Preparation and Cyclic Testing of Partially Saturated Sands

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Abstract

A special laboratory experimental setup is described that permits preparation, and testing of large size partially saturated sand specimens. A unique liquefaction box was designed and built that has two of its walls hinged at the bottom of the box thus allowing rotation and inducing simple shear in the sample. A shaking table is utilized with the box to induce controlled shear strains in the sand specimen. Electrolysis technique was used to generate oxygen and hydrogen gases uniformly within the specimen without causing any change in the density of the loose sand. Experimental test results demonstrate that partially saturated sands have larger strength against liquefaction than fully saturated sands. Induced partial saturation can be a liquefaction mitigation measure. Further research is required to explore the technical and practical feasibility of this potential.

Introduction

During the past few years, there has been increased interest in the geotechnical research community to understand the dynamic properties and behavior of partially saturated soils. Partially saturated soils can be found in natural deposits where the ground water table fluctuates significantly or where there is significant capillary action above a water table. The effect of partial saturation on dynamic properties of soils is not very well understood. Recent laboratory investigations have demonstrated the potential influence of partial saturation on the shear and compressive wave velocities of sands (Yang et al. 2003, Ishihara et al. 2002). Also, preliminary research indicates that partially saturated sands exhibit larger cyclic strength against liquefaction than fully saturated sands at the same density (Xia and Hu et al. 1991, Ishihara et al. 2002, Chaney 1978, Yoshimi et al. 1989).

The authors have been conducting experimental research aimed at evaluating the effect of partial saturation on the liquefaction strength of sands. There are significant challenges in preparing laboratory samples of partially saturated sands and in testing them under cyclic conditions. To induce partial saturation, air or gases need to be introduced uniformly within the sample and without affecting the density of the sand. Potential diffusion of the air/gas has to be minimized to ensure that the degree of saturation induced is maintained during sample preparation and testing. The cyclic shear stresses or strains induced in the sample need to be uniform to be able to make valid inferences from the pore pressure measurements made within the sample.

Triaxial setups have been used with some success to test small samples (Xia and Hu et al. 1991). Such a setup allows the calculation of the degree of partial saturation quite accurately using the pore pressure parameter B, and the testing of the sample can be conducted under undrained conditions. However, the small size of the sample used limits ability to create uniformly partially saturated sample, to accurately measure the pore pressures within the sample, and to test under cyclic simple shear condition, which is more representative of seismic excitation.

Large size fixed-walls or laminar boxes have also successfully been used to evaluate the dynamic response of partially saturated sands using a shaking table. Such experimental setups permit the preparation, testing, and monitoring of very large samples with uniform degree of saturation, thus addressing many of the challenges that were listed earlier in conducting experimental research on partially saturated sands. Because of the complexities involved in utilizing large samples in a laminar box on a shaking table, performance of many repeated tests in which the sample density, the degree of saturation, the method of inducing partial saturation and the testing of large number of samples under varying cyclic excitation amplitudes and frequencies, becomes quite a daunting task.

Understanding of the effect of partial saturation on dynamic soil properties and response is at its infancy. Further laboratory investigations need to be conducted to evaluate various techniques of inducing partial saturation and to determine the influence of various parameters on the properties and responses of such sands. For this purpose, the authors have developed a unique experimental setup that permits rapid preparation and testing of partially saturated sands.

This paper describes a special liquefaction box that was designed and built in which a large specimen of partially saturated sand can be prepared using various techniques and then tested under cyclic simple shear strain to assess the liquefaction strength of the sand. The paper also provides details of sample preparation, testing, and example test results.

Rotating-Wall Liquefaction Box

A special liquefaction box was designed to allow preparation and testing of partially saturated sands. Figure 1 shows the plan and elevation of the box. The box has four walls and a bottom plate all made of Plexiglas. The box is large enough to

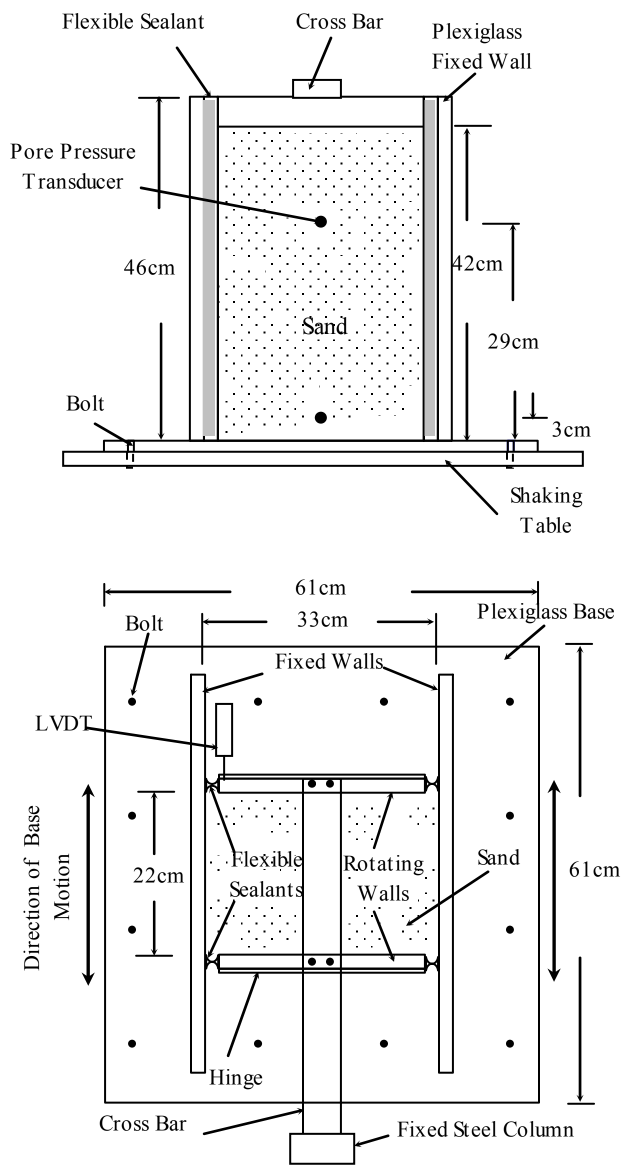

Figure 1. Details of the rotating-wall liquefaction box for testing fully and partially saturated sands.

allow preparation of 22 cm x 33 cm x 42 cm sand specimen. The uniqueness of the box is that two of the sidewalls are hinged to the bottom plate, and through rotation can induce simple shear strain within the sample.

Figure 2 shows a photograph of the empty box showing the hinge of one of the two rotating walls. The two rotating walls are connected to the two fixed walls and the bottom plate by a joint sealant that makes the joints water tight yet flexible allowing movements along the joints.

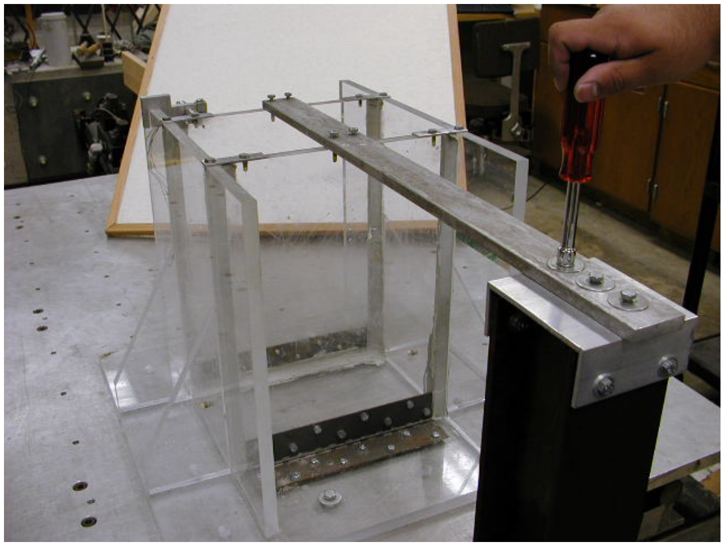

Figure 2. Photograph of the rotating-wall liquefaction box showing a bottom hinge and the cross bar.

The sand specimen in the box is tested under cyclic excitation through the use of a shaking table. Throughout the sample preparation and subsequent testing, the base plate of the box is fixed on the shaking table. Also, the tops of the two rotating walls are connected to one end of a cross bar. The other end of the cross bar is bolted on top of a steel column fixed on the floor of the lab, in front of the shaking table. This mechanism allows the use of the shaking table to induce controlled relative displacements between the tops and bottoms of the rotating walls. Since the box is fixed on top of the table and since the two tops of the rotating walls are also joined together by a stationary cross bar, a displacement history applied to the table induces a relative displacement between the bottom and top of the two rotating walls. A displacement transducer (LVDT) placed near the top of one of the rotating wall monitors this relative displacement. Dividing this relative displacement by the height of the LVDT location from the base of the box yields the simple shear strain history induced by the box within the sand specimen. It is noted that the same mechanism can be utilized to induce any random and transient strain history by exciting the shaking table with that history.

Preparation of Partially Saturated Samples

Another challenge faced in this research was to devise a procedure for preparing a partially saturated sand specimen in the rotating-wall liquefaction box. Ideally, the technique should allow the preparation of specimens with different degrees of saturation and that this degree of saturation be uniform within a specimen.

Various methods were evaluated and their advantages and disadvantages were noted (Eseller 2004). In this paper, one of the techniques for inducing partial saturation that showed good promise for use in laboratory experiments and possibly in field application is briefly presented.

Electrolysis (electrokinetic) is increasingly being used in geotechnical and geoenvironmental engineering for site remediation and dewatering of clays. The process of electrolysis involves the use of an anode and a cathode through which conduction of low amplitude current generates oxygen and hydrogen gases at the anode and cathode, respectively. Preliminary tests were conducted to asses the potential feasibility of electrolysis to generate gases in a large specimen of sand prepared in the liquefaction box. Figure 3 shows the amount of gases generated under 6 mAmp of current in a test tube of 4 cm in diameter and 25 cm in length. It was concluded that within a few hours large quantities of gases can be generated to reduce significantly the degree of saturation of a fully saturated sand specimen prepared in the liquefaction box.

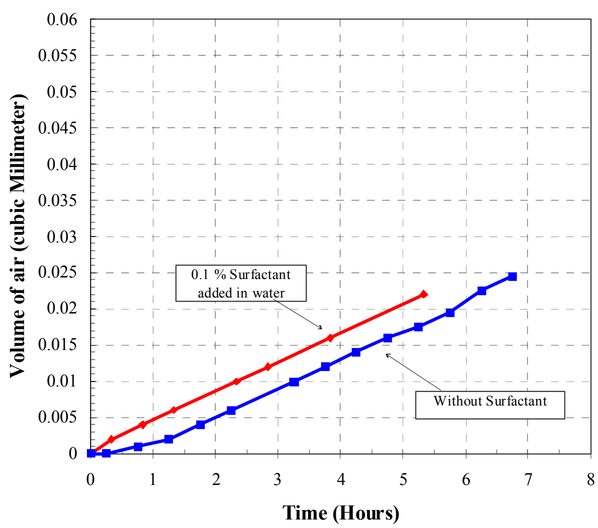

Figure 3. Small-scale test to determine gas generation rate in saturated sands (Ali 2003).

One of the phases of the research program reported in this paper was focused on using electrolysis to induce partial saturation of sand specimens within the box and then testing them under cyclic simple shear strains. Figure 4 shows an elevation of the box with the electrolysis setup.

To avoid oxidization of the electrodes and to ensure uniform generation of gases in a specimen of sand, titanium meshes were purchased and cut to desired sizes as shown in Figure 5.

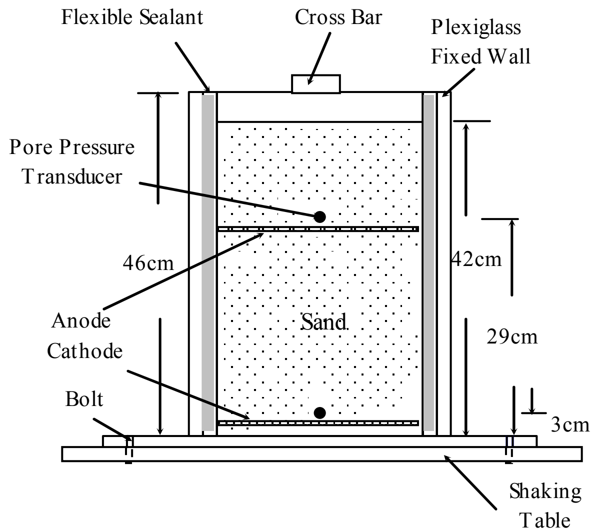

Figure 4. Setup used to induce partial saturation using electrolysis.

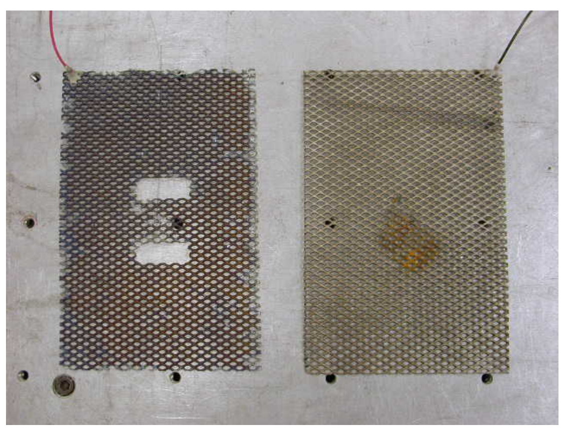

Figure 5. Titanium meshes used as anode and cathode in electrolysis to induce partial saturation.

The two holes in one of the meshes that were used as the anode in the upper region of a specimen were needed to allow insertion of radar antennas that was part of another phase of the research in which radar was used to detect partial saturation. Two pore pressure transducers were attached to each of the meshes and then the two meshes were placed at the desired depths within the box. A measured amount of water was placed in the box. Dry Ottawa sand was then poured slowly and uniformly into the box to achieve a fully saturated sample. This technique referred to as wet pluviation is known to be very well suited for preparation of large fully saturated sand specimens. Figure 6 shows a photograph of the electrolysis setup showing the box full with the sand specimen and the wires extending to the current generator. It is noted that the free standing water on top of the specimen is the outcome of electrolysis where certain volume of gas has replaced equal volume of water in the pores of the sand specimen.

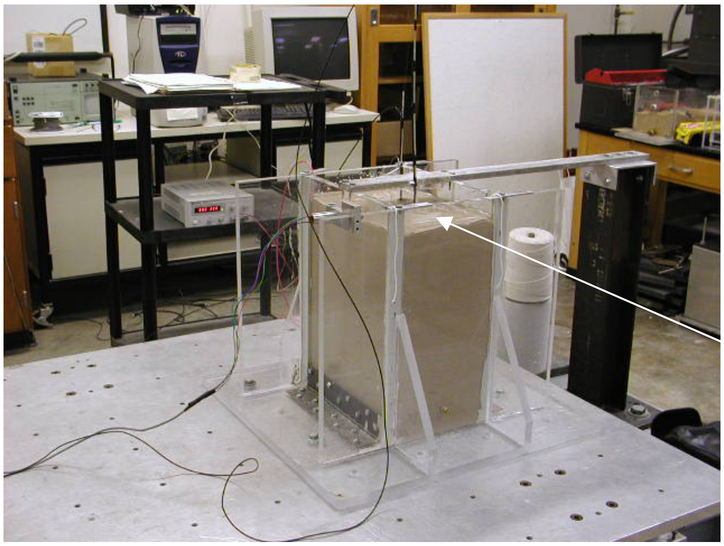

Figure 6. Photograph of the electrolysis setup and an example of partially saturated specimen.

Typically, 525 mAmp current was used for a duration ranging from 1.5 to 3 hrs to achieve desired levels of degree of saturation. During the process of electrolysis, generation of bubbles could be observed within the specimen through the Plexiglas. Further evidence that bubbles were being entrapped could be seen by the accumulation of free water on top of the originally fully sutured specimen. The amount of displaced water was used together with phase relationships to compute the degree of saturation of a specimen at the end of electrolysis. Upon completion of the preparation of the specimen, it was immediately tested under controlled cyclic shear strain. It is noted that throughout the entire sample preparation, the liquefaction box was fixed on the 1.5 m x 2 m stable shaking table, and the two rotating walls were also rigidly connected to an external fixed column. Thus, during the sample preparation, the box experienced no external disturbances or vibrations ensuring that the density of the prepared specimen stayed constant and all initial pore water pressures were hydrostatic.

Example Test Results

The experimental research program included testing of many different fully and partially saturated sand specimens. Different types of sands were also utilized to assess the effect of particle angularity of the sands on the induced degree of saturation and liquefaction strength. One of the sand used was the commonly referred Ottawa sand, which has a uniform gradation and has known minimum and maximum densities and porosity. In this paper typical result on the Ottawa sand are presented. Table 1 shows the index properties of the Ottawa sand used.

Table 1. Characteristics of the Ottawa sand used in this investigation. (Holtz and Kovacs 1981, modified after Hough, 1969)

<table>
<tr><td colspan="4">Particle Size and Gradation</td><td colspan="4">Voids</td></tr>
<tr><td colspan="2">Approx. Size Range (mm)</td><td rowspan="2">Approx. D_{10} (mm)</td><td rowspan="2">Approx. Range C_u</td><td colspan="2">Void Ratio</td><td colspan="2">Porosity (%)</td></tr>
<tr><td>D_{max}</td><td>D_{min}</td><td>e_{max}</td><td>e_{min}</td><td>n_{max}</td><td>n_{min}</td></tr>
<tr><td>0.84</td><td>0.59</td><td>0.67</td><td>1.1</td><td>0.80</td><td>0.50</td><td>44</td><td>33</td></tr>
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<table>
<tr><td colspan="6">Density (Mg/m^3)</td></tr>
<tr><td colspan="2">Dry Density, ρ_d</td><td colspan="2">Wet Density, ρ</td><td colspan="2">Submerged Density, ρ'</td></tr>
<tr><td>Min (Loose)</td><td>Max (Dense)</td><td>Min (Loose)</td><td>Max (Dense)</td><td>Min (Loose)</td><td>Max (Dense)</td></tr>
<tr><td>1.49</td><td>1.78</td><td>1.51</td><td>2.12</td><td>0.93</td><td>1.12</td></tr>
</table>

To evaluate the effect of partial saturation on liquefaction potential and pore pressure generation in sands, fully saturated and partially saturated sands were tested. A specimen of fully saturated sand was prepared using the pluviation method mentioned earlier. The resulting void ratio of the sample was 0.74. Comparison of this void ratio with the minimum and maximum values shown in Table 1 leads to the conclusion that the fully saturated sand had a relative density of about 20 %. The degree of saturation of the specimen was calculated to be 99.5 % using phase relationships and measured quantities of mass and volume.

The fully saturated Ottawa sand specimen was then subjected to a controlled level of harmonic shear strain with amplitude of 0.25 %, using the shaking table. Figure 7 shows the shear strain history that the fully saturated specimen was subjected to. The pore water pressures at the two locations shown in Figure 4 were monitored continuously during the test. The results are shown in Figure 8.

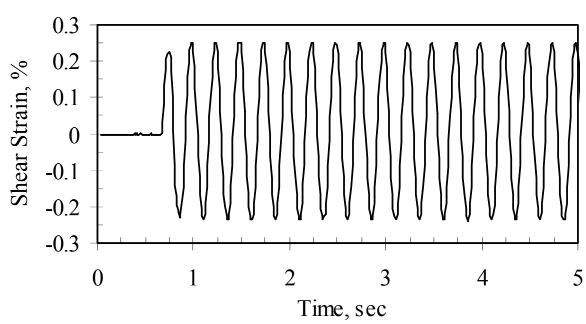

Figure 7. Harmonic simple shear strain history applied to the Ottawa sand specimens tested.

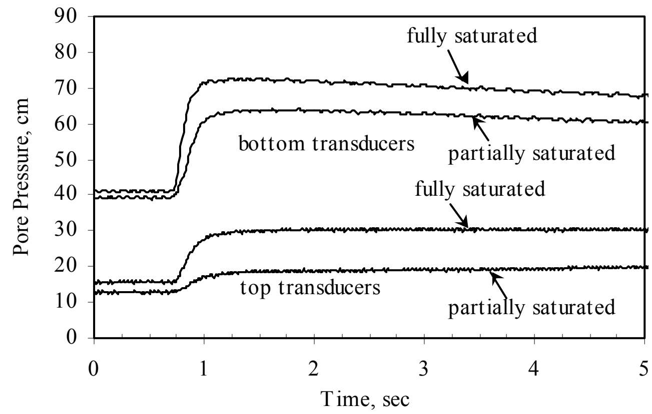

Figure 8. Pore water pressures measured during cyclic shear strain tests in fully and partially saturated sands.

From the results shown in Figure 8 it is noted that initial liquefaction was induced in the fully saturated sand within one to two cycles of application of shear strain. Bottom and top transducers both show that the sand within the entire specimen liquefied. The maximum excess pore pressure ratio, r_u at the time of initial liquefaction was calculated to be 1 from the bottom transducer and 0.93 from the top transducer, thus confirming the visual observation of manifestation of liquefaction at the time of the testing.

A second sample of Ottawa sand was prepared using the same quantities of mass of water and sand and total volume of specimen that were used in the preparation of the fully saturated sand, but this time the titanium meshes were placed in the box for electrolysis. After placing the sand through wet pluviation and accounting for the volume of the meshes in the specimen, the void ratio of the sample was calculated to be the same as that of the fully saturated specimen (0.74).

A current of 525 mAmp for 3 hours was used to generate gases in the specimen, thus inducing partial saturation. During the electrolysis, as a result of gases generated and entrapped in the specimen, a water layer accumulated on top of the originally saturated specimen. The resulting degree of saturation of the specimen after three hours of electrolysis was 96.3 %.

The partially saturated specimen was then subjected to the same shear strain history that was used to test the fully saturated sand (Figure 7). The resulting pore pressures measured again at the bottom and near the top of the specimen are shown in Figure 8. Clearly, the partially saturated sand did not achieve initial liquefaction. The maximum excess pore pressure ratio did not exceed 0.7 at the bottom of the specimen and 0.43 at the top.

This typical test result from the experimental research demonstrates that there is potential benefit in inducing partial saturation in a loose sand. A small amount of entrapped air or gases can minimize the generation of excess pore water pressures in liquefaction susceptible sand and may even prevent liquefaction.

Conclusion

An experimental setup was designed, built, and used to induce partial saturation in loose sands, and to test the specimens under strain controlled excitations. A special Plexiglas box was built that has two rotating walls that induce simple shear strains in a large specimen of sand. Flexible sealant connects the rotating walls of the box with the fixed walls, which makes the joints water tight and allows movements between the rotating and fixed walls of the box.

After preparing a fully saturated sand specimen in the box, partial saturation is induced using the process of electrolysis. Titanium meshes are used in the box acting as anode and cathode and current is passed through the system generating oxygen and hydrogen bubbles in the specimen. The experimental results lead to the conclusion that uniform degree of partial saturation can be induced in large specimen of sand in the laboratory using electrolysis.

Fully and partially saturated Ottawa sand specimens were tested using a unique setup that utilizes shaking table and induces uniform shear strains in the specimen. The experimental results demonstrate that small reduction in the degree of a fully saturated specimen can lead to significant reduction in excess pore pressures generated in loose liquefaction susceptible sand. Induced partial saturation can be a potential inexpensive liquefaction mitigation measure at sites where using conventional mitigation techniques are prohibitive. Further research is required to explore the technical and practical feasibility of this concept.

Acknowledgments

This research was funded by the National Science Foundation through the Small Grant Exploratory Research (SGER) program, under grant No. CMS-0234365. The support of NSF and Program Director Dr. Clifford Astill is greatly appreciated. The authors thank Laboratory Director at Northeastern David Whelpley for his help in the manufacture of the liquefaction box and former graduate student Syed Ali for his contributions in the experimental setup and cyclic tests.

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