are applied on the soil specimen in the horizontal plane. The surfaces of the upper and lower platens have concentric circular fins to provide a rough interface and minimize relative movement between the soil specimen and the top cap.

2.3. Sample Preparation

Reconstituted specimens of 70 mm in diameter and 25 mm high were prepared. In order to minimize density variations across the specimen height and improve specimen uniformity, the under-compaction moist-tamping procedure [15] was adopted for specimen preparation. Relatively uniform and very loose specimens were readily created with this method as capillary among moist particles holds them together. The small amount of matric suction was however eliminated by saturating the specimens after preparation. A small normal stress of 5 kPa was applied on the specimens to ensure proper seating of the top platen. A moist tamped specimen can be thought to represent an in-situ soil fabric formed by moist-compaction or end-tipping of a sandy soil above the water table, loose tailings with minimal compaction, silty sands, or loess formed by the deposition of loose particles by pore water suction.

2.4. Consolidation and Shearing

Initial void ratio (e_o) was chosen by trial and error so that the specimen would densify to a given relative density (D_{rc}) after consolidation at the target effective vertical stress (σ'_{vc}). Following consolidation, the specimens were subject to constant-volume stress-controlled cyclic shearing. The cyclic stress ratio (CSR) was defined as the maximum cyclic shear stress applied on the soil specimen normalized by σ'_{vc}. Sinusoidal cyclic shearing was applied at a frequency of 0.1 Hz in order to maintain a constant amplitude of cyclic shear stress, allow a better control of shear loads and data acquisition, as well as complete excess pore pressure dissipation. An automated electro-mechanical control system was used to actively maintain a constant specimen height during shearing by adjusting the vertical load on the specimen. As drainage was allowed no shear-induced pore water pressure was produced, and the change in vertical stress required to maintain a constant height was taken as the equivalent pore water pressure that would have been generated in a truly undrained test on a saturated sample [16, 17].

The effect of recurrent liquefaction was examined by applying the first cyclic loading until the specimens liquefied at $\gamma_{DA} > 7.5\%$. This simulated in-situ loading conditions for a freshly-deposited soil that had never experienced seismic loading after initial deposition or had been re-deposited by upward migration of excess pore pressure after a seismic event. Upon reaching liquefaction ($\gamma_{DA} = 7.5\%$) by the first loading, cyclic shear was terminated, and the shear stress was reverted to zero while recording the residual shear strain (γ_{res}). The specimens were then allowed to reconsolidate by subjecting them to the same σ'_{vc} until the vertical strain stabilized at a nearly constant plateau. This condition is similar to a level-ground liquefaction event where shear strains imparted to the ground are not taken back to zero, and reconsolidation and subsequent cyclic stresses are applied to the pre-sheared soil with residual strains. Accordingly, the soil remained largely deformed throughout subsequent cyclic loading. The same CSR applied in the first cyclic loading was subsequently re-applied to the pre-sheared specimens at the same cyclic frequency of 0.1 Hz. During consolidation and cyclic shearing, vertical deformation of the specimen was measured using an external LVDT attached to the side of the specimen. Void ratio changes were thus continually measured throughout the consolidation and shearing stages of the test.

3. Test Results

Close to 120 K_0-consolidated CDSS tests were carried out in this study on specimens consolidated at different relative densities (D_{rc}), σ'_{vc} and subjected to different cyclic stress ratios (CSR). Figure 1 illustrates typical normalized cyclic stress paths and stress-strain plots for a CDSS test following the initial and repeated cyclic loading. Similar to Figure 1, all samples exhibited cyclic liquefaction behavior, characterized by specimens showing a cyclic strain-softening response. A large reduction in σ'_v occurs in the first quarter-cycle of loading, followed by a progressively slow σ'_v reduction as reflected by the gradual reduction of spacing between successive stress cycles in the stress path plots. This corresponds to a rapid increase in equivalent excess pore pressure ratio, $r_u = \Delta u/\sigma'_{vc}$, where Δu is the equivalent shear-induced pore pressure and σ'_{vc} is the initial effective vertical stress. Cyclic shear strains remain relatively small until $r_u > 0.6 – 0.7$, after which γ_{cyc} grows rapidly with each additional cycle of loading and the specimen liquefies in two to three additional loading cycles as shown in Figures 1c, d.

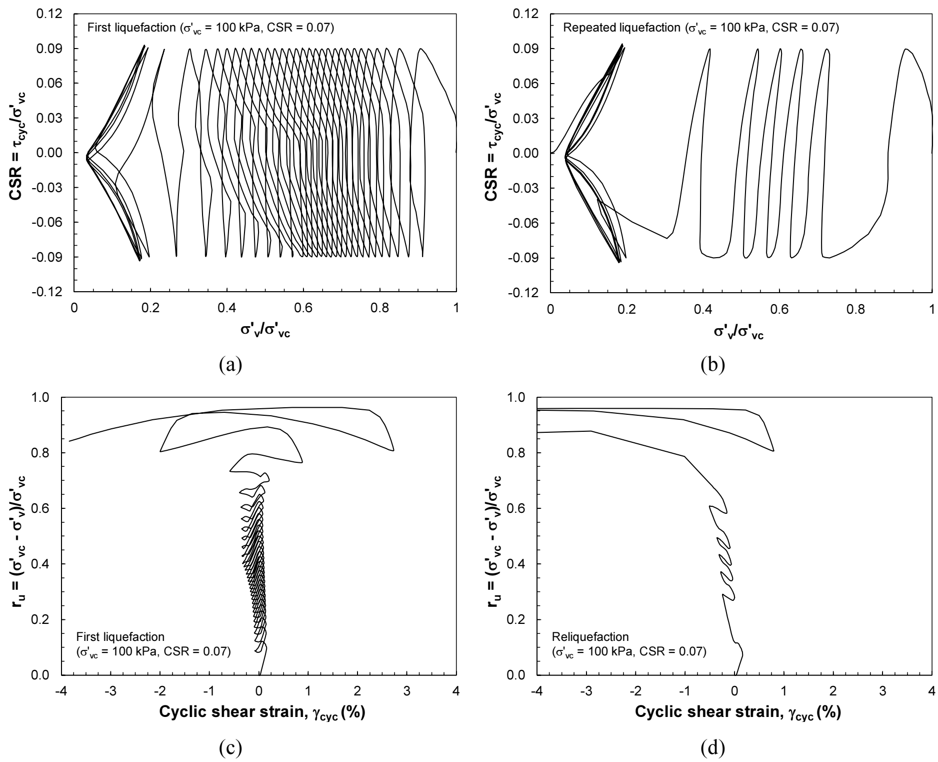

Figure 1. Typical cyclic stress paths and excess pore pressure accumulation of Boler sand in a CDSS test at $D_{rc} = 25\%$.

4. Re-liquefaction Resistance

The liquefaction failure criterion is defined as the number of cycles (N_L) required to cause a double amplitude shear strain, γ_{DA} of 7.5% [18]. This is a sufficiently large shear strain that if produced in-situ would lead to a rapid loss of serviceability. Figure 2 compares cyclic resistance curves (CSR vs. N_L) of specimens following the first and second cyclic loads. According to this figure, at lower CSR (< 0.10) cyclic resistance curves following re-liquefaction are lower than those from the first liquefaction occurring. At higher CSR, however, they approach and tend to exceed those from the first cyclic loading episode. The effect of N_L is also suppressed as demonstrated by the relatively flatter CSR-N_L trends in re-liquefaction. These occurs even though D_{rc}

increased by an average of 11%. Ishihara and Okada [19] show that residual shear strain (γ_{res}) has a key effect on liquefaction resistance. The trends shown in Figure 2 are perhaps due to changes in sand fabric by the residual shear strains (γ_{res}) locked-in after the first cyclic loading. When the cyclic load was re-applied, γ_{res} still prevailed, increasing the sensitivity of N_L to CSR changes. Nevertheless, their effect becomes progressively erased with increasing CSR and D_{rc}. It is also inferred from Figure 2 that the impact of γ_{res} is more significant in loose (D_{rc} = 25%) and medium-dense (D_{rc} = 45%) specimens. For dense samples (D_{rc} = 65%) however, the cyclic resistance curves following re-liquefaction are often higher than those of the first cyclic loading.

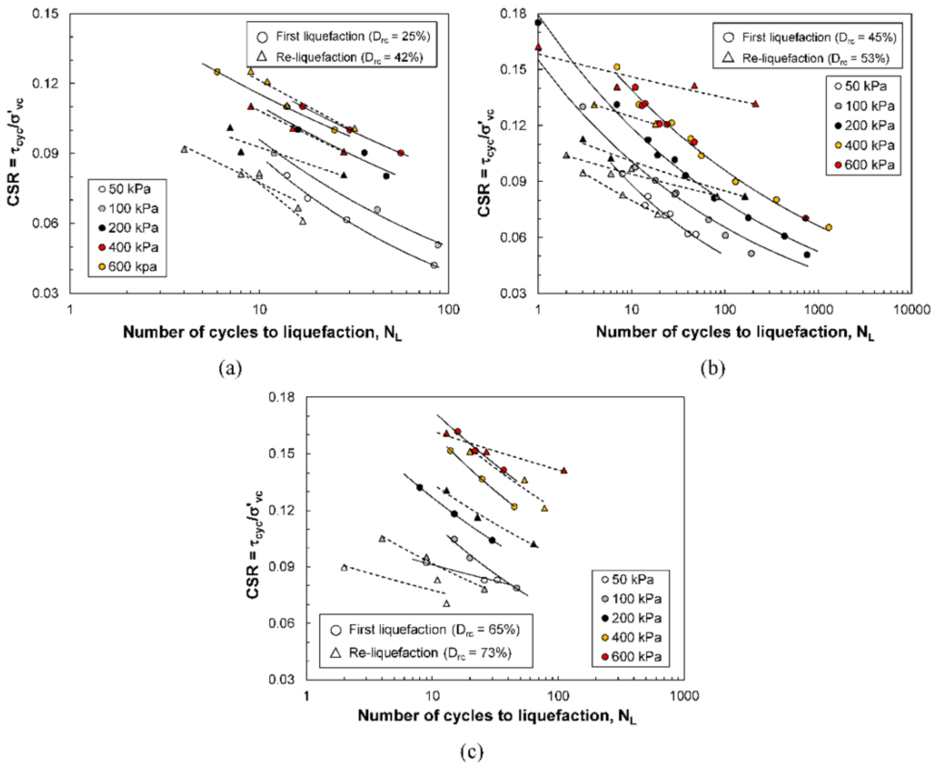

Figure 2. Comparison of cyclic resistance curves following the initial and repeated liquefaction.

Cyclic resistance ratio ($CRR_{NL=15}$) is described as the CSR required to reach liquefaction in 15 uniform loading cycles, which corresponds to an earthquake magnitude of 7.5. The effect of prior liquefaction history on CRR is better demonstrated by comparing changes in liquefaction resistance corresponding to the first (CRR_f) and repeated liquefaction (CRR_{re}) events. These are shown by the ratio CRR_{re}/CRR_f and the relative change of $(CRR_{re} - CRR_f)/CRR_f \times 100$ in Figure 3. This figure shows clear reductions in CRR_{re} despite increases in D_{rc} and densification following reconsolidation after the first cyclic loading. This could be due to the weakening effect of large shearing to liquefaction (γ_{DA} > 7.5%) as well as changes in fabric anisotropy of the rather isotropic moist-tamped sands [10, 12]. This observation has far-reaching implications as a site that has suffered liquefaction in an earlier earthquake may re-liquefy during a subsequent aftershock. For example, silica sand deposits were observed to re-liquefy in the aftershocks of the 1983 Nihonkai Chubu earthquake [2].

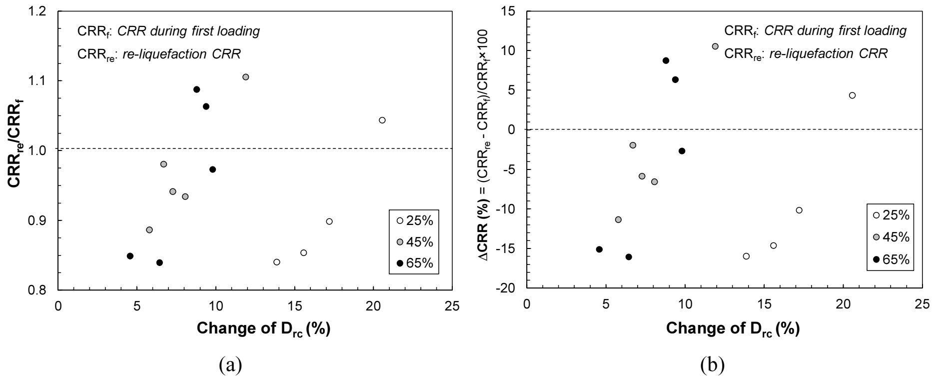

Figure 3. Comparison of CRR resulting from the first and repeated liquefaction events.

On the other hand, a higher re-liquefaction resistance is only realized in Figure 3 after a sufficient amount of densification and D_{rc} increases of about 9 to 20%, which overrides the effect of pre-shearing on sand fabric. Larger D_{rc} increase (i.e. densification) occurs in loose samples due to their more compressible fabric. Changes of CRR with pre-shearing for loose and dense specimens found in this study are similar to those observed in some other experimental studies on silica sands [7, 9, 10, 12-14] in which CRR reduced as a result of a large pre-shearing cyclic load. For example, Oda et al. [10] found that the cyclic resistance of Toyoura sand samples decreased following liquefaction in cyclic triaxial tests, despite reconsolidation and an increase in D_{rc}. In 1g shaking table tests on five different sand models, Ha et al. [13] obtained a substantially reduced number of cycles to re-liquefaction following a prior liquefaction event. Recurrent liquefaction was also observed by Wang et al. [14] in a sequence of centrifuge shaking table experiments on Fujian sand models.

5. Effect on Pore Pressure Accumulation

In order to highlight the effect of pre-shearing on pore pressure generation behavior, patterns of cyclic pore pressure ratio (r_u) behavior of the virgin and the pre-sheared specimens of loose and dense specimens are compared in Figure 4. At σ'_{vc} = 100 kPa, pre-sheared specimens of Boler sand show a more rapid excess pore pressure generation compared to virgin specimens without pre-shearing. Whereas with increasing σ'_{vc} (e.g., at 600 kPa in Fig. 4), specimens subject to repeated loading exhibit slower rate of r_u accumulation compared to the first cyclic loading.

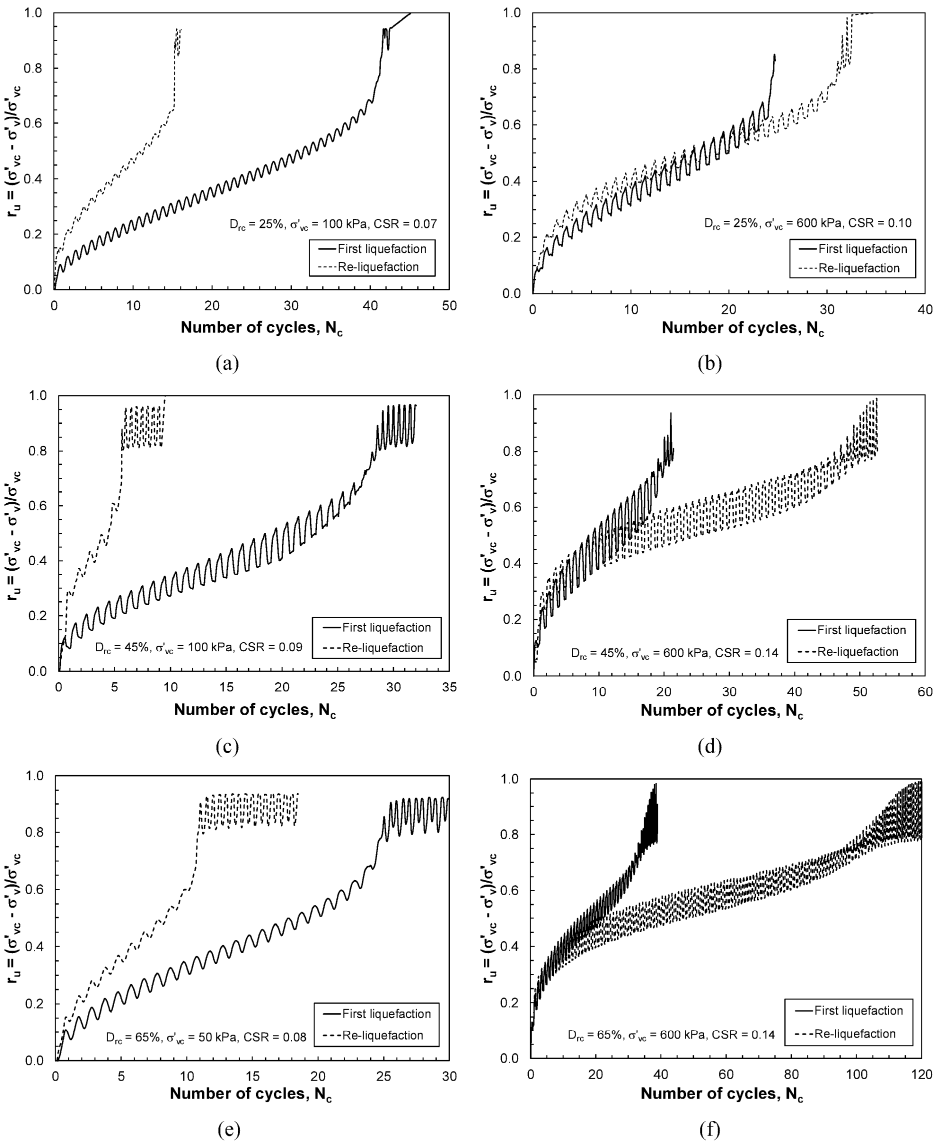

Figure 4. Comparison of r_u accumulation for samples subjected the first and repeated cyclic loading.

Finally note that other mechanisms (e.g., ageing, secondary compression, chemical bonding, cementation, and over-consolidation) would further complicate the effect of multiple earthquake events on a site's liquefaction resistance over geologic time. Such phenomena however were not replicated in the reconstituted specimens of this study. The effect of multiple cyclic loading and liquefaction on re-liquefaction resistance will be investigated in a future research program.

6. Conclusions

The results of this study show that even though liquefied sand deposits may become denser, their resistance to liquefaction will not necessarily improve. In other words, a previously liquefied sand deposit could still re-liquefy by a smaller earthquake in the future. This suggests that relative density alone may not be a reliable measure of the liquefaction potential of a sand deposit. Specifically, liquefaction resistance appears to decrease following a prior liquefaction event at low CSR and in particular for loose sands. Whereas at higher CSR and for dense sands, the re-liquefaction resistance tends to approach and even exceed the virgin liquefaction resistance.

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