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Liquefaction responses of specimens prepared by IPS tested in DSS-C and shaking table

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ABSTRACT: In this study, the liquefaction responses of partially saturated sand samples prepared by Induced Partial Saturation (IPS) technique were investigated on small-size specimens tested in dynamic simple shear test device with confining pressure (DSS-C) and compared to the published findings from large-size specimen tests performed on shaking table. The small-size specimens were prepared at 70–87% degrees of saturation (S). The tests were performed under 50–150 kPa vertical effective stresses (σ'_v) where equal amount of back pressure (u_0) was applied. Shaking table tests were performed by Eseller-Bayat et al. (2013) on large-size specimens with S=60–80% and excess pore water pressures were measured under σ'_v=2–3 kPa. In both experimental setups, shear strain amplitudes (γ) were kept constant at 0.1–0.2%. As a comparison of strain controlled liquefaction tests, excess pore water pressure ratio (r_u) increased with number of cycles (N) and stabilized at a maximum value ($r_{u,max}$) which was less than 1.0 in large-size specimens. However, in small-size specimens, r_u was increasing with increasing N and did not stabilize at a constant $r_{u,max}$ value.

1 INTRODUCTION

During the last decade, liquefaction behavior of partially saturated sands has been studied by many researchers in the literature. Researchers have developed several techniques to reduce the degree of saturation of fully saturated samples such as; Induced Partial Saturation (IPS) technique (Yegian et al., 2007), air injection (Okamura & Teraoka, 2005, Okamura & Soga, 2006, Yasuhara, et al., 2008, Takemura et al., 2009, Okamura et al., 2011, Marasini & Okamura, 2015), micro-bubble injection (Nagao et al., 2007), desaturation using biogas (Rebata-Landa V. & Santamarina J.C., 2012 and He et al., 2013) and denitrification-induced desaturation method (O'Donnell et al., 2017).

In this paper, IPS method was used as a partially saturated specimen preparation technique which aims to mitigate the liquefaction potential of fully saturated sands by generation of oxygen bubbles inside the sand voids. IPS method was used on both small-size (7 cm in diameter and 2.8 cm in height) and large-size (19 x 30 cm in inside plan and 49 cm in height) samples to decrease the degree of saturation of the specimen. Small-size sample tests were performed in VJ Tech brand dynamic simple shear test device with confining pressure (DSS-C) and large-size sample tests were performed in shaking table test setup by Eseller-Bayat et al. (2013).

Firstly, small-size and large-size specimen tests performed in DSS-C and shaking table setup were introduced in Sections 2 and 3. In each section; experimental setups, partially saturated specimen preparation methods and strain-controlled liquefaction test procedures were explained in details. Then, liquefaction test analysis results of small-size and large-size specimens were examined and the effect of vertical effective stresses on the excess pore pressure generation were compared in Section 4. Finally, the discussions and conclusion of the findings were presented in the last section.

2 DYNAMIC SIMPLE SHEAR TEST DEVICE WITH CONFINING PRESSURE (DSS-C)

2.1 *Experimental setup*

Small-size specimen tests were performed in VJ Tech brand dynamic simple shear testing device with confining pressure. The testing system was established in Geotechnical Earthquake Engineering Laboratory of Civil Engineering Faculty at Istanbul Technical University. DSS-C experimental setup composes of main dynamic simple shear apparatus, dynamic servo controller (DSC), hydraulic (back) and pneumatic (cell) pressure controllers, water tank, vacuum machine and air compressor (Figure 1).

In this testing system, the unreinforced latex membrane was used to prepare specimens, as being different from SGI (Swedish Geotechnical Institute) and NGI (Norwegian Geotechnical Institute) type systems. Since, there is not any ring surrounded or no wire reinforced membrane exists around the specimen, the shear failure plane occurs in the diagonal plane of the specimen during dynamic simple shear tests in DSS-C device as explained by Joer et al. (2011). The shear failure mechanisms in DSS-C device were demonstrated by Gulen & Eseller-Bayat (2018) according to the assumptions of place of shear failure planes which occur either in horizontal plane or diagonal plane of the specimen.

2.2 *Specimen preparation method*

Small-size specimens were prepared in a mold with dimensions of 70 mm in diameter and 28 mm in height by using an unconfined latex membrane. Induced Partial Saturation (IPS) technique was used to prepare partially saturated specimens. IPS technique, which was improved by Yegian et al. (2007), aims to decrease the degree of saturation of the specimen by generating air (oxygen gas) bubbles inside the voids of sand samples. This specimen preparation technique enabled generating minute amount of air/gas bubbles in the voids, where the matric suction is minimal for degrees of saturation (S) over 70%.

Oxygen gas was generated as a product of chemical reaction between sodium percarbonate and water. A uniform distribution of air bubbles in the voids was achieved by wet pluviation of dry sand into the sodium percarbonate-water mixture which enabled to prepare loose and partially saturated specimens. The changes in the degree of saturation with different weight ratios (R) of sodium percarbonate to dry sand mixture were presented in Figure 2 (Gulen & Eseller-Bayat, 2017). At the beginning of the specimen preparation procedure, the specimen was prepared at a certain degree of saturation by using different weight ratios of sodium percarbonate-dry sand mixture as shown in Figure 2 to gain an undeformed small-size specimen inside the unconfined latex

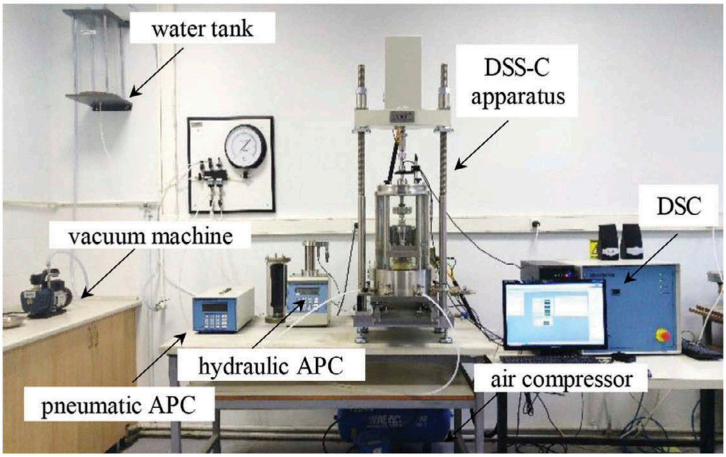

Figure 1. Dynamic simple shear testing device with confining pressure (DSS-C, VJ Tech).

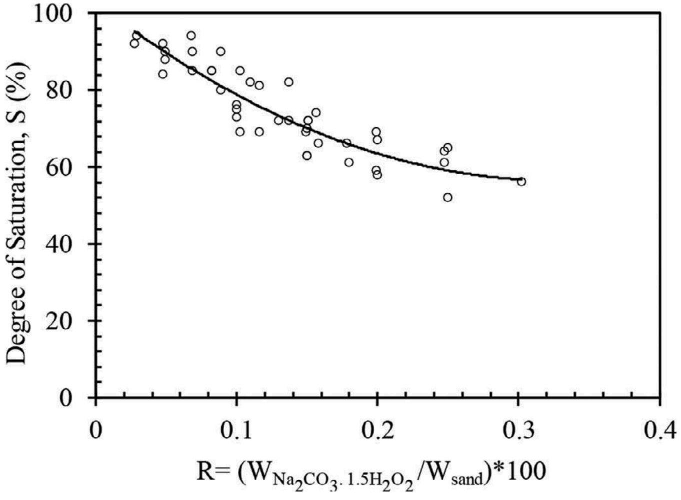

Figure 2. Correlation between degree of saturation and R values (Gulen & Eseller-Bayat, 2017).

(a) (b)

Figure 3. Partially saturated specimen prepared in DSS-C device by wet pluviation of dry sand into the water-chemical powder mixture: (a) the chemical reaction completed (b) the mold removed.

membrane. Then, the final degree of saturation was achieved in a range of 70–87% by applying the back pressure into the specimen during saturation stage as reported by Gulen (2017).

A typical small-size partially saturated specimen prepared in DSS-C device was presented in Figure 3.

2.3 *Testing procedure*

Liquefaction response of partially saturated small-size sand specimens was investigated through undrained dynamic simple shear tests in DSS-C device and Clisp Studio software. The testing procedure consists of saturation, isotropic consolidation and undrained cyclic loading liquefaction stages.

Firstly, saturation test was performed and back pressure was applied into the specimen to reach the target degree of saturation ranging between 70–87%. Secondly, isotropic consolidation tests were performed on partially saturated specimens under 50 kPa, 100 kPa and 150 kPa effective vertical stresses. Since, the change in the back pressure (initial pore water pressure) affected the excess pore pressure generation in the partially saturated sands compared to fully saturated sands (Gulen, 2017) in addition to the effective vertical stresses, same amount of back pressures was applied to the specimens in the consolidation stage. Finally, undrained cyclic liquefaction tests were performed on consolidated partially saturated specimens under strain-controlled conditions.

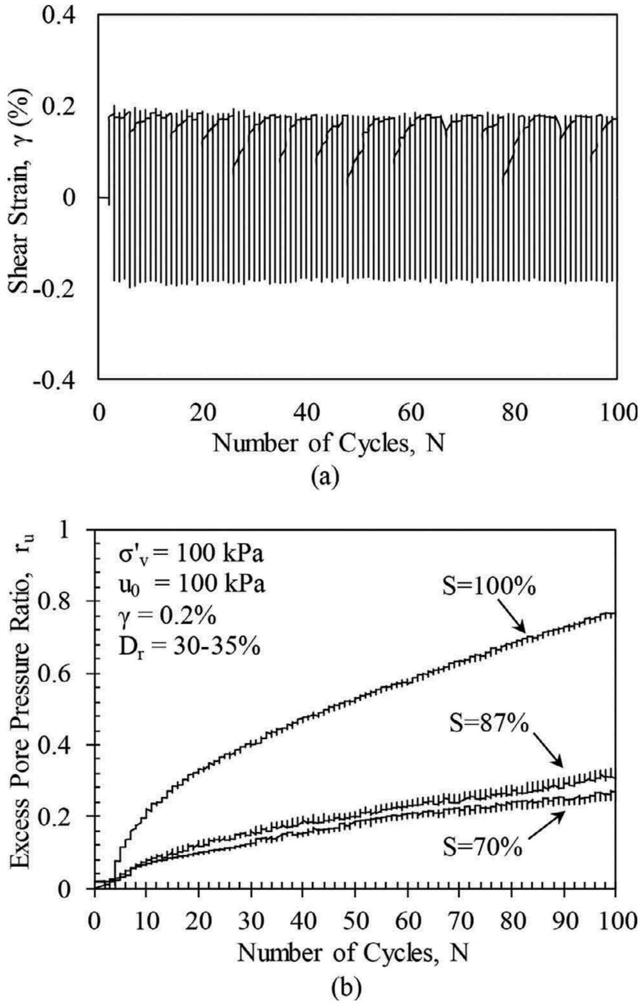

Figure 4. Effect of degree of saturation on excess pore pressure generation in partially saturated specimens at u_0=100 kPa, γ=0.2% and σ'$_v$=100 kPa.

As a result of liquefaction tests, the changes in the excess pore pressure generations in partially saturated samples with different degrees of saturation were presented in Figure 4 where the tests were performed under 100 kPa vertical effective stresses (σ'$_v$) and back pressures (u_0) at 0.2% constant cyclic shear strain amplitude.

It was clear that the excess pore pressure generation decreased with decreasing degree of saturation under the constant vertical effective stress. However, while the number of cycles increased, the excess pore pressure ratio continued to increase.

3 SHAKING TABLE TEST SETUP

3.1 *Experimental setup*

The liquefaction resistance of partially saturated sands in a cyclic simple shear liquefaction box (CSSLB) on the shaking table was studied by Eseller-Bayat et al. (2013). The tests performed on CSSLB experimental setup which had dimensions of 19 x 30 cm in inside plan and 49 cm in height. The side view of the box and the experimental setup were shown in Figure 5 with two fixed and two rotating side walls, which were connected to the bottom plate of CSSLB.

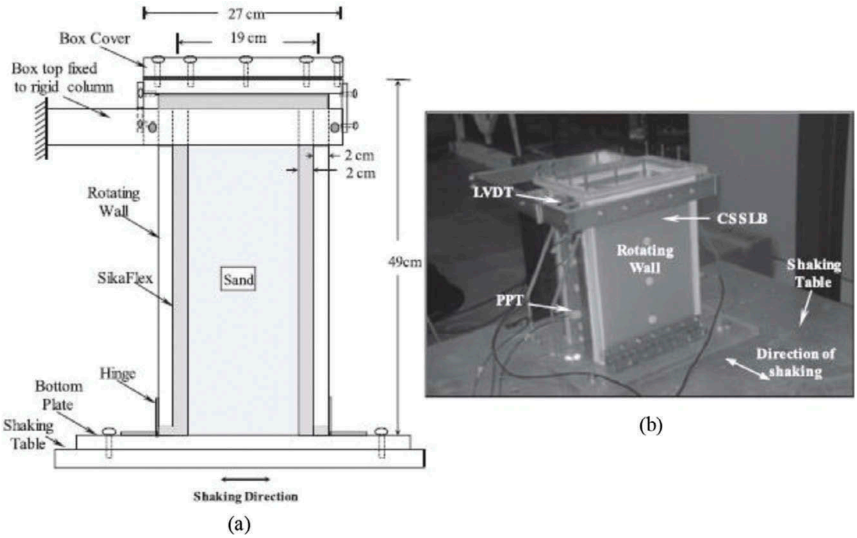

Figure 5. (a) Side view of CSSLB (b) Experimental setup (Eseller-Bayat et al., 2013).

3.2 *Specimen preparation method*

In the shaking table setup, large-size partially saturated specimens were prepared by using sodium perborate monohydrate chemical powder (Efferdent) to generate oxygen gas bubbles inside the voids of the sand specimens. The specimen preparation of partially saturated sands through wet pluviation of Efferdent and sand mixture was demonstrated in Figure 6 (Eseller-Bayat, 2009).

3.3 *Testing procedure*

Eseller-Bayat et al. (2013) investigated the liquefaction response of partially saturated sands in shaking table setup by measuring the excess pore pressure generation at different degrees of saturation. The experiments were performed on partially saturated specimens with S=60–80% and 35–40% relative densities (D_r). Similar to the tests performed in DSS-C, cyclic simple shear tests were conducted under strain-controlled conditions with 0.1–0.2% shear strain amplitudes (γ). However, relatively small amount of vertical effective stresses (σ'_v) such as 2–3 kPa could be applied to the large-size specimens.

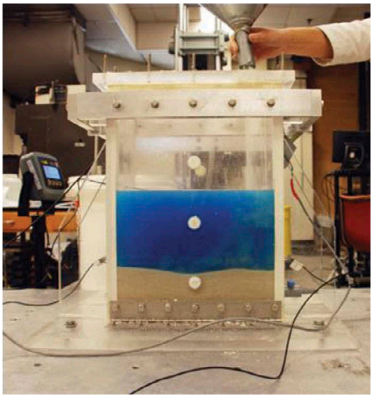

Figure 6. Preparation of partially saturated specimen with powdered Efferdent-dry sand mix (Eseller-Bayat, 2009).

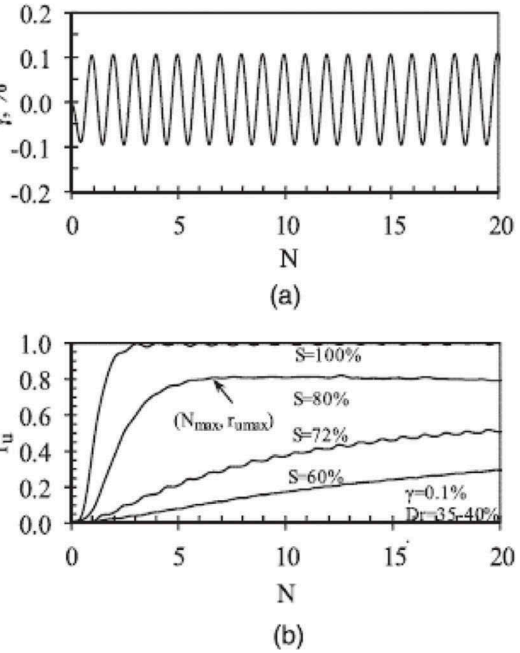

Figure 7. (a) Typical cyclic shear strain record; (b) effect of degree of saturation (S) on excess pore pressure ratio (r_u) (σ'_v=2.5 kPa) (Eseller-Bayat et al., 2013).

As a result of the liquefaction tests, Eseller-Bayat et al. (2013) observed that the maximum excess pore pressure ratio ($r_{u,max}$) did not reach to initial liquefaction criteria (r_u=1.0) with decreasing degrees of saturation in partially saturated large-size specimens. The comparison of excess pore pressure generations at different degrees of saturation were presented in Figure 7.

According to the shaking table tests presented in Figure 7, maximum excess pore pressure ratio ($r_{u,max}$) stabilized under r_u=1.0 level and it decreased with decreasing degrees of saturation.

4 COMPARISON OF THE RESULTS OF LIQUEFACTION TESTS ON SMALL-SIZE AND LARGE SIZE SPECIMENS

The comparison of liquefaction responses of partially saturated small-size and large-size specimens with S=70–75% and D_r=20–36% were presented in this section. Both small-size and large-size specimen tests were performed under strain-controlled conditions at 0.1% and 0.2% strain amplitudes. In contrast to shaking table tests, higher vertical effective stresses were applied in specimens tested in DSS-C device.

The main differences between testing in small-sample and shaking table tests are the boundary effects and stress levels. The boundary effects in CSSLB used for shaking table tests was eliminated by embedding the instruments in the middle of the samples and at a certain height above the base, according to the results of the numerical studies performed in FLAC software program (Eseller-Bayat et al., 2013). The stress effects were discussed in this study.

The excess pore pressure generations in DSS-C and shaking table tests were examined under different effective vertical stress conditions and the results were grouped for 0.1% and 0.2% shear strain levels respectively (Figure 8). It was clearly observed that the excess pore pressure generation in partially saturated samples decreased by increasing vertical effective stresses. In Figure 8 (a), while maximum excess pore pressure ratio ($r_{u,max}$) stabilized at nearly 0.50 in the shaking table test, r_u generation just reached to nearly 0.05 at 20 cycles in DSS-C test. Besides in Figure 8 (b), $r_{u,max}$ stabilized at nearly 0.70 in large-size sample tests, while excess pore pressure ratio nearly reached to 0.2, 0.1 and 0.06 under 50 kPa, 100 kPa and 150 kPa effective vertical stresses, respectively.

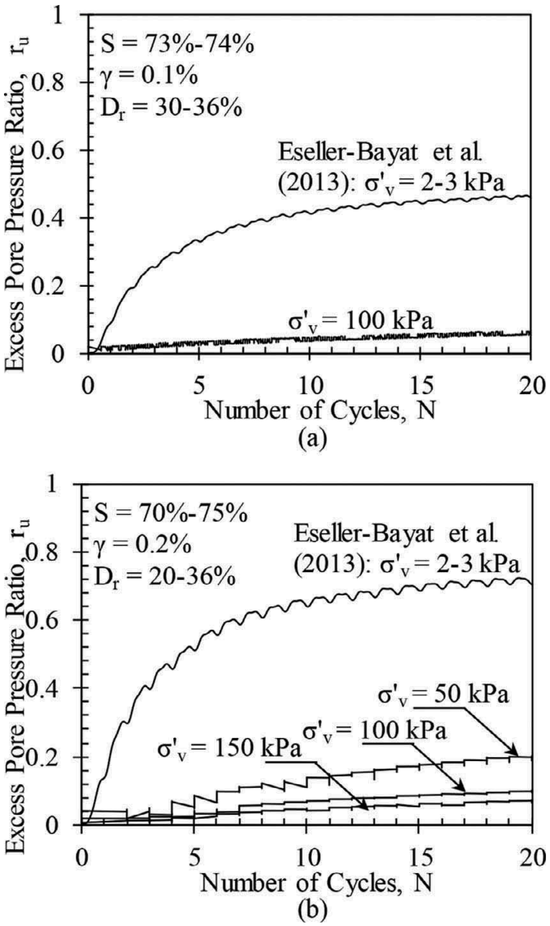

Figure 8. Comparison of liquefaction response of partially saturated sands tested in DSS-C and shaking table setups under different effective vertical stresses (a) γ=0.1% (b) γ=0.2%.

5 DISCUSSION AND CONCLUSION

In this research, undrained dynamic responses of partially saturated sands were investigated by cyclic simple shear tests performed on small-size samples, in VJ Tech brand dynamic simple shear test device with confining pressure (DSS-C). The results were compared with the cyclic simple shear tests performed on large size specimens prepared in a cyclic simple shear liquefaction box (CSSLB) on the shaking table, and published in the literature. Partially saturated specimens were prepared by Induced Partial Saturation (IPS) method which decreases degree of saturation of the sample by generating air/oxygen gas bubbles inside the soil voids. Experiments on small samples were performed at similar degrees of saturation ranging between S=70–87% and similar relative densities ranging between D_r=20–36% as in the large size specimens, however at higher effective stresses, that were 50 kPa, 100 kPa and 150 kPa.

Based on the comparisons of the liquefaction test results on small-size and large-size specimens, vertical effective stress had a great influence on the excess pore pressure generation in partially saturated sands. Excess pore pressure ratio reduced by increasing vertical effective stress. Furthermore, Eseller-Bayat et al. (2013) stated that $r_{u,max}$ stabilized and remained at a maximum value that was less than 1.0 (r_u=1.0) in large-size specimen tests, in small-size specimen tests it was observed that r_u generation continued to increase by increasing number of cycles.

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