Induced-Partial Saturation for Liquefaction Mitigation: Experimental Investigation

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Abstract: The technical feasibility of a new liquefaction mitigation technique is investigated by introducing small amounts of gas/air into liquefaction-susceptible soils. To explore this potential beneficial effect, partially saturated sand specimens were prepared and tested under cyclic shear strain controlled tests. A special flexible liquefaction box was designed and manufactured that allowed preparation and testing of large loose sand specimens under applied simple shear. Partial saturation was induced in various specimens by electrolysis and alternatively by drainage-recharge of the pore water. Using a shaking table, cyclic shear strain controlled tests were performed on fully and partially saturated loose sand specimens to determine the effect of partial saturation on the generation of excess pore water pressure. In addition, the use of cross-well radar in detecting partial saturation was explored. Finally, a setup of a deep sand column was prepared and the long-term sustainability of air entrapped in the voids of the sand was investigated. The results show that partial saturation can be achieved by gas generation using electrolysis or by drainage-recharge of the pore water without influencing the void ratio of the specimen. The results from cyclic tests demonstrate that a small reduction in the degree of saturation can prevent the occurrence of initial liquefaction. In all of the partially saturated specimens tested, the maximum excess pore pressure ratios ranged between 0.43 and 0.72. Also, the cross-well radar technique was able to detect changes in the degree of saturation when gases were generated in the specimen. Finally, monitoring the degree of partial saturation in a 151 cm long sand column led to the observation that after 442 days, the original degree of saturation of 82.9% increased only to 83.9%, indicating little tendency of diffusion of the entrapped air out of the specimen. The research reported in this paper demonstrated that induced-partial saturation in sands can prevent liquefaction, and the technique holds promise for use as a liquefaction mitigation measure.

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Introduction

Liquefaction of loose saturated sands has been observed in almost every past moderate to large earthquake, most recently in 1995 Hyogoken Nanbu (Kobe) and in 1999 Adapazari (Turkey). During an earthquake, saturated loose sands can lose shearing resistance, associated with a sudden increase in pore water pressure, often resulting in large lateral spreading, settlement, and foundation and building damage.

Over the past three decades, intensive efforts have been made by the geotechnical research community to understand the mechanism of liquefaction, and to develop methods for evaluating liquefaction potential at a site during a given seismic event. Recent research (Mitchell et al. 1995) has focused on the use of various soil remediation measures to reduce or eliminate liquefaction potential. Such measures include: Improved site condition through densification, enhanced drainage, increased effective stress (hence strength), and change of soil fabric using grout. These remedial measures for protecting structures from liquefaction-induced damages are expensive and often are only applied in projects involving large and important structures. The potential vulnerability of existing structures founded on liquefiable soils continues to be of major concern worldwide. Cost-effective liquefaction mitigation techniques, which can be easily and widely used for new and, more important, for existing structures, are urgently needed.

Research results of many investigators have shown that a small reduction in the degree of saturation of a fully saturated sand can result in a significant increase in shear strength against liquefaction. Martin et al. (1975) explained that a 1% reduction in the degree of saturation of a saturated sand specimen with 40% porosity can lead to 28% reduction in the pore water pressure increase per cycle. According to Yang et al. (2003), a reduction in saturation by 1% led to a reduction in the excess pore pressure ratio from 0.6 to 0.15 under pure horizontal excitation. Chaney (1978) and Yoshimi et al. (1989) have shown that the resistance to liquefaction was about two times that of fully saturated samples when the degree of saturation reduced to 90%. Also, Xia and Hu (1991) demonstrated that minute quantities of entrapped air can significantly increase the liquefaction strength of a sand specimen. Their laboratory data demonstrated that a reduction in the degree of saturation from 100 to 97.8% led to greater than 30% increase in liquefaction strength. Fig. 1 shows their experimental results plotted in terms of normalized cyclic shear stress

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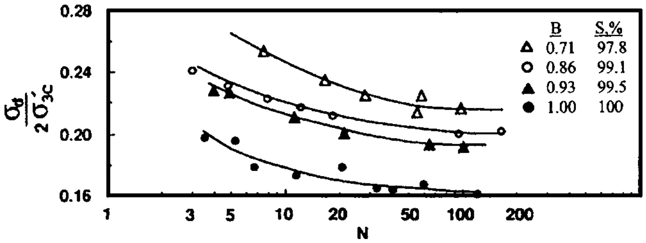

Fig. 1. Effect of degree of saturation on liquefaction strength from laboratory tests (from Xia and Hu 1991, ASCE)

$(\sigma_d/2\sigma'_{3c})$ as a function of the applied number of cycles, N. Ishihara et al. (2002) studied the liquefaction resistance of partially saturated sands. They concluded that the resistance to liquefaction increased with decreasing value of pore pressure parameter B. When the B value dropped to zero with a degree of saturation of $S=90\%$, the cyclic strength became twice as much as that of the fully saturated condition.

It is noted that the primary thrust of the previous researchers, with the exception of Ishihara et al. (2002), was to demonstrate the importance of achieving 100% saturation in laboratory sand specimen to avoid overestimating the strength of the specimen against liquefaction. It is the intent of this paper to demonstrate that the higher strength of partially saturated sands can be potentially exploited to develop a new cost effective liquefaction mitigation measure. The research reported in this paper evaluated the reduction in liquefaction potential as a result of introducing small amounts of gas through electrolysis and air through drainage-recharge of the pore water. The first phase of the research involved the design and fabrication of a liquefaction box made of Plexiglass that permitted the application of cyclic simple shear strains with the use of a shaking table. Then, hydrogen and oxygen gases were generated through electrolysis in the saturated sand specimen and both saturated and partially saturated specimens were tested using the shaking table facility. In the second phase of the research, an alternative method was employed to induce partial saturation by draining the initially saturated specimens and then recharging them slowly from the top. The cyclic tests were then performed on these specimens to again evaluate the potential reduction in the liquefaction-induced excess pore pressure. Finally, the detection of partial saturation using cross-well radar was investigated, and the long-term sustainability of partial saturation was monitored.

Liquefaction Box and Test Setup

A special flexible liquefaction box (Fig. 2) was designed and constructed. A sand specimen in the box was subjected to a simple shear deformation generated by a shaking table excitation at the bottom of the box. The liquefaction box was designed by considering strength, flexibility, and workability, allowing (1) the preparation of a sizable loose saturated sand specimen; (2) the introduction of gas/air into the specimen; (3) the measurement and detection of gas/air using cross-well radar; and (4) the performance of cyclic strain-controlled tests with pore water pressure measurements to evaluate the effect of partial saturation on liquefaction potential.

The liquefaction box provided the ability to subject a soil specimen to controlled shear strains at different frequencies, induced by the shaking table. Fig. 2 shows the dimensions and

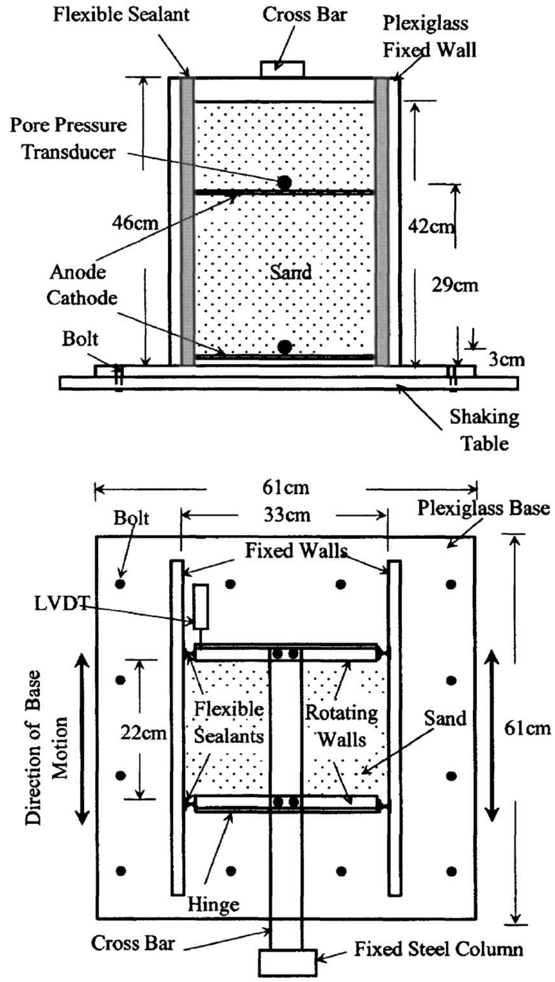

Fig. 2. (a) Liquefaction box and setup for testing of specimens partially saturated through electrolysis; (b) plan view of the liquefaction box

details of the box. The box walls and base are made of Plexiglas material. Two sides of the box are designed to rotate about their bottom edges and the other two sides are fixed to the base of the box, which in turn is fixed on the shaking table. The tops of the two movable sides are joined together at one end of an aluminum cross bar. The other end of the cross bar is fixed to a steel column in front of the shaking table. A special construction joint sealant (Sikaflex-15LM) is used as a flexible watertight joint between the Plexiglas sides. The sealant is a strong adhesive and acts as a flexible membrane allowing large deformations without rupture.

The box is sufficiently large to minimize boundary effects, and to allow the preparation of representative samples as well as the placement of two pore pressure transducers and two electrode plates for performing electrolysis and generating gases in the sand pores.

The sample preparation involved first bolting the entire box on top of the shaking table and then attaching one end of the cross bar to the tops of the two movable sides and the other end bolting to the top of the fixed steel column located off the shaking table. During specimen preparation, two miniature pore pressure transducers (PDCR 81) were inserted, one close to the top and the other close to the bottom of the specimen, as shown in Fig. 2(a). The transducers were small enough ($0.6\ cm^3$) not to affect the behavior of the sand during the cyclic tests. A linear variable

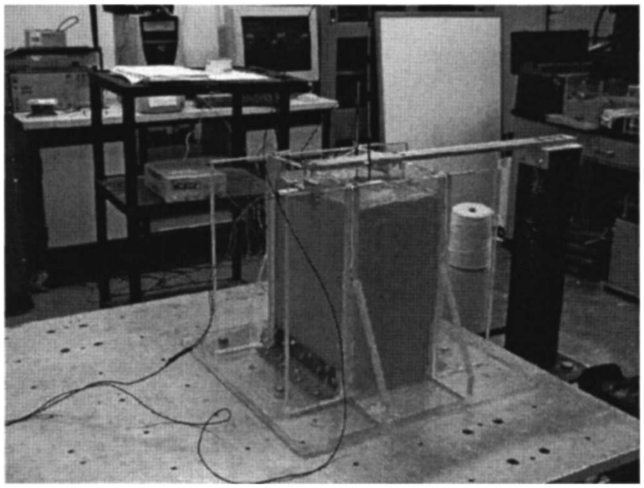

Fig. 3. Typical test setup showing the flexible liquefaction box fixed on the top of the shaking table

displacement transformer (LVDT) was mounted at the top of one of the movable sides to monitor the controlled shear strains induced in the specimens. A specimen was subjected to cyclic shear strains by inducing cyclic displacements at the base of the box through the shaking table. The motion of the fixed-base induced rotation of the two movable walls with their tops fixed by the crossbar. The pore pressure and LVDT responses were measured using a PC-based data acquisition system. Fig. 3 shows a photograph of the shaking table, the flexible liquefaction box, and a typical test setup.

Cyclic Tests on Sand with Gas Generated through Electrolysis

In this phase of the research, electrolysis, which is the ionization of hydrogen and oxygen gases when a current is sent to electrodes in water, is used to entrap gas molecules in saturated specimen. Electrolysis has been used for dewatering fine-grained soils and studied by geotechnical engineers (Casagrande 1949; Esrig 1968). Recently, electrolysis and electroosmosis have been further developed as effective and inexpensive methods for the enhancement of in situ remediation of contaminated soils (Acar and Alshawabkeh 1993). Also, Thevanayagam and Jia (2003) have explored the use of electrokinetics to grout soils for liquefaction mitigation applications.

Electrolysis was selected as an efficient application to induce partial saturation since it introduces gas into the soil pores without application of any pressure. Water electrolysis produces oxygen and hydrogen gases at the anode and cathode, respectively, as follows:

$$\text{At the cathode:} \quad 4H_2O + 4e^- \rightarrow 4OH^- + 2H_2 \qquad (1)$$

$$\text{At the anode:} \quad 2H_2O - 4e^- \rightarrow 4H^+ + O_2 \qquad (2)$$

While the gas quantities produced by electrolysis are not high enough to produce any safety hazard (especially H_2 gas), they are significant enough to change the degree of saturation. Further, electrolysis changes the pore fluid pH (Acar and Alshawabkeh 1993). The experiments showed that this pH change would not cause any significant change in the physics of saturation, pore pressure development, and liquefaction.

Two rectangular meshes (20 cm × 33 cm) made of titanium coated mixed metal oxides (MMO for high electrolysis efficiency and to prevent electrode corrosion) were used as electrodes. The cathode was placed at the bottom of the box, where twice the number of gas molecules (hydrogen) was produced when compared to gas molecules (oxygen) produced at the anode, which was hung at the top, as shown in Fig. 2(a). After saturated specimens were prepared, various tests were performed to determine the level of current and length of time needed to generate an appreciable amount of gases in the sand specimens, as well as to note the effect of gas generation on the density and average degree of saturation (Ali 2003). The process of electrolysis was maintained until hydrogen bubbles were generated at the cathode and migrated through the soil specimen toward the anode. The large sized titanium meshes used as electrodes ensured the generation and vertical migration of gases to be well distributed within the specimen. Visual inspection and probing of specimens partially saturated through electrolysis confirmed that the process indeed reduced the average degree of saturation of the specimens.

For comparison purposes, cyclic tests were performed on fully saturated and partially saturated specimens developed through electrolysis.

Saturated Specimen Preparation

Pluviation is a sample preparation method used to prepare soil samples with different relative densities and gradation. Pluviation can be performed in water (wet pluviation) or in the dry (dry pluviation). According to the study done by Vaid and Negussey (1998), pluviation in water is favored over dry pluviation in that it results in initially fully saturated sand samples and replicate sand samples can be produced more conveniently. Also, research performed by Frost and Yang (2002) in imaging of void distributions in sand during shearing and variation in the initial void distributions due to sample preparation demonstrated that wet pluviated specimen showed a higher number of larger voids than air pluviation and moist tamping. Therefore, fully saturated specimens were prepared by raining dry sand very slowly from a specific height (20 cm distance above the water level) into a predetermined amount of water placed in the liquefaction box. The sand used was Ottawa sand, which is uniform sand with rounded particle shape.

Since saturation could not be controlled by measuring the B value as is typically done in a triaxial cyclic test, the degree of saturation was calculated using phase relationships. The volume of the specimen was obtained by carefully measuring the average height and using a height versus volume chart that was prepared for the box. Knowing the weight of water placed in the box at the start of the sample preparation, the mass of dry sand, and the total volume of the saturated specimen, the volume of solids, volume of voids, the average void ratio, and the average degree of saturation were calculated using phase relations. The void ratio for the loose Ottawa sand specimen was about 0.74. The maximum and the minimum void ratios of the Ottawa sand were measured to be 0.5 and 0.8, respectively. Thus, the relative density of the loose saturated sand specimen was estimated to be 20%. The saturated density of the soil specimen was about 1.96 g/cm^3.

Cyclic Tests on Fully Saturated and Gas-Generated Specimens

For comparison purposes, two cyclic tests on fully saturated specimens and two cyclic tests on partially saturated specimens induced by electrolysis were performed.

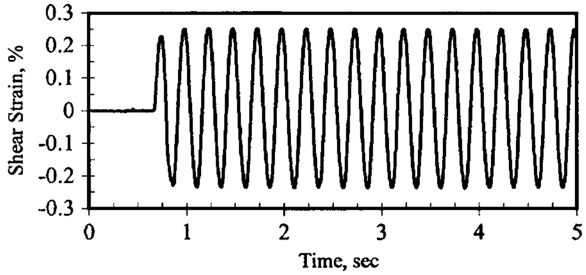

Fig. 4. Cyclic shear strain history induced in the fully and partially saturated sand specimens

Table 1. Effect of Degree of Saturation on Maximum Excess Pore Pressure Ratio, r_u. Partial Saturation Induced through Electrolysis

Sand specimen	Degree of saturation S (%)	Max excess pore pressure ratio, r_u	
		Bottom transducer	Top transducer
Fully saturated (1)	99.4	1.00	0.81
Partially saturated (1)	96.3	0.70	0.53
Fully saturated (2)	99.5	1.05	0.93
Partially saturated (2)	96.3	0.70	0.43

Cyclic Tests on Fully Saturated Specimens

Following the specimen preparation and testing procedures described earlier, two fully saturated sand specimens were prepared for cyclic testing. The degrees of saturation for the two specimens that were prepared using wet pluviation were 99.4 and 99.5% and the void ratio was 0.74 for both specimens.

Constant amplitude sinusoidal shear strains at 4 Hz were applied for about 15 s and pore pressure measurements from the two transducers and displacement measurements from the LVDT were recorded throughout the shaking. A 16 bit data acquisition card was used to obtain the data at a sampling rate of 100 Hz. The first 5 s of the cyclic shear strains induced in the specimen is shown in Fig. 4 This strain history was used in all tests.

Fig. 5 shows the pore pressure build-up in the top and the bottom transducers in one of the fully saturated specimens tested. The initial pore water pressures of the two transducers matched well with the hydrostatic pressures determined by the locations of the bottom and top transducers 41 and 16 cm, respectively. Results from the two specimens were consistent and initial liquefaction occurred within one or two cycles of excitation. The parameter, r_u, defined as the ratio of maximum excess pore water pressure and the initial effective stress, was calculated for both bottom and top transducers. As shown in Table 1, r_u for the two fully saturated specimens was 1.0 and 1.05 from the bottom transducers, indicating initial liquefaction. The maximum excess pore pressure ratios for the top transducer from the two tests were 0.81 and 0.93. The values of r_u slightly less than one for the top transducer, even though both specimens liquefied, are probably because of the free draining surface of the specimen. In addition, possible leakage may have occurred along the top transducer cable that in these two tests were extended vertically out of the specimens. In later tests, the transducer cables were all extended laterally out of the specimens to avoid vertical diffusion of gas/air and water pressure along the cables. However, this reduction of pore pressure in the top transducer did not affect the results of the study because the main purpose of the investigation was to compare the pore pressure responses of saturated and partially saturated specimens.

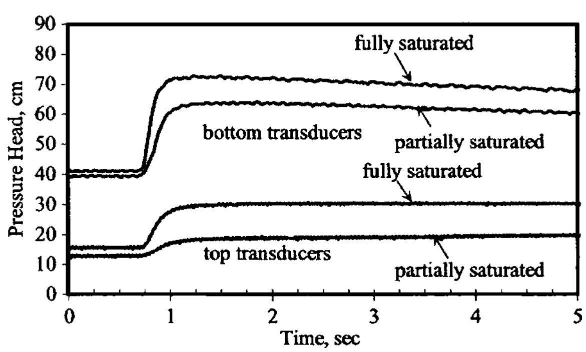

Fig. 5. Comparison of excess pore water pressures generated in fully saturated Ottawa sand specimen, and partially saturated Ottawa sand specimen prepared through electrolysis (S=96.3%) (sample size: 21 cm×33 cm×42 cm)

Cyclic Tests on Partially Saturated Specimens

In this phase of the research, partially saturated sand specimens developed through electrolysis were tested under controlled cyclic shear strains. After setting the box on the shaking table, the cathode and anode meshes were placed within the box. The same instrumentation setup (pore pressure transducers and LVDT locations) used in the fully saturated tests was maintained with slight differences in the locations of the transducers. Fig. 2(a) shows the schematic of the setup for testing the specimens partially saturated through electrolysis. After preparing a fully saturated specimen, hydrogen and oxygen gases were generated in the saturated specimen for $1\,1/2$ h for the first test and for 3 h for the second test, at a current of 525 mA.

As the electrolysis process proceeded, a water layer slowly formed on top of the originally fully saturated specimen and no change in the original volume of the saturated sand was detected. This was clear evidence that while gases were generated in the soil specimen, the gases were indeed trapped in the specimen and forced the water out of the specimen without changing the relative density of the sand. Hence, it was demonstrated that the electrolysis process can generate, at least under laboratory conditions, a controlled amount of gases without changing the void ratio of the specimen. Since the volume of voids did not change, the volume of gas entrapped within the soil was almost equal to the volume of the water layer formed on top of the saturated specimen surface. Based on this, the degree of saturation, the void ratio, and the density of the partially saturated specimen were calculated using phase relations. In both specimens, a degree of saturation of about 96.3% was achieved. The amount of gas produced within the specimen was also calculated by Faraday's law of equivalence of mass and charge, and the equation of state for gases

$$\text{Gas collected, } (n) = \text{moles of } O_2 + \text{moles of } H_2 = \left(\frac{1}{4}\frac{I}{F} + \frac{1}{2}\frac{I}{F}\right)\Delta t \tag{3}$$

$$V=\frac{nRT}{P} \quad (4)$$

where I=current applied (525 mA); Δt=time of current generation (3 h for the second test); and F=Faraday's constant (96,485 C/mol). P=pressure in Pa (1 atm=101,325 Pa at 25°C); V=volume of gas produced; n=number of moles, which is calculated from Eq. (3); R=ideal gas law constant (8.314 Pa m^3/mol); and T=absolute temperature (K). Total amount of gas produced in 3 h was 0.044 mol. The volume of gas produced was calculated as 1,077 cm^3 using Eq. (4), for 100% efficiency and accordingly the degree of saturation would be 92.1%. Since the electrolysis efficiency is usually less than 100% and some of the gas bubbles were able to find a way through the wires and escape to the surface, the actual degree of saturation of the specimen after electrolysis (96.3%) was higher than that calculated by Faraday's law and the equation of state for gases.

Controlled cyclic shear strains were induced in the partially saturated specimens again using the excitation history shown in Fig. 4. The bottom and top pore pressure transducers were monitored during shaking and typical test results for the first 5 s of the excitation are plotted in Fig. 5. The maximum excess pore pressure ratios for the two specimen tests were less than 0.7 for the bottom transducer and less than 0.53 for the top transducer, as shown in Table 1. The slightly smaller pore pressure ratio of the top transducer is again because of the likely drainage occurring during cyclic loading near the free surface of the specimen.

Fig. 5 presents a comparison of the pore pressure generation in the fully and partially saturated specimens. The test results show that a small reduction in the degree of saturation (from 99.5 to 96.3%) led to significant reduction in the excess pore pressure. The maximum excess pore pressure ratios in the fully and partially saturated specimens using electrolysis are compared in Table 1. The results indicate that a reduction in the degree of saturation by about 3% prevented the onset of initial liquefaction.

Cyclic Tests on Sand with Air Entrapped by Drainage-Recharge

In the preceding section, it was demonstrated that electrolysis can induce partial saturation in sands leading to the prevention of liquefaction and reduction in the potential generation of excess pore water pressures. In this section, the results of investigations conducted to assess the beneficial effect of induced partial saturation using an alternative technique herein referred to as drainage-recharge method is presented. In this method, after preparing a fully saturated sand specimen, the pore water was slowly drained from the bottom of the liquefaction box and then the drained water was reintroduced from the top of the specimen at a slow rate. Fig. 6 shows a schematic of the test setup. After reintroducing all the drained water, a significant amount of water remained above the surface of the sand specimen indicating entrapment of air during recharge. The degree of saturation of the specimen was calculated using the volume of the surface water as a measure of the volume of the entrapped air.

During the drainage-recharge tests, the void ratio of the two specimens tested remained at 0.74. The degrees of saturation achieved were 86.2 and 86.5%. Visual evidence through the Plexiglas sides also confirmed the presence of almost uniformly distributed small bubbles of air trapped in the sand specimen. Similar to the gas-generated specimen tests, cyclic strain-controlled tests were performed on both the saturated and air-entrapped specimens to investigate the effectiveness of the drainage-recharge method in reducing the pore pressure build-up during shaking.

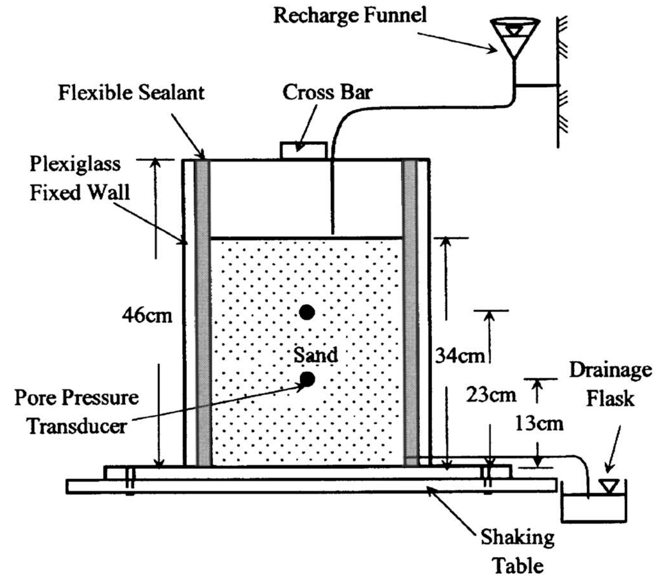

Fig. 6. Test setup for inducing partial saturation using drainage-recharge method. The drawing shows a cross section perpendicular to the direction of shaking.

Cyclic Tests on Fully Saturated and Air-Entrapped Specimens

One cyclic test on a fully saturated specimen and two cyclic tests on air-entrapped specimens were carried out using the shaking table facility.

Cyclic Test on Fully Saturated Specimen

A fully saturated Ottawa sand specimen was prepared in the liquefaction box following the wet pluviation procedure described earlier. The degree of saturation of the specimen was 99.7%.

The specimen was then subjected to the sinusoidal shear strain history shown in Fig. 4. Within one or two cycles, the specimens liquefied, and the maximum excess pore pressure ratios were computed for the bottom and top transducers as 1.0 and 1.04, respectively, as shown in Table 2. The pore pressure response plots for the first 5 s of the excitation are shown in Fig. 7. The results are consistent with the fully saturated specimens described earlier, indicating reproducibility of test results.

Cyclic Tests on Air-Entrapped Specimens

Two partially saturated specimens were prepared using the drainage-recharge procedure resulting with degrees of saturation of 86.2 and 86.5%. Applying the cyclic shear strains shown in Fig. 4, pore pressures in both bottom and top transducers were monitored during the tests.

Fig. 7 shows a typical plot of the measured pore pressures during the cyclic strain application. The maximum excess pore pressure ratios computed from the two specimens tested ranged between 0.63 and 0.72 and are summarized in Table 2. Thus, air-entrapped specimens never liquefied, although significant excess pore pressures nevertheless developed because of the very low relative density of the sand (20%) and the high amplitude of the applied shear strains (0.2%).

Table 2. Effect of Partial Saturation Induced through Drainage-Recharge on Liquefaction-Induced Pore Pressure and Settlement

Sand specimen	Degree of saturation S (%)	Max excess pore pressure ratio, r_u: Bottom transducer	Max excess pore pressure ratio, r_u: Top transducer	Settlement (cm)	Axial strain (%)
Fully saturated	99.7	1.00	1.04	1.71	5.1
Partially saturated (1)	86.2	0.72	0.63	0.82	2.4
Partially saturated (2)	86.5	0.68	0.66	0.65	1.9

In summary, the cyclic test results on the fully and partially saturated specimens, prepared using the drainage-recharge method, are compared in Fig. 7. As shown in Fig. 7, significant reductions in the excess pore pressures were observed in the air-entrapped (partially saturated) specimen compared with the fully saturated test results. The decrease in the degree of saturation from 99.7 to about 86% using the drainage-recharge method reduced the maximum excess pore pressure ratio from 1 to approximately 0.65. Settlements of the fully and partially saturated specimens were recorded after 15 s (60 cycles) of strain application. Table 2 shows a summary of the settlements and axial strains. The results show that the partially saturated specimen compared to fully saturated specimen experienced less than half the axial strain (5.1% for the fully saturated and typically 2.1% for the partially saturated specimens).

The test results demonstrated that the drainage-recharge method can induce partial saturation without change in the void ratio of the sand. Further, the results confirm the earlier conclusion made from the tests on partially saturated sands prepared by electrolysis, that a small reduction in the degree of saturation of a loose sand can prevent liquefaction and reduce the excess pore pressures and settlement of the sand.

Effect of Sand Type

The test results presented earlier were on specimens of Ottawa sand that have round shaped particles and uniform gradation. To confirm the applicability of the results to a natural sand that has more angular shape and a well graded distribution of particles, selected tests were performed on saturated and partially saturated specimens. Fig. 8 shows a comparison of the gradation curves of the Ottawa and the natural sands tested.

The partially saturated specimen of the natural sand was prepared again using the drainage-recharge method. The void ratios of the fully and partially saturated specimens were the same, 0.75. The induced cyclic shear strains were again as in the other tests. Fig. 9 shows a comparison of the excess pore pressures generated in the fully and partially saturated specimens. Again, significant reductions in the excess pore pressures were observed due to induced partial saturation. Whereas the fully saturated specimen under the applied shear strains liquefied, the excess pore pressures in the partially saturated specimen never reached the initial effective stress. The maximum excess pore pressure ratios (r_u) in the partially saturated specimens were less than 0.66, as shown in Table 3. Induced partial saturation in the natural sand also reduced the axial strain from 4.7% for the fully saturated to 1.7% for the partially saturated.

In summary, the tests demonstrated that partial saturation in natural sands can prevent initial liquefaction as was observed in the Ottawa sand specimens. Based on the tests, it appears that the benefits of partial saturation with respect to liquefaction strength and settlement are slightly better when the sand is angular than well graded.

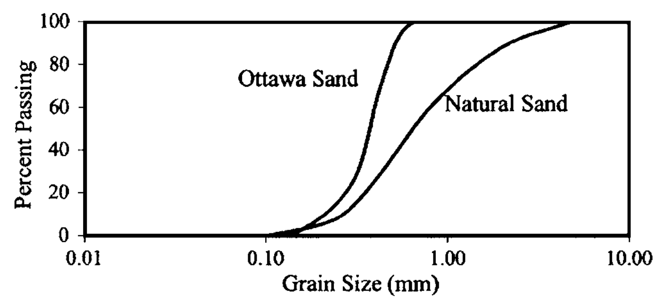

Fig. 8. Gradation curves of the Ottawa and natural sands tested

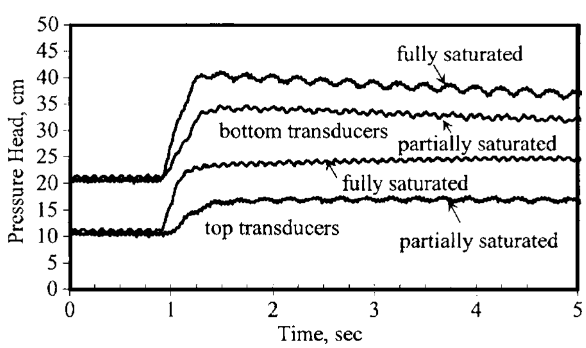

Fig. 7. Effect of entrapped air on the excess pore water pressure generation in the partially saturated Ottawa sand specimen (S=86.2%), prepared by drainage-recharge during shear strain controlled cyclic test (sample size: 21 cm×33 cm×34 cm)

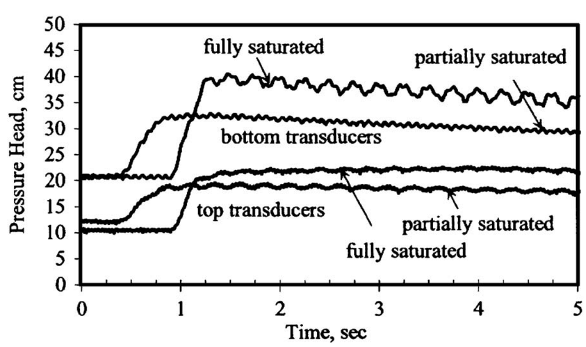

Fig. 9. Effect of entrapped air on the excess pore water pressure generation in the partially saturated natural sand specimen (S=84.2%), prepared by drainage-recharge, during shear strain-controlled cyclic test (sample size: 21 cm×33 cm×34 cm)

Table 3. Results of Cyclic Tests on Fully and Partially Saturated Natural Sand Specimens

Sand specimen	Degree of saturation S (%)	Max excess pore pressure ratio, r_u Bottom transducer	Top transducer	Settlement (cm)	Axial strain (%)
Fully saturated	99.1	0.97	0.98	1.57	4.7
Partially saturated[a]	84.2	0.62	0.66	0.58	1.7

[a]Partial saturation by drainage-recharge.

Gas/Air Detection and Air Diffusion Tests

When partial saturation was induced by both procedures—gas generation and drainage-recharge, free water layer was formed on the soil surface. The free water volume produced on top of the soil surface is estimated to be equal to the gas/air volume generated in the voids. This volume of generated water at the specimen surface was evidence of the gas/air presence within the soil specimen. However a more scientific approach for detection of presence of gas/air bubbles in a sand specimen was explored as a possible field technique. Therefore, the next phase of the research involved the potential use of cross-well radar (CWR) in detecting the presence of entrapped gas/air and its rate of long-term diffusion.

Gas Detection Test by Cross-Well Radar

Radar has been used (Trop et al. 1980; Lange 1983; Knoll and Clement 1999) in determining the water content of saturated soils, and in identifying large subsurface voids. In this research, a preliminary effort was made to determine if the application of a nondestructive test, such as radar, holds promise for the characterization of a three-phase system consisting of sand, water, and gas. Cross-well radar is an electromagnetic (EM) geophysical method for high resolution detection, imaging, and mapping of soils. A typical CWR system has two main components: transmitter and receiver. The transmitter radiates a short EM pulse into the soil, which is refracted, diffracted, and reflected primarily as it meets any contrast in dielectric permittivity and electric conductivity. These contrasts are because of the existence of different materials in the media.

Exploratory tests were performed in the SoilBED Laboratory of the Center for Subsurface Sensing and Imaging Systems (CenSSIS), at Northeastern University using the experimental setup shown in Fig. 10. A partially saturated specimen was prepared using the electrolysis method described earlier. The transmitter and receiver antennas were placed within the middepth of the specimen as shown in Fig. 10.

The degree of saturation in the specimen prior to electrolysis was 99.6%. Initially, transmission measurements were taken for a fully saturated specimen, and the response data were reduced in a vector network analyzer. Transmission measurements are the responses of the media in dB, which is defined as dB $=20\log(A_r/A_t)$, where A_r and A_t=amplitudes of the received and transmitted signals. Measurements were made over a frequency range of 0.4–2.2 GHz.

Fig. 11 shows the transmission measurement data for a fully saturated specimen, which is the response of the background field, i.e., soil and water without gases. Next, gas generation was initiated in the same specimen, and the response data was recorded every half an hour. After 40 h of gas generation through electrolysis, free water of an average depth of 1.47 cm was observed on the soil surface and the degree of saturation of the specimen was calculated as 91.5%. Fig. 11 also shows the transmission measurements obtained from the partially saturated specimen tested after 40 h of electrolysis. Included in Fig. 11 are the measurements on the same specimen 24 h after the gas generation was terminated. The pattern of the variation of each response is gov-

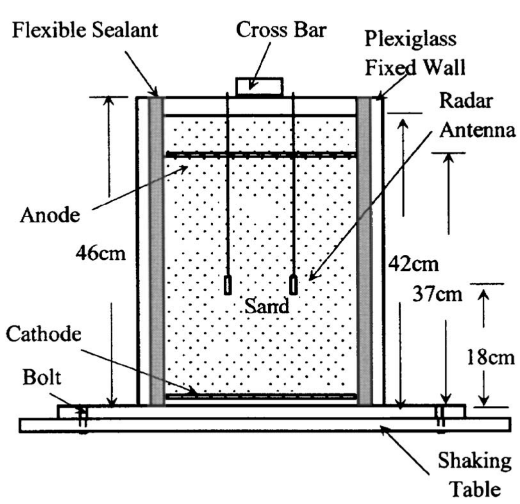

Fig. 10. Experimental test setup for gas/air detection test by cross-well radar

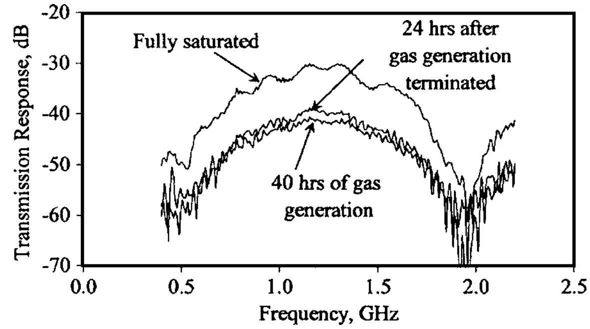

Fig. 11. Comparison of transmission response dB for (1) a fully saturated specimen; (2) a partially saturated specimen prepared through 40 h of electrolysis; and (3) the partially saturated specimen 24 h after termination of gas generation

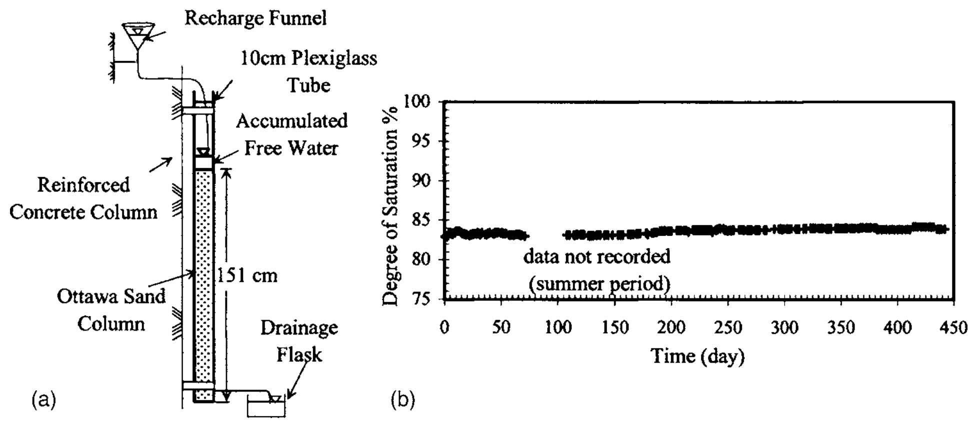

Fig. 12. (a) The test setup used to investigate the long-term sustainability of air bubbles in a partially saturated sand column and (b) long-term monitoring of the degree of saturation

erned by the transmission and reflection characteristics of the antennas, Farid et al. (2006). The resonant frequency of both antennas was 1.1 GHz.

A comparison of the transmission responses shown in Fig. 11 indicates that the received signal intensity changed appreciably as gases were generated in the specimen. Further, 24 h after halting the gas generation, there was little change in the transmission measurements, thus indicating that there was little if any loss of gas shortly after its generation. Even after 1 week, entrapped gases could be seen in the sand through the Plexiglas walls of the box.

The fact that there are differences between the responses of the partially and fully saturated specimens suggests that cross-well radar holds potential promise as a field technique for detection of presence of gas in soils and quantification of degree of saturation. Further research is needed to explore the technical feasibility of using cross-well radar in large sand deposits under field conditions.

Long-Term Air Diffusion Test

The cross-well radar test confirmed the short-term sustainability of induced partial saturation in sands. A further test was conducted to investigate whether or not air bubbles would remain entrapped for a long time or have the tendency to quickly diffuse out of liquefaction susceptible sands. All the earlier tests were performed on samples 34–42 cm deep. In reality, in a deep soil layer the water pressure will be higher and may force the air out of the voids. On the other hand, one can argue that it would be more difficult for the air molecules to find a path and escape through a deep soil layer. To evaluate the potential long-term tendency of diffusion of air from a thick soil layer, the degree of saturation of a 151 cm column of partially saturated sand is being monitored. Fig. 12(a) shows the test setup used. A 184 cm plastic tube with an outer diameter of 10.12 cm (4 in.) was rigidly fixed to a concrete column in the basement of the engineering building to minimize the effect of ambient vibrations. A 151 cm column of loose fully saturated Ottawa sand specimen was prepared in the tube again by the wet pluviation method. The void ratio and the degree of saturation of the specimen were calculated as 0.80 and 96.7%, respectively. Partial saturation was induced in the specimen using the drainage-recharge method.

From daily measurements of the volume of water above the sand, and the sand height, the degree of saturation of the specimen was computed using phase relations. Fig. 12(b) shows the measured data to date. The results indicate that the initial degree of saturation of 82.1% only slightly increased to 83.9%, after 442 days of monitoring. It is noted that this small increase in the degree of saturation was recorded within the first few days after partial saturation was induced. Visual observations showed rearrangement of air bubbles in isolated regions within the specimen until equilibrium was achieved. The long-term monitoring of sustainability of induced partial saturation in a deep (151 cm) sand specimen led to the conclusion that under hydrostatic conditions, small well-distributed air bubbles can remain trapped for a long time.

Summary and Conclusions

Using induced-partial saturation (IPS) in loose sands as a measure for liquefaction mitigation was investigated experimentally. A flexible liquefaction box that permitted the application of cyclic simple shear strains in large loose sand specimens using a shaking table was designed and manufactured. This new box eliminates the limitations associated with the fixed walls that are typical for conventional boxes used for liquefaction or other types of soil-structure tests using a shaking table.

Fully saturated loose sand specimens were prepared in the flexible box using the wet pluviation method. The relative density of the sand was about 20%. Using the process of electrolysis, oxygen and hydrogen gases were uniformly generated in saturated sand specimens, resulting in a degree of saturation of 96.3%. Cyclic shear strains induced in the fully saturated sands yielded maximum excess pore pressure ratios close to unity, indicating initial liquefaction under about 2 cycles of shear strain with a frequency of 4 Hz, and an amplitude of 0.2%. Cyclic tests on sand specimens partially saturated through electrolysis yielded maximum excess pore pressure ratios significantly smaller than unity, thus confirming visual observations that initial liquefaction was never achieved in these specimens. These tests indicate the potential beneficial effect of a small reduction in the degree of saturation in sands on liquefaction potential.

An alternative technique to induce partial saturation, referred to as drainage-recharge method, was also employed, and its effect on liquefaction potential was investigated. In this method, partial saturation was achieved by slowly draining water from a specimen, and then slowly reintroducing the drained water to the specimen from its top. The degree of saturation of the specimens prepared in this manner was about 86%. Cyclic simple shear tests on these specimens resulted in maximum excess pore pressure ratios smaller than unity, again confirming visual observations that the partially saturated specimens did not liquefy, although considerable excess pore pressures were still generated under the large amplitude of shear strains applied (0.2%) to the loose sand with a relative density of about 20%. The axial strains at the end of 60 cycles of excitation in the partially saturated specimens were significantly smaller than in the fully saturated specimens. The results obtained from these tests confirm earlier conclusions arrived at from testing specimens subjected to electrolysis that induced-partial saturation can prevent liquefaction and lead to a reduction in the excess pore water pressures.

The cross-well radar technique was employed to explore its potential applicability in detecting partial saturation in sands. Tests on both fully and partially saturated sand specimens showed that received signal intensity obtained from a partially saturated specimen deviated significantly from the signals obtained from a fully saturated sand specimen. Thus, the cross-well radar technique holds promise as a potential field method for detecting and maybe quantifying degree of saturation of sands.

A 151 cm column of loose sand was prepared to study the potential long-term diffusion of entrapped air. Partial saturation was induced in the sand column using the drainage-recharge method. After 442 days, the degree of saturation of the sand column only slightly increased from about 82.9 to 83.9%.

The experimental results reported in this paper demonstrated that IPS holds promise as a liquefaction mitigation measure. To advance this concept for eventual use in field applications, further research is required on: The behavior of a sand-water-air mixture under varying field conditions and subjected to seismic excitation; long-term diffusion of air under large overburden and small hydraulic gradient; and development of cost-effective field methods for inducing and verifying partial saturation in liquefaction susceptible sands.

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