Liquefaction Response of Partially Saturated Sands. I: Experimental Results

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Abstract: The liquefaction response of partially saturated loose sands was experimentally investigated to assess the effect of partial saturation on the generation of excess pore water pressures. An experimental setup including a cyclic simple shear liquefaction box was devised and manufactured. The box includes pore pressure and displacement transducers as well as bender elements and bending disks to monitor the response of partially saturated specimens. Uniform partially saturated specimens with controlled density and degree of saturation were prepared by wet pluviation of powdered sodium perborate monohydrate mixed with Ottawa sand. The reaction of the sodium perborate with pore water released minute oxygen bubbles, thus reducing the degree of saturation of the specimens. The uniformity of a specimen was confirmed with S wave velocity measurements and a high-resolution digital camera. The P wave velocity measurements could only confirm the presence of partial saturation but not the degree of saturation. Partially saturated specimens with varying relative densities and degrees of saturation when tested under a range of cyclic shear strains do not achieve initial liquefaction defined by maximum pore pressure ratio ($r_{u,\max}$) being 1.0. For a given degree of saturation and cyclic shear strain amplitude, the larger the relative density, the smaller is $r_{u,\max}$. For a given degree of saturation and relative density, the larger the shear strain amplitude, the larger is $r_{u,\max}$. The excess pore pressure ratio (r_u) can be significantly smaller than $r_{u,\max}$ depending on the number of cycles of shear strain. Tests on the sustainability of partial saturation under upward flow gradient and base excitation led to the conclusion that the specimens remained partially saturated without significant change in the degree of saturation. Based on the experimental test results presented in this paper, an empirical model for the prediction of r_u in partially saturated sands under earthquake excitation is presented in a companion paper. **DOI: 10.1061/(ASCE)GT.1943-5606.0000815.** *© 2013 American Society of Civil Engineers.*

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Introduction

Devastating effects of liquefaction have been widely observed during most moderate- to large-size earthquakes and recently during the 2010 Chile, the 2011 New Zealand, and the 2011 Great East Japan Earthquakes. Liquefaction of fully saturated loose sands results in loss of shearing resistance, leading to dramatic geotechnical slope instability and foundation failures. Loss of shear strength is attributable to a buildup of excess pore pressures during dynamic excitation of loose sands. For many years, research on liquefaction has been focused primarily on understanding the mechanism of liquefaction and its effect on the built environment and on developing liquefaction analysis procedures. Limited research has been conducted to develop cost-effective liquefaction mitigation measures. Current field techniques for mitigation are often expensive, and their applications are limited to sites where there are no existing structures.

There is an urgent need for development of liquefaction mitigation measures that can be readily implemented at new sites as well as underneath existing structures such as buildings, dams, pipelines, and other critical facilities (Earthquake Engineering Research Institute 2002). In recent years, a number of researchers have been exploring liquefaction mitigation techniques that are different from commercially available measures. Haldavnekar et al. (2004) explored the use of a thixotropic fluid to treat a liquefiable soil. DeJong et al. (2006) have been exploring a method that relies on bacteria to form cementation and increase the strength of the soil. Okamura et al. (2006, 2011) have been investigating ways to pump air without hydrofracturing the soil. Similarly, trying to pump air or dissolved air into sands has been tried (U.S. Patent No. 7,192,221). Rebata-Landa and Santamarina (2012), looking at the effect of microbial activity on soil behavior, have suggested biogenic gas generation as a potential liquefaction mitigation measure. Gallagher et al. (2007) and Gallagher and Lin (2009) have explored the use of colloidal silica grouting. The use of electro-osmosis to create a gradient, potentially leading to reduction in excess pore water pressure, has been explored (U.S. Patent No. 7,331,143).

Yegian et al. (2007) proposed a new liquefaction mitigation technique that involves inducing partial saturation (IPS) in sands in

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a manner that creates small-size gas bubbles and, most importantly, does so without disturbing the in situ stress conditions and density of the sand skeleton. The technique is based on injection of a dissolved, eco-friendly chemical, which reacts and generates oxygen gas over time in saturated sand. To further evaluate the feasibility of IPS as a potential field liquefaction mitigation measure, the authors have conducted experimental research on the cyclic behavior of partially saturated sands. This paper presents the experimental test setup and the results of excess pore pressure generation in partially saturated sands. In a companion paper, an empirical model developed for the prediction of excess pore pressures, using the experimental test results in partially saturated sands, is presented (Eseller-Bayat et al. 2013).

Mechanism of Pore Pressure Generation in Partially Saturated Sand

During dynamic loading, in fully or partially saturated loose sands, excess pore pressures are developed because of the momentary prevention of water drainage. It is noted that in this research partial saturation in loose sands is induced by in situ generation of distributed gas bubbles below the water table (Fig. 1), and therefore, hydrostatic pore pressures are positive (no capillarity). In such a condition, under dynamic loading, excess air (Δu_a) and water pressures (Δu_w) will be positive and equal to each other, because the surface tension between air and water is neglected (Fredlund and Rahardjo 1993). Finn et al. (1976) presented a constitutive model that relates excess pore pressure (Δu) for one loading cycle as a function of the volumetric strain increment and soil parameters in fully saturated sands as shown in Eq. (1)

$$\Delta u = \frac{\Delta \varepsilon_{vd}}{\frac{1}{\overline{E}_r} + \frac{n_p}{K_w}} \tag{1}$$

where $\Delta \varepsilon_{vd}$ = net volumetric strain increment; E_r = rebound modulus of soil skeleton characteristic; n_p = porosity of soil; and K_w = bulk modulus of water. In Eq. (1), excess pore pressure (Δu) depends on the bulk modulus of water (K_w), which can be expressed in terms of the compressibility (C_w) of pore water ($C_w = 1/K_w$). In partially saturated sands, the pores contain a mixture of water and gas/air bubbles. In such a condition, the compressibility of the pore fluid (C_{aw}) can be expressed as in the following equation (Fredlund and Rahardjo 1993):

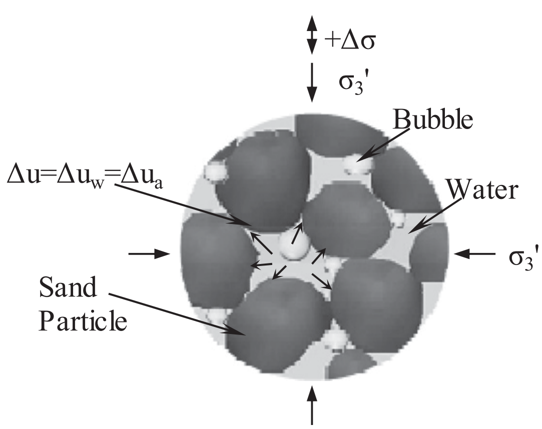


Fig. 1. Partially saturated sand element with distributed gas bubbles, under undrained dynamic loading

$$C_{aw} = SC_w + (1 - S)C_a \tag{2}$$

Eq. (2) implies that the compressibility of the pore fluid depends on the degree of saturation (S) and the compressibility of water (C_w) and gas/air (C_a). The compressibility of gas/air can be expressed as $C_a = 1/u_a$ using Boyle's law (Fredlund and Rahardjo 1993), where u_a is the absolute gas/air pressure. Hence, in partially saturated sands Eq. (1) can be expressed as follows:

$$\Delta u = \frac{\Delta \varepsilon_{vd}}{\frac{1}{\overline{E}_r} + n_p\left[SC_w + \frac{(1-S)}{u_a}\right]} \tag{3}$$

Therefore, the excess pore water pressure generated in each loading cycle in partially saturated sand will be less than that in fully saturated sand depending on the degree of saturation (S) and the initial air pressure (u_a).

A number of researchers have investigated the resistance of partially saturated sands to liquefaction based on experimental test results. Chaney (1978) and Yoshimi et al. (1989) evaluated liquefaction resistance of partially saturated sands in terms of 5% double-amplitude strain. Tsukamoto et al. (2002) and Ishihara and Tsukamoto (2004) investigated the liquefaction resistance of partially saturated sands in terms of stresses. Yang et al. (2004) proposed an empirical correlation between the liquefaction strength of partially saturated sands and P wave velocity. These researchers evaluated the cyclic response of partially saturated sands for a range of S = 90–99.9% and in terms of stresses and double-amplitude strains. It was shown by Dobry et al. (1982) that excess pore pressure generation is more related to cyclic strains induced by an earthquake rather than cyclic stresses.

In this investigation, using cyclic simple shear strain tests, the benefits of induced partial saturation against liquefaction were evaluated in terms of the excess pore pressure ratio $r_u = \Delta u/\sigma'_v$, where Δu is the excess pore pressure and σ'_v is the vertical effective stress. As will be demonstrated through the experimental results, partially saturated sands do not achieve $r_u = 1$, as fully saturated sands do when enough shear strain cycles are applied. Because the goal of this research was to demonstrate the beneficial effect of induced partial saturation on the reduction of excess pore pressures, evaluation of r_u under strain-controlled cyclic simple shear tests was considered most suitable.

Experimental Test Setup

An experimental test setup was devised to conduct cyclic simple shear strain tests on fully and partially saturated sand specimens. The setup included a cyclic simple shear liquefaction box (CSSLB), a one-dimensional (1D) shaking table, a data-acquisition system (*LabVIEW*), and a set of transducers for measuring excess pore pressures, displacements, and shear and compressional wave velocities.

Cyclic Simple Shear Liquefaction Box

In the preliminary research by Yegian et al. (2007), a simple liquefaction box was used for mostly qualitative and comparative measurements of excess pore pressures between fully and partially saturated sands. In this research, a new special liquefaction box (CSSLB) was designed and built in which fully and partially saturated sand specimens can be prepared and tested under cyclic simple shear strains using a shaking table. The box was designed to accommodate a set of transducers, induce uniform shear strains in relatively large sand specimens, and minimize the sidewall boundary effects.

Fig. 2 shows a side-view sketch and a photograph of the CSSLB, which is made of Plexiglas and has inside plan dimensions of 19×30 cm $(7.5 \times 12$ in.) and a height of 49 cm (19.3 in.). The box consists of two side walls that are fixed to a bottom plate and two rotating walls that are hinged also to the bottom plate. The connections between the two rotating walls and both the two fixed walls and the bottom plate are sealed with a flexible joint compound called Sikaflex 15LM. The sealant makes the joints watertight and allows the rotation of the hinged walls through compression and extension of the sealant. Cyclic simple shear strains are induced in the box through the use of a shaking table and a vertical rigid column fixed to the floor of the laboratory. The CSSLB is fixed on the shaking table with the rotating walls oriented in a direction perpendicular to the direction of the table motion. The top of the rotating walls are fixed to the vertical rigid column. Therefore, by moving the CSSLB bottom plate using the shaking table, shear strains are induced in the sand specimens placed in the box. The elastic compression and elongation capacity of the joint sealant between the rotating and fixed walls allows the application of shear strains of up to 1%.

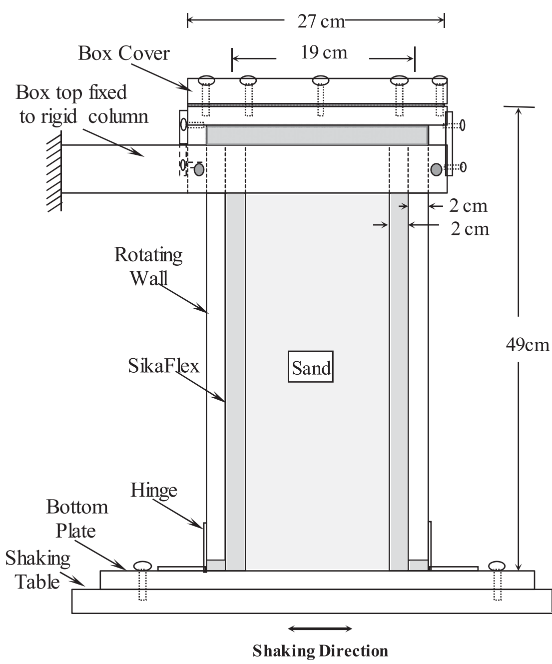
The adequacy of the design of the CSSLB with respect to boundary effects was evaluated numerically using the two-dimensional (2D) explicit finite-difference program *FLAC 5.0* (Ortakci 2007). Plan and elevation sections of a sand model in the designed box were investigated under externally applied shear strains. To simulate the potential slip between the sand particles and the Plexiglas walls of the box, the parameters used in the design were the shear modulus of the sand material, the Plexiglas wall elastic modulus, the shear modulus and Poisson's ratio of the flexible joint sealant, and the cohesion of the interface elements. The results showed that the boundary effects were minimal, and the shear strain distribution is uniform down to 8 cm from the bottom plate, where the sand is restricted from slipping. Therefore, the pore pressure transducers were placed above this elevation.

Pore Pressure and Displacement Transducers

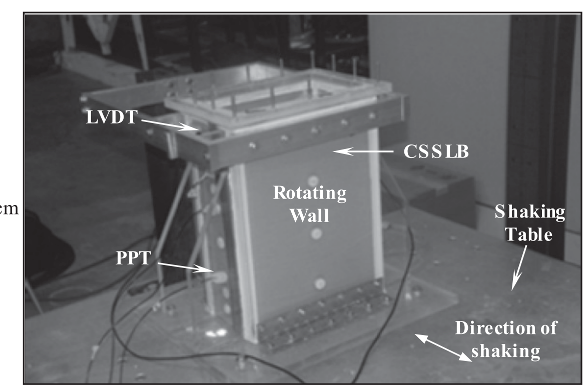
Pore pressure transducers (PPTs; Druck PDCR 81) were inserted into a specimen through special fittings located on the fixed walls of the CSSLB [Fig. 2(b)]. The PPTs were used to measure the hydrostatic as well as the excess pore pressures generated within fully and partially saturated specimens. The cyclic simple shear strain time histories were obtained from the records of two linear variable displacement transducers that measured the relative displacements between the top and bottom of each of the two rotating walls [Fig. 2(b)]. The two records showed identical displacements, thus confirming the box orientation to be perfectly aligned to induce simple shear strains.

Bender Elements and Bending Disks

Multiple bender elements (BEs) and bending disks (BDs) were incorporated in the CSSLB to measure shear wave (S) and compressional wave (P) velocities. The BEs were used to measure the S wave velocities to assess the uniformity of the relative density of a sand specimen prepared in the CSSLB. The BDs were used to measure the P wave velocities as a potential means of determining the degree of saturation of a sand specimen (Fig. 3). The use of BEs and BDs in geotechnical testing has been promoted and reported in the literature by many researchers (Shirley and Hampton 1978; Dyvik and Madshus 1985; Gohl and Finn 1991; Brignoli et al. 1996; Leong et al. 2005; Lee and Santamarina 2006). Most of the researchers used such transducers in small triaxial specimens (10 cm long) and usually made measurements through a single wave path. In this research, because of the relatively large specimen size, eight BEs or eight BDs were used through multiple wave paths to assess the potential variability of the soil parameters within a specimen. The details of the experimental setup, including the equipment used to generate various types of wave signals, the power amplifier, and the digital oscilloscope are described by Deniz (2008) and Eseller-Bayat (2009).



(a)



(b)

Fig. 2. (a) Side view of CSSLB; (b) experimental setup

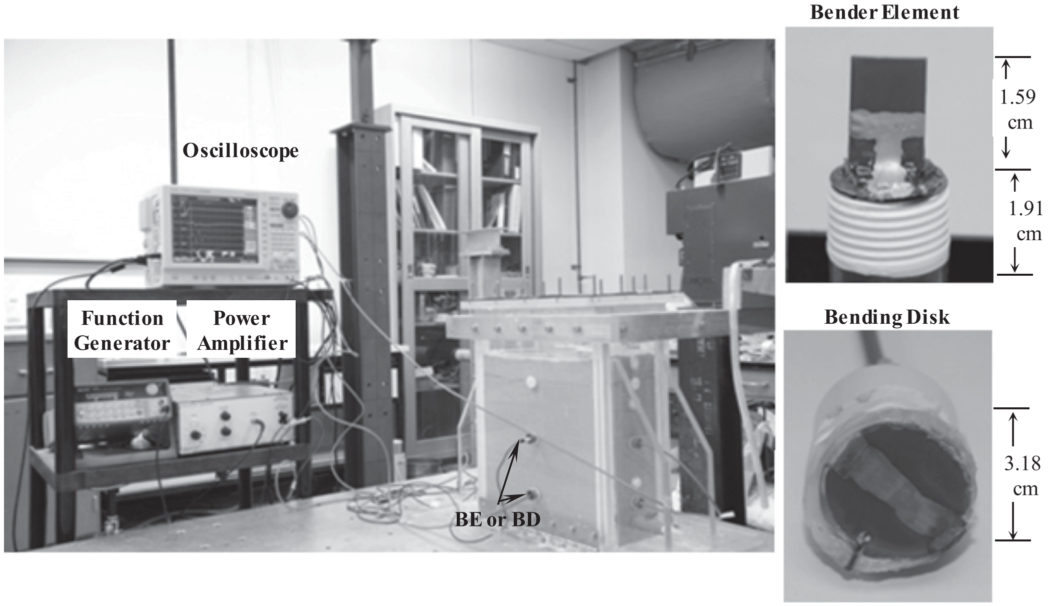


Fig. 3. Details of BE, BD, and measurement setup

Preparation of Uniform Partially Saturated Laboratory Specimens

Two laboratory techniques to prepare partially saturated sand specimens were described by Yegian et al. (2007). The first one utilized the process of electrolysis in which oxygen and hydrogen gases were generated at a cathode and an anode, thus reducing the degree of saturation. It was noted that, although in electrolysis the degree of saturation was controllable by adjusting the current intensity, it was not effective enough to achieve uniform distribution of gas bubbles in the sand specimens. The second technique involved draining the water from the bottom of a specimen and reintroducing it from its top, thus trapping air bubbles within the specimen. This technique was referred to as drainage-recharge and resulted in generally uniform partially saturated specimens; however, the degree of saturation was limited to $S = 82$–86%.

In this research, the chemical compound sodium perborate monohydrate ($NaBO_3{\bullet}H_2O$) was used to generate oxygen bubbles in sand specimens through its reaction with water. It is noted that this compound can be readily found in tablet form under the trade name Efferdent. Sodium perborate monohydrate reacts with water and generates hydrogen peroxide (H_2O_2), which is a ready source of oxygen gas. The chemical reactions are introduced as follows in Eqs. (4) and (5):

$$2(NaBO_3{\bullet}H_2O) + 2H_2O \rightarrow 2H_2O_2 + 2BO_3^{-3} + 2Na^+ + 4H^+ \quad (4)$$

$$2H_2O_2 \rightarrow 2H_2O + O_2 \quad (5)$$

Partially saturated specimens were prepared by a wet pluviation technique in which Efferdent powder mixed with dry Ottawa sand (ASTM Grade C778) was rained into the CSSLB that was partly filled with water. The sand used is uniform in gradation with a coefficient of uniformity (C_u) of 1.1 and D_{10} of 0.67 mm. The maximum and minimum void ratios of the sand are 0.80 and 0.50, respectively. Partial saturation was created while the chemical reacted in the pore water of the specimen, generating minute oxygen bubbles and displacing the pore water to the surface of the specimen. A desired degree of saturation could be achieved in a specimen based on a proportional mixing of Efferdent and dry sand. The details of the specimen preparation can be found in Gokyer (2009).

Average values of the initial bulk soil density, relative density (D_r), and degree of saturation (S) of a specimen were determined by using phase-relation equations with measurements of the amount of water, dry mass of sand, and height of the specimen, which represents the total volume of the specimen. Effective stresses were calculated at a particular depth using the height of sand and the height of water from the point of interest. After each shaking, sufficient time was allowed for excess pore pressures to dissipate as indicated by the transducers. The new bulk soil density and the new relative density were calculated using the new height of the settled specimen. Also, the new degree of saturation was calculated using the new height measurements of the specimen and the amount of water that dissipated to the top of the specimen. Whether the adopted sample preparation technique indeed resulted in a uniform relative density as well as a uniform degree of saturation was investigated. The BE setup of the CSSLB was used to measure S wave velocities along different wave paths (between two rotating walls and two fixed walls) at two elevations within the specimen (Fig. 3). Initial tests were run to demonstrate that shear wave velocity is primarily influenced by the soil skeleton and effective stress and not by the degree of saturation. By doing so, any differences in shear wave velocity measurements through a specimen could then be attributed to differences in the relative density and overburden effective stress. Fig. 4 shows a comparison of BE test results between fully ($S = 100\%$) and partially saturated ($S = 77\%$) sand specimens with similar relative densities of about 20% and under vertical effective stresses of 9.6 kPa. The shear wave velocities in the fully and partially saturated specimens were similar, 69.8 and 66.8 m/s, respectively, thus confirming that S has little effect on the V_s.

The uniformity of the relative density within a partially saturated specimen was then investigated through measurements of V_s along different wave paths and at different depths. Fig. 5 shows typical results of V_s measurements between fixed (45 m/s along the long distance) and rotating walls (41 m/s along the short distance) of the

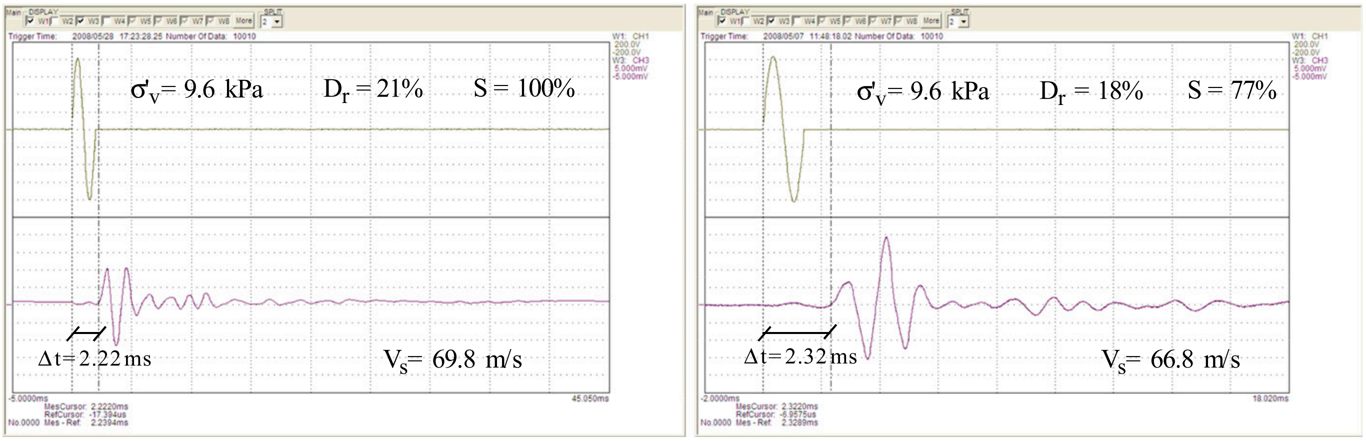


Fig. 4. Velocity measurements for S waves in fully and partially saturated sand specimens

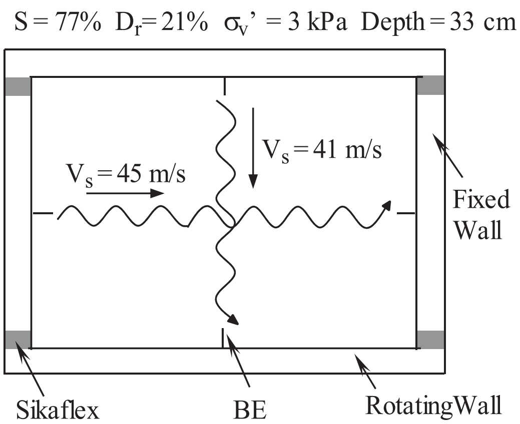


Fig. 5. Velocity measurements for S waves in partially saturated sand specimen along different wave paths

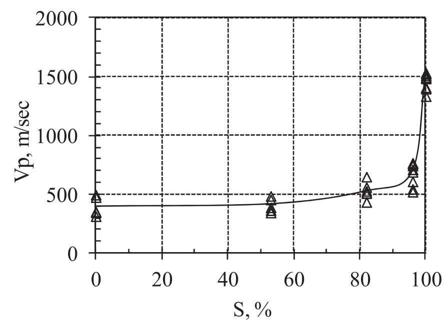


Fig. 6. Velocities for P waves (V_p) versus degree of saturation (S)

CSSLB at a depth of 33 cm (3 kPa). Consistency in the measured shear wave velocities along the two different wave paths at the depth of 33 cm confirms the uniformity of density within that cross section of the specimen. The V_s value measured at a depth of 22 cm (32 m/s along the short distance) was slightly lower than that at a depth of 33 cm (41 m/s along the short distance). This can be attributed to the difference in the effective stresses (2 kPa and 3 kPa). The ratio between the two shear wave velocities can be approximately related to the fourth root of the ratio of effective stresses as suggested by Seed et al. (1986). These and other similar V_s measurements reported by Eseller-Bayat (2009) led to the conclusion that the wet pluviation technique of the powdered Efferdent and dry sand mixture can lead to a reasonably uniform density for partially saturated specimens.

The BD setup in the CSSLB was utilized to determine if measuring P wave velocity (V_p) could be used as an indirect way to find the degree of saturation (S). Ishihara and Tsukamoto (2004) and Yong (2002) have demonstrated that P wave velocities measured in triaxial test specimens reduced dramatically as the degree of saturation was reduced from 100 to 98%. In this research, P wave velocities of sand specimens with similar D_r (20–30%) were measured for a range of the degree of saturation between 100 (fully saturated) and 0% (dry). Fig. 6 shows the test results, which confirm the general observation of Ishihara and Tsukamoto (2004) and Yong (2002) that V_p dramatically decreases when S decreases only slightly from 100 to 96% (from an average of 1,460 to 690 m/s). When S decreases from 96 to 0% (dry sand), V_p only slightly decreases from 690 to 400 m/s. It is evident that P wave velocity measurements can indicate the presence of partial saturation but cannot be used to determine the specific degree of saturation of a specimen nor the uniformity of a partial degree of saturation.

The presence, size, and distribution of oxygen bubbles and hence the uniformity of partial saturation within a sand specimen prepared by wet pluviation of a mixture of dry sand and Efferdent powder were investigated by using a high-resolution digital camera, a microlens with a focal distance of 15 cm, and two light-emitting diode (LED) lights (Gokyer 2009). The digital images were taken from side walls of the sand specimen, and the oxygen bubbles were identified by the reflection of the two LED lights that were pointed at the bubbles. Fig. 7 shows an enlarged digital image of a partially saturated specimen in which a typical oxygen bubble and sand particle are identified. The results of digital imaging led to the finding that generally oxygen bubbles were smaller in size (0.1–0.3 mm in diameter) than the observed void space (0.6 mm in equivalent diameter as observed on the digital image). To evaluate the uniformity of the degree of saturation, 2D digital images were taken on the sides of the specimen. The distribution of oxygen bubbles in various sections of the 2D images was digitally evaluated. With the measurement tools of *Adobe Photoshop Extended*, the degree of saturation in each section was computed by measuring the area of oxygen bubbles and noting the porosity of the specimen. For the example specimen shown in Fig. 7, the degree of saturation computed from the digital image was 77%, which was in agreement with the average degree of saturation of the specimen that was calculated using phase relations (80%). The results from the digital imaging technique confirmed that wet pluviation of a mixture of dry sand and Efferdent powder leads to a reasonably uniform degree of saturation.

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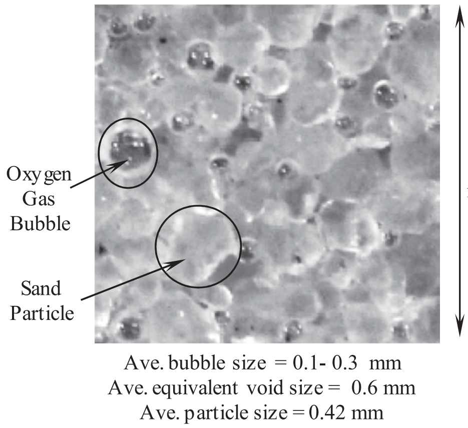

Fig. 7. Partially saturated sand specimen prepared through wet pluviation with Efferdent–dry sand mix ($S = 80\%$ from phase relations, $S = 77\%$ from the digital image)

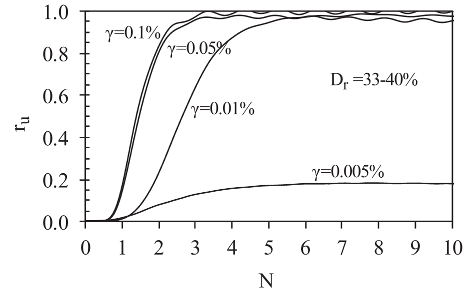

Fig. 8. Excess pore pressure ratio (r_u) in fully saturated sands under different shear strain amplitudes (γ) ($\sigma'_v = 2.5$ kPa)

In summary, shear wave velocity measurements in the CSSLB confirmed that the sample preparation technique leads to uniform density sand specimens. Similarly, 2D digital imaging confirmed the uniformity of the degree of saturation within a specimen prepared by the wet pluviation method. Therefore, the average values of D_r and S computed using phase-relation equations were considered appropriate for use in the interpretation of cyclic simple shear test results from a sand specimen.

Cyclic Simple Shear Strain Tests

As stated earlier, cyclic simple shear strain tests were considered to be the most suitable for the evaluation of the liquefaction response of sands in terms of the excess pore pressure ratio $r_u = \Delta u/\sigma'_v$. Therefore, cyclic simple shear tests were conducted on fully and partially saturated sand specimens to evaluate the effect of partial saturation on cyclic response.

Tests on Fully Saturated Sands

Cyclic simple shear strain tests were performed on fully saturated sand specimens to determine the ranges of relative density (D_r), shear strain amplitude (γ), and frequency of excitation that would lead to initial liquefaction $r_{u,\max} = 1.0$ and allow comparisons between fully and partially saturated test results.

Fully saturated sand specimens were prepared by wet pluviation of dry Ottawa sand, resulting in an initial relative density range of 20–30%. After each run of the cyclic simple shear strain test, the resulting relative density of the specimen was recalculated using the new height of the specimen. Multiple cyclic simple shear strain tests were run on a specimen measuring excess pore pressures for selected shear strain amplitudes and different resulting relative densities. At the start of each subsequent test, pore pressures were ensured to be hydrostatic. To prevent dissipation of excess pore pressures during cyclic testing, a frequency of 10 Hz was used for the applied cyclic shear strain. In denser specimens tested under low-amplitude shear strains, a frequency of 20 Hz was used to minimize the duration of the test and potential dissipation of excess pore pressures during testing.

A total of 19 tests were performed on fully saturated sand specimens at $D_r = 20$–90% and under shear strain amplitudes of 0.005–0.2%. Fig. 8 shows typical test results of the excess pore pressure ratio (r_u) as functions of the amplitude and number of cycles of shear strain. Initial liquefaction was achieved for γ values of 0.01% and higher. Initial liquefaction was not observed for a γ value of 0.005%. This threshold shear strain was in good agreement with values published by Dobry et al. (1982) and Dobry and Abdoun (2011). Also, for a given D_r, the larger the γ, the fewer were the number of cycles required to achieve initial liquefaction. These test results on fully saturated specimens confirmed the adequacy of the test setup, sample preparation, measurements of transducers, and the data acquisition system for use in cyclic simple shear strain testing of partially saturated specimens.

Tests on Partially Saturated Sands

A total of 96 tests were performed on partially saturated specimens prepared by wet pluviation of an Efferdent powder and dry Ottawa sand mixture in the liquefaction box. Different degrees of saturation ($40\% < S < 90\%$) were achieved by varying the mass ratio of Efferdent powder to dry sand. Initial relative densities of partially saturated specimens, obtained by the wet pluviation technique, were in the range of 20–30%. Similar to tests run on fully saturated specimens, multiple shear strain tests on partially saturated specimens were run for selected shear strains, and the resulting relative densities were recalculated with the new height of the specimen after each subsequent test. In these specimens, initial hydrostatic pore pressures were positive, confirming partial saturation without surface tension. It is noted that, because of the lower permeability of partially saturated specimens compared with that of fully saturated ones, a frequency range of 4–10 Hz of the applied cyclic shear strains was adequate to prevent dissipation of excess pore pressures during the tests.

Test results were obtained for $D_r = 20$–67%, $\gamma = 0.01$–0.2%, and $40\% < S < 90\%$. Fig. 9 presents a typical set of excess pore pressure generations in partially saturated specimens as a function of the number of cycles of strain application. For a specimen with a specific degree of saturation, as the number of cycles of shear strain increases, excess pore pressures and hence r_u increase to a maximum value of $r_{u,\max}$. The number of cycles to reach $r_{u,\max}$ is referred to as $N_{\max}$.

The following observations are made from Fig. 9 and other similar test results.

1. While fully saturated specimens achieve initial liquefaction ($r_{u,\max} = 1.0$), partially saturated sand specimens, for $S < 90\%$ based on data from this research and for $S = 96.3\%$ based on data published earlier by the authors (Yegian et al. 2007), do not achieve initial liquefaction ($r_{u,\max} < 1.0$).
2. For a given strain and relative density, $r_{u,\max}$ decreases with reduction in the degree of saturation (S).
3. Larger $N_{\max}$ was observed in specimens with lower degrees of saturation.

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4. Depending on the number of applied cycles of shear strain (N), r_u can be significantly less than $r_{u,\max}$.

In Fig. 10, the entire set of 96 test results are presented of $r_{u,\max}$ as a function of S for different ranges of D_r values obtained in multiple shear strain tests and for γ of 0.01, 0.05, 0.1, and 0.2%. The number of tests that were run for each strain level differed depending on the resulting relative densities obtained after shaking. In the development of the empirical model presented in the companion paper, the exact values of D_r for each strain test were used. The following additional observations can be made from the data. (1) For constant S and γ, the larger the relative density, the smaller is $r_{u,\max}$. (2) For constant S and D_r, the larger the strain amplitude, the larger is $r_{u,\max}$.

In summary, a partial degree of saturation prevents the occurrence of initial liquefaction ($r_{u,\max} = 1.0$) and significantly reduces the excess pore pressure ratio (r_u) depending on the degree of saturation (S), relative density (D_r), shear strain amplitude (γ), and number of cycles (N). In a companion paper, an empirical model for the prediction of the excess pore pressure ratio (r_u) in partially saturated sands is presented, which is based on the experimental test results described in this paper.

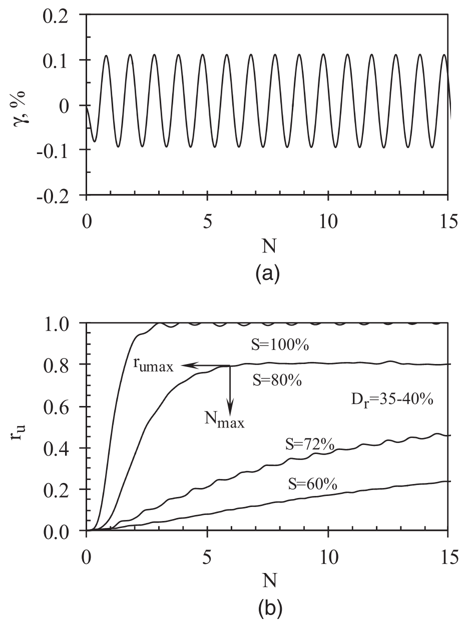

Fig. 9. (a) Typical cyclic simple shear strain history applied on partially saturated sand specimens; (b) comparison of excess pore pressure ratio (r_u) for different degrees of saturation ($\gamma = 0.1\%,\ \sigma'_v = 2.5$ kPa)

Long-Term Sustainability of Partial Saturation in Sands

Partially saturated sands can be encountered in the field naturally or induced as a liquefaction mitigation measure (Yegian et al. 2007). Whether partially saturated sands remain so on a long-term basis under varying groundwater flow conditions, under ground shaking such as during an earthquake, and under pressure changes that may dissolve the gas bubbles was also investigated in this research.

Fig. 11(a) shows one of the test setups in which partially saturated sand specimens were prepared in a Plexiglas tube using the drainage-recharge technique. One of the tests conducted was to monitor the partial degree of saturation under long-term hydrostatic conditions. Fig. 11(b) shows the results for 115 weeks, indicating that the average degree of saturation only slightly increased from 82 to 84% because of the escape of air bubbles from the top 5 cm of the specimen. Additional tests were conducted in a similar Plexiglas tube to monitor the partial degree of saturation under vertical upward hydraulic gradients of $i = 0.01$–0.52 applied at 30-h intervals. The results shown in Fig. 11(c) demonstrate that the degree of saturation is unaffected by the upward flow through the partially saturated specimen. The sustainability of the partial degree of saturation under

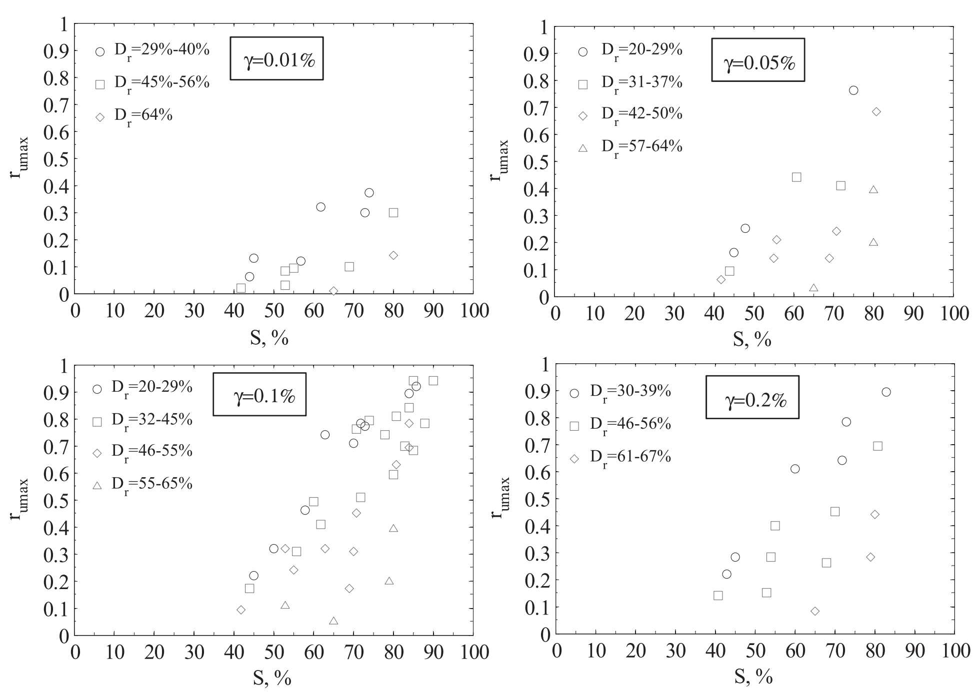

Fig. 10. Maximum excess pore pressure ratios ($r_{u,\max}$) measured in partially saturated sand specimens during cyclic simple shear strain tests

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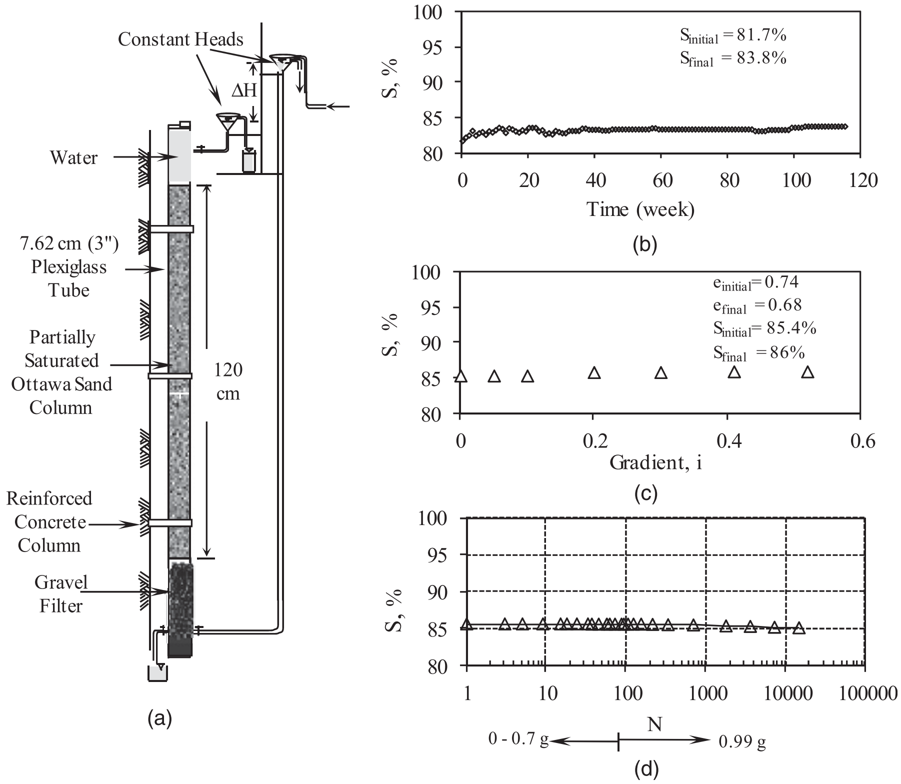

Fig. 11. (a) Experimental setup for testing long-term sustainability of gas bubbles; (b) degree of saturation under hydrostatic conditions; (c) degree of saturation under upward flow gradient; (d) degree of saturation under base excitation

horizontal cyclic base excitation was also investigated by vibrating the bottom of the test tube using a small shaking table. Fig. 11(d) shows that the degree of saturation in a partially saturated specimen did not change under base excitation of up to 1 g for over 10,000 cycles.

Further evidence of long-term sustainability of gas bubbles in sands was presented by Okamura et al. (2006), who showed that gas bubbles introduced in sands during the process of installation of soil compaction piles (SCPs) had remained entrapped 4–26 years after the installation of the piles.

The theory of solubility of the oxygen gas in the pore water as a function of pressure increase was used to evaluate its effect on the degree of saturation. Within a profile of 20 m of saturated soil, an increase of 1 m in water pressure led to a 3% increase for an initial degree of saturation of 80% and a 6% increase for an initial degree of saturation of 50% (Gokyer 2009).

In summary, partially saturated specimens tested under the hydrostatic condition, upward flow gradients, and horizontal cyclic base excitation experienced only slight increase in the degree of saturation (by less than 2%), indicating that a partial degree of saturation in sands can be sustained on a long-term basis as also confirmed by field data of Okamura et al. (2006).

Summary and Conclusions

The cyclic response of partially saturated sands was experimentally investigated to evaluate the benefit of partial saturation on the liquefaction response of sands. An experimental setup was devised and manufactured to perform controlled cyclic simple shear tests on sand specimens with varying degrees of saturation (S), relative densities (D_r), and amplitudes of shear strain (γ). A special liquefaction box (CSSLB) was built in which sand specimens can be prepared and tested under cyclic simple shear strains using a shaking table. The CSSLB includes pore pressure and displacement transducers as well as BEs and BDs to monitor the response of partially saturated sand specimens. Partially saturated specimens with uniform density and degree of saturation were prepared by wet pluviation of the chemical compound sodium perborate monohydrate ground into powder form and mixed with dry Ottawa sand. The reaction of the compound with the pore water released minute oxygen bubbles partially displacing pore water, hence reducing the degree of saturation of a specimen. The uniformity of a specimen was evaluated using BEs measuring S wave velocities, BDs measuring P wave velocities, and a high-resolution digital camera measuring void and bubble sizes as well as observing bubble distribution within the specimen. Cyclic simple shear strain tests were conducted on 19 fully saturated specimens and 96 partially saturated specimens, and excess pore pressures were measured for $S = 40$–90%, $D_r = 20$–90%, and $\gamma = 0.005$–0.2%. Finally, the long-term sustainability of a partial degree of saturation was investigated using a long column of a partially saturated specimen subjected to hydrostatic and upward flow conditions as well as horizontal cyclic base excitation simulating the potential effect of seismic ground motions. Based on the experimental test results presented in this paper, an empirical model for the prediction of the excess pore pressure ratio (r_u) in partially saturated sands was developed and presented in a companion paper. The following observations and conclusions are made from these investigations:

- Sand specimens with controlled and uniform relative densities and degrees of partial saturation can be prepared in a laboratory using wet pluviation of a sodium perborate monohydrate ($NaBO_3 \bullet H_2O$) powder and dry sand mixture. The S wave velocity measurements using BEs can confirm the uniformity of the density. The P wave velocity measurements can only

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confirm the presence of partial saturation but not the degree of saturation. Digital imaging can indicate the distribution of gas bubbles and hence the uniformity of the degree of saturation.

- The liquefaction box (CSSLB) is suitable for the preparation of large partially saturated sand specimens and testing under controlled cyclic simple shear strains.
- Fully saturated specimens achieve initial liquefaction when the maximum excess pore pressure ratio is 1 ($r_{u,\max} = 1.0$). Partially saturated specimens with $S < 90\%$ from this research and with $S = 96.3\%$ from data published earlier by the authors (Yegian et al. 2007) do not achieve initial liquefaction ($r_{u,\max} < 1.0$) regardless of the amplitude and the number of cycles of shear strains. For a given S and γ, the larger the relative density, the smaller is $r_{u,\max}$. For a given S and D_r, the larger the strain amplitude, the larger is $r_{u,\max}$. The excess pore pressure ratio (r_u) can be significantly smaller than $r_{u,\max}$ depending on the number of applied cycles of shear strain.
- Partial saturation in sands can be sustained on a long-term basis even under an upward flow gradient and base excitation.

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References

Brignoli, E. G. M., Gotti, M., and Stokoe, K. H. (1996). "Measurement of shear waves in laboratory specimens by means of piezoelectric transducers." *J. ASTM Geotech. Test.*, 19(4), 384–397.

Chaney, R. (1978). "Saturation effects on the cyclic strength of sands." *Earthq. Eng. and Soil Dynamics*, 1, 342–358.

DeJong, J. T., Fritzges, M. B., and Nusslein, K. (2006). "Microbially induced cementation to control sand response to undrained shear." *J. Geotech. Geoenviron. Eng.*, 132(11), 1381–1392.

Deniz, O. (2008). "Bender elements and bender disks for measurement of shear and compressional wave velocities in large sand specimens." M.S. thesis, Northeastern Univ., Boston.

Dobry, R., and Abdoun, T. (2011). "An investigation into why liquefaction charts work: A necessary step toward integrating the states of art and practice." *Proc., 5th Int. Conf. on Earthquake Geotechnical Engineering*, Chilean Geotech. Soc., Santiago, Chile, 13–45.

Dobry, R., Ladd, R. S., Yokel, F. Y., Chung, R. M., and Powell, D. (1982). *Prediction of pore water pressure buildup and liquefaction of sands during earthquakes by the cyclic strain method*, U.S. Dept. of Commerce, Washington, DC.

Dyvik, R., and Madshus, C. (1985). "Lab measurements of gmax using bender elements." *Proc., Advances in the Art of Testing Soils under Cyclic Conditions*, ASCE, New York, 186–196.

Earthquake Engineering Research Institute. (2002). "Arresting the growth of earthquake vulnerability: Needs and opportunities for earthquake engineering draft plan." Earthquake Engineering Research Institute, El Cerrito, CA.

Eseller-Bayat, E. (2009). "Seismic response and prevention of liquefaction failure of sands partially saturated through introduction of gas bubbles." Ph.D. dissertation, Northeastern Univ., Boston.

Eseller-Bayat, E., Yegian, M. K., Alshawabkeh, A., and Gokyer, S. (2013). "Liquefaction response of partially saturated sands. II: Empirical model." *J. Geotech. Geoenviron. Eng.*, 139(6), 872–879.

Finn, W. D. L., Byrne, P. M., and Martin, G. R. (1976). "Seismic response and liquefaction of sands." *J. Geotech. Engrg. Div.*, 102(8), 841–856.

FLAC 5.0 [Computer software]. Minneapolis, Itasca Consulting Group.

Fredlund, D. G., and Rahardjo, H. (1993). *Soil mechanics for unsaturated soils*, Wiley, New York.

Gallagher, P. M., Conlee, C. T., and Rollins, K. M. (2007). "Full-scale field testing of colloidal silica grouting for mitigation of liquefaction risk." *J. Geotech. Geoenviron. Eng.*, 133(2), 186–196.

Gallagher, P. M., and Lin, Y. Z. (2009). "Colloidal silica transport through liquefiable porous media." *J. Geotech. Geoenviron. Eng.*, 135(11), 1702–1712.

Gohl, W. B., and Finn, W. D. L. (1991). "Use of piezoelectric bender elements in soil dynamics testing." *Recent advances in instrumentation, data acquisition, and testing in soil dynamics*, ASCE, Reston, VA, 118–133.

Gokyer, S. (2009). "Inducing and imaging partial degree of saturation in laboratory sand specimens." M.S. thesis, Northeastern Univ., Boston.

Haldavnekar, V., Bobet, A., Santagata, M., and Drnevich, V. (2004). "Soil treatment with a thixotropic fluid: An auto-adaptive design for liquefaction prevention." *Proc., 11th Int. Conf. on Soil Dynamics & Earthquake Engineering (11th ICSDEE), 3rd Int. Conf. on Earthquake Geotechnical Engineering (3rd ICEGE)*, Vol. 2, Earthquake Engineering Research Center and Pacific Earthquake Engineering Research Center, Berkeley, CA, 553–560.

Ishihara, K., and Tsukamoto, Y. (2004). "Cyclic strength of imperfectly saturated sands and analysis of liquefaction." *Proc. Japan Acad. Ser. B*, 80(8), 372–391.

LabVIEW 7.0 [Computer software]. Austin, TX, National Instruments.

Lee, J. S., and Santamarina, J. C. (2006). "Discussion: 'Measuring shear wave velocity using bender elements' by Leong, E. C., Yeo, S. H., and Rahardjo, H." *J. ASTM Geotech. Test.*, 29(5), 439–441.

Leong, E. C., Yeo, S. H., and Rahardjo, H. (2005). "Measuring shear wave velocity using bender elements." *J. ASTM Geotech. Test.*, 28(5), 488–498.

Okamura, M., Ishihara, M., and Tamura, K. (2006). "Degree of saturation and liquefaction resistances of sand improved with sand compaction pile." *J. Geotech. Geoenviron. Eng.*, 132(2), 258–264.

Okamura, M., et al. (2011). "In-situ desaturation test by air injection and its evaluation through field monitoring and multiphase flow simulation." *J. Geotech. Geoenviron. Eng.*, 137(7), 643–652.

Ortakci, A. E. (2007). "Design and manufacturing of a cyclic simple shear liquefaction box (CSSLB)." M.S. thesis, Northeastern Univ., Boston.

Rebata-Landa, V., and Santamarina, J. C. (2012). "Mechanical effects of biogenic nitrogen gas bubbles in soils." *J. Geotech. Geoenviron. Eng.*, 138(2), 128–137.

Seed, H. B., Wong, R. T., Idriss, I. M., and Tokimatsu, K. (1986), "Moduli and damping factors for dynamic analyses of cohesionless soils." *J. Geotech. Engrg.*, 112(11), 1016–1032.

Shirley, D. J., and Hampton, L. D. (1978). "Shear-wave measurements in laboratory sediments." *J. Acoust. Soc. Am.*, 63(2), 607–613.

Tsukamoto, Y., Ishihara, K., Nakazawa, H., Kamada, K., and Huang, Y. N. (2002). "Resistance of partly saturated sand to liquefaction with reference to longitudinal and shear wave velocities." *Soils Found.*, 42(6), 93–104.

Yang, J., Savidis, S., and Roemer, M. (2004). "Evaluating liquefaction strength of partially saturated sand." *J. Geotech. Geoenviron. Eng.*, 130(9), 975–979.

Yegian, M. K., Eseller-Bayat, E., Alshawabkeh, A., and Ali, S. (2007). "Induced-partial saturation for liquefaction mitigation: Experimental investigation." *J. Geotech. Geoenviron. Eng.*, 133(4), 372–380.

Yong, J. (2002). "Liquefaction resistance of sand in relation to p-wave velocity." *Geotechnique*, 52(4), 295–298.

Yoshimi, Y., Tanaka, K., and Tokimatsu, K. (1989). "Liquefaction resistance of a partially saturated sand." *Soils Found.*, 29(3), 157–162.

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