A NEW MITIGATION TECHNIQUE FOR PREVENTING LIQUEFACTION-INDUCED BUILDING DAMAGES DURING EARTHQUAKES

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ABSTRACT

The research presented in this paper introduces a new liquefaction mitigation measure, "Induced Partial Saturation (IPS)", which will be a cost-effective and practical solution for new as well as existing structures. The liquefaction mitigation measure that is being explored improves earthquake resistance of loose sands by introducing some amount of air/gas in the voids of the sand. This research explores two different methods to introduce air/gas in the fully saturated sands. These methods include; generation of hydrogen and oxygen gases in the sand through electrolysis and air entrapment in the voids by draining and reintroducing water in the fully saturated sand. Uniform cyclic simple shear tests performed, using a shaking table, on air/gas entrapped specimens demonstrated that air/gas entrapment reduces the pore pressure build-up significantly, thus preventing initial liquefaction. Also, the tests performed on air entrapped specimens under vertical upward/downward and lateral flow regimes showed that air/gas bubbles remain entrapped in the sand. The research reported in this paper demonstrated that induced-partial saturation (IPS) in sands can prevent liquefaction and the technique holds promise for use as a liquefaction mitigation measure. Based on the observations and the results from the study being presented here, further research focuses on the development of a methodology for predicting liquefaction strength of the partially saturated sand specimens, to be applicable in practice, and on exploring the field application techniques.

Keywords: Liquefaction; Partial Saturation; Electrolysis; Drainage; Shake Table Tests; Liquefaction Mitigation; Air entrapment.

INTRODUCTION

Liquefaction-induced damages have been observed in every moderate to large earthquakes, most recently in August 17 1999 Adapazari and November 12 1999 Duzce Earthquakes in Turkey. Liquefaction is the loss of shear strength in fully saturated loose sands due to excess pore water pressure build-up during a repeated loading or dynamic excitation, such as an earthquake. Intensive efforts have been made to understand the mechanism of liquefaction, and to develop procedures for analyzing the liquefaction potential at a site during a given seismic event. While research on liquefaction continues, the geotechnical engineering practice has developed various techniques for site improvement that can mitigate the potential effects of liquefaction. Existing mitigation measures are expensive and often are applicable only for a new project. Mitigating the liquefaction-induced damages to an existing structure in an urban community and/or to special structures remains to be a major challenge.

Fig. 1 Bearing capacity failure of a building after Izmit EQ, 1999

This research introduces a promising cost-effective liquefaction mitigation technique which can be applicable for new as well as existing structures. This new technique prevents the liquefaction by inducing some amount

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of air/gas in the voids of the fully saturated sand. This study shows the experimental evaluation of the reduction in liquefaction potential as a result of air/gas entrapment.

The paper presents the two methods which were developed to introduce air/gas in the saturated specimens prepared in the laboratory; the first one is gas generation by electrolysis and the second is air entrapment by draining the water in the initially saturated specimen and reintroducing it from its surface (so-called drainage-recharge, D-R). Then, a special liquefaction box which can be used in the shaking table facility to perform cyclic simple shear strain tests is introduced. Furthermore, the cyclic simple shear tests applied on fully and partially saturated specimens and their results are provided. Finally, the study of the endurance of air/gas staying entrapped in the voids under several flow regimes is presented.

Concept of Air/ Gas Entrapment as a Liquefaction Mitigation Measure

During liquefaction, excess pore water pressures build up high enough that the soil contact stresses, so called effective stresses, become zero. Recent laboratory investigations have demonstrated the potential influence of partial saturation on pore pressure build up. (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 primary goal of the previous researchers, with the exception of Ishihara (2002), was to demonstrate the importance of achieving 100% saturation in laboratory sand specimen to avoid overestimating the strength of the specimen against liquefaction. Ishihara et al. (2002) from their study of resistance of partially saturated sand to liquefaction concluded that the resistance to liquefaction was found to increase with decreasing B-value. When the B-value drops to zero with the degree of saturation of 90%, the cyclic strength becomes twice as much as that at the full saturation.

Fig 2 illustrates the concept of air/gas entrapment as a liquefaction mitigation measure. Basically, since entrapped air/gas increases the compressibility of pore fluid (water), which is incompressible; the excess pore pressure can be relieved by the volume decrease of air bubbles. Therefore, lower excess pore water pressures increase the effective stresses, hence the soil strength during dynamic loading.

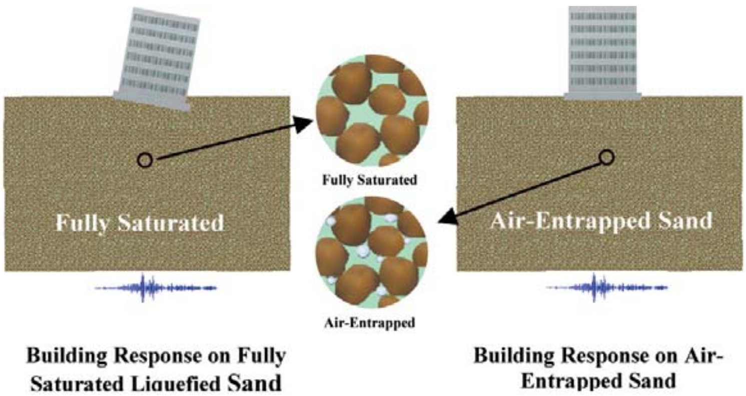


Fig.2 Concept of liquefaction mitigation using entrapped air.

Induced Partial Saturation (IPS) Techniques Explored

The ideal technique for induced partial saturation should allow the preparation of specimens with different degrees of saturation and that this degree of saturation is uniform within a specimen. Various techniques were evaluated and their advantages and disadvantages were noted (Eseller 2004). Two techniques were found to be the most effective to induce partial saturation in sand specimens; the first one is the gas generation by electrolysis and the second one is the drainage-recharge (D-R).

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:

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

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

Two rectangular meshes (20 cm x 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. 5. After preparing the fully saturated specimen in the liquefaction box, by wet pluviation; the electrodes were excited at a specific current. A preliminary study was performed by Ali (2003) to assess the current amplitude and the duration of electrolysis. For desired levels of degree of saturation, 525 mAmp current was used for a duration ranging from 1.5 to 3 hrs. Degree of saturation was obtained around 96%. During the process of electrolysis, generation of bubbles could be observed within the specimen through the liquefaction box walls. Further evidence that bubbles were being entrapped could be seen by the accumulation of free water on top of the originally fully sutured specimen. Another encouraging observation was as the water accumulates on the surface, no change in the original volume of the saturated sand was detected.

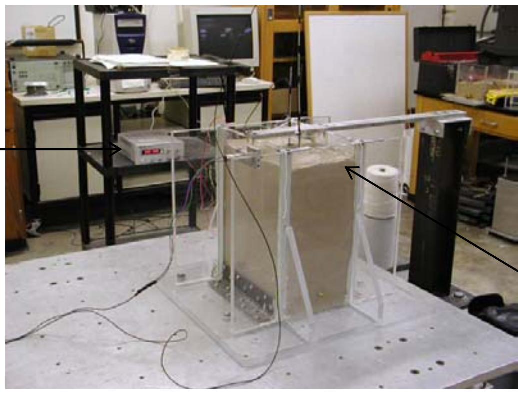


Fig.3 Gas generation in saturated sand specimen by electrolysis as an induced partial saturation technique

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. Hence, it was demonstrated that the electrolysis process can generate, at least under laboratory conditions, a controlled amount of gases without disturbing the specimen.

Drainage-Recharge (D-R) was the second technique developed to induce uniform partial saturation in sands. In this technique, after preparing a fully saturated sand specimen, the pore water was slowly drained from the bottom of the specimen and then the drained water was reintroduced from the top of the specimen at a slow rate. Fig. 4 shows a picture 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. With D-R, the degree of saturation was obtained as 86%.

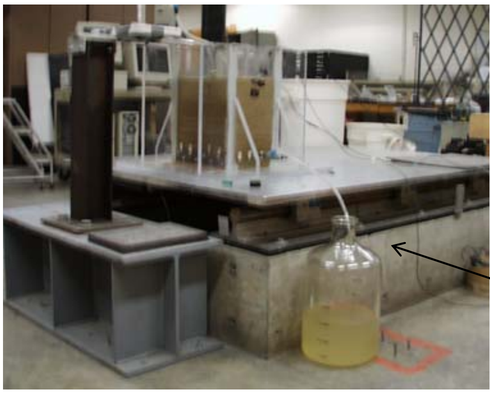


Fig.4 Air Entrapment in saturated sand specimen by Drainage-Recharge (D-R) as an alternative induced partial saturation technique

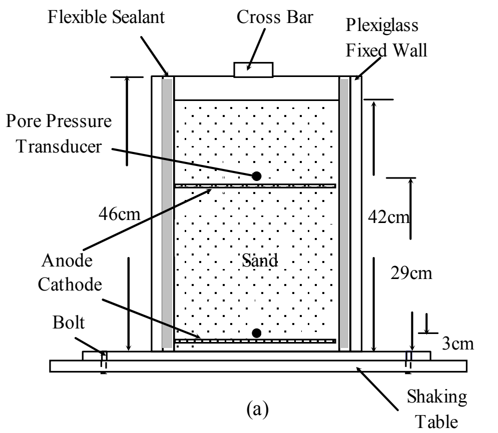
Cyclic Simple Shear Strain Tests on a Shaking Table

Cycle simple shear strain tests were performed on the fully and partially saturated large specimens prepared by the two techniques explained in the preceding section. In order to induce cyclic simple shear strains on large specimens, a special experimental setup was developed.

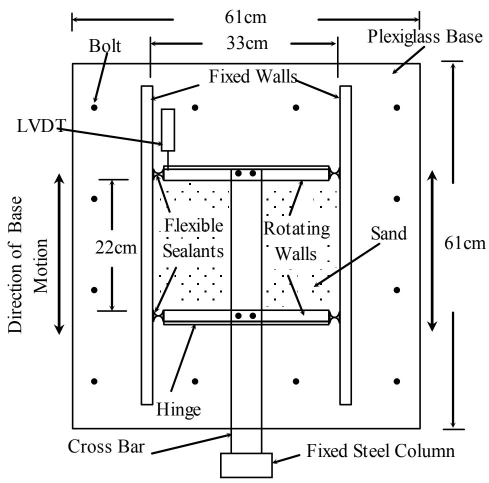
Experimental Test Setup

A special plexiglas liquefaction box was designed to allow preparation and testing of large size specimens (specimen size: 21cm x 33cm x 34cm) as well as testing them under cyclic motion induced on a shaking table. Fig. 5 shows the sketch of the setup. The box has two rotating and two fixed walls (fixed walls being in the direction of shaking). The two rotating walls are hinged to the bottom plate and also 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. Also, the tops of the two rotating walls are fixed to an outside steel beam. Hence, when the shaking table is excited with cyclic displacements, through rotation around the bottom hinge, controlled simple shear strains can be induced in the large specimens. 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. 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.

A displacement transducer (LVDT) placed near the top of one of the rotating wall monitors the 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. Miniature pore pressure transducers (PDCR 81) were inserted in the specimens at different depths, to measure excess pore water pressures during shearing as well as to investigate the uniformity of induced partial saturation throughout the specimen.



(a)



(b)

Fig.5 Side (a) and top (b) view sketches of the liquefaction box setup.

Comparative Liquefaction Tests

Loose fully saturated sand specimens were prepared in the liquefaction box, by wet pluviation. Wet pluviation is a specimen preparation technique very well suited for preparation of large fully saturated sand specimens. The wet pluviation was applied 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. Ottawa sand, a uniform sand type with rounded particle shape was used and saturated specimens approximately at a void ratio of

0.74, which corresponds to 20% relative density, were obtained. The degrees of saturation of the fully saturated specimens were ranged between 99.5% and 99.7%.

To evaluate the effect of partial saturation on liquefaction potential and pore pressure generation in sands, cyclic simple shear strains were applied on fully and partially saturated specimens. Fig. 6 shows the cyclic simple shear strain history induced in all tests. The shear strain amplitude was 0.25% and the frequency was 4 Hz. A comparison of the pore pressure generation in the fully and partially saturated specimens from one set of tests is presented in Fig. 7. The test results show that the reduction in the degree of saturation from 99.7 % to 86 % led to significant reduction in the excess pore pressure. The maximum pore pressure ratios and axial strains obtained in one fully and two partially saturated specimens tested are demonstrated in Table 1.

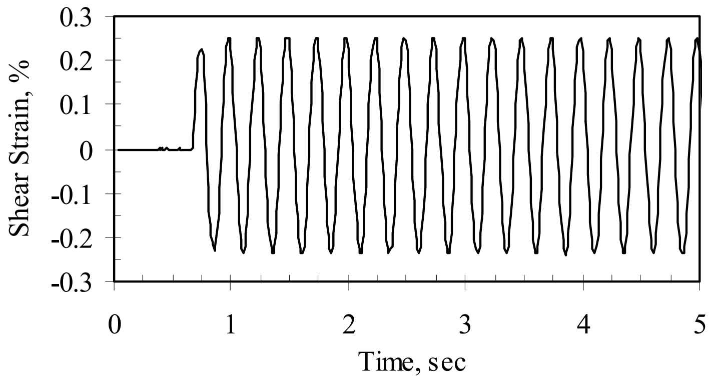


Fig.6 Cyclic simple shear strain history to the sand specimens tested

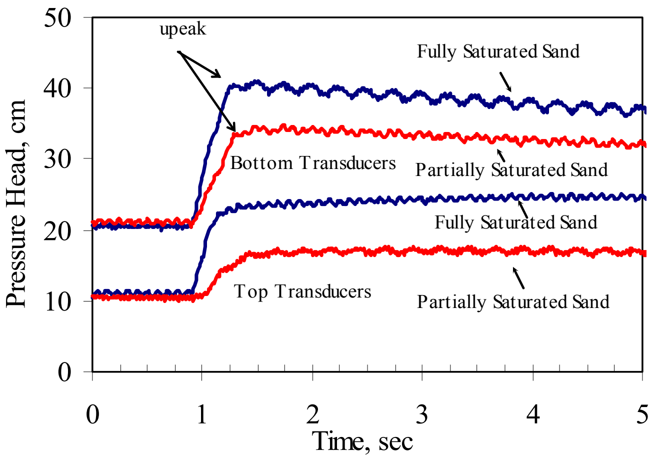


Fig.7 Comparison of pore pressure generations in fully saturated (S=99.7%) and partially saturated (S=86.2 %) specimens

Table 1 Effect of Induced Partial Saturation on Liquefaction RelatedExcess Pore Pressure and Settlement.

Sand Specimen	Degree of Saturation, S,%	Max. Excess Pore Pressure Ratio, r_u		Settlement, cm	Axial Strain, %
		Bottom Transducer	Top Transducer		
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

Long-Term Endurance of Air/Gas in the Sand

Long-term endurance of entrapped air/gas in the voids under several natural and man-driven conditions was a problem to be examined. Okamura et al. (2002) showed that during the improvement of a site by Soil Compaction Pile (SCP), where the compaction piles are pushed into the soil by pressurized air supplied from the top of the casing, some of the air percolated into the sand and some spouted from the ground surface. Based on this observation, Okamura et al. (2002) investigated another site improved 26 years ago by SCP and concluded that air bubbles survived for 26 years. Having this supportive evidence, the authors also investigated whether or not air/gas will remain entrapped under groundwater flow at low and high gradients. Large scale constant head flow test setups were designed.

A 1.2 m partially saturated vertical sand specimen was prepared in a long plexiglas tube and tested under upward and downward flows, as shown in Fig. 8. Air escaped, if there is any, was collected at the top of the specimen. Each gradient was applied for 3 hours, consecutively from 0.05 to 0.5. At the end of 18 hours of flow, volume of water in the specimen was replaced more than 50 times (Fig. 9). Test results demonstrate that very little amount of air escaped from the upper portion of the specimen in the beginning of the tests and stayed in equilibrium even at high gradients. Degree of saturation increased slightly from 82.6% to 83.6% as shown in Fig. 10.

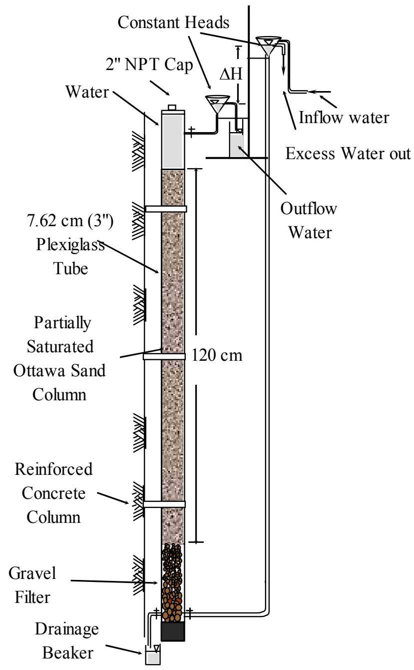


Fig.8 Vertical partially saturated sand column tested under upward hydraulic gradients

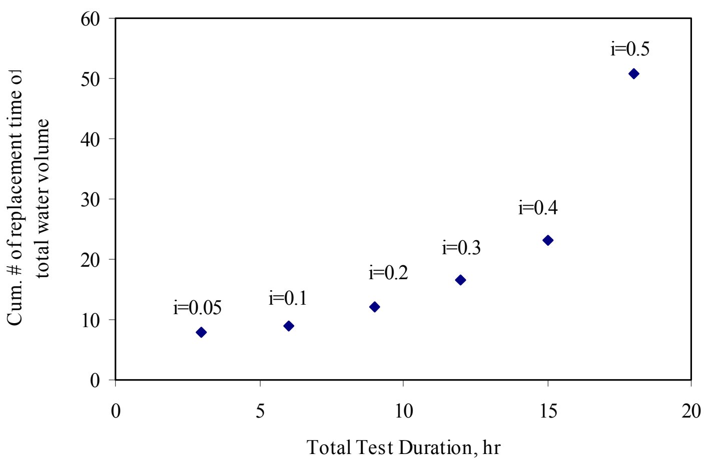


Fig.9 Cumulative # of replacement of water volume in the sand at the end of hydraulic gradient tests

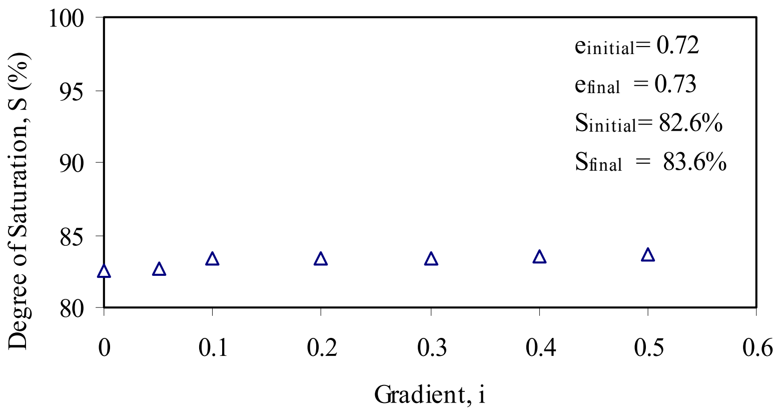


Fig.10 Change in the degree of saturation at the end of each gradient

A 1.8 m of soil column was tested under lateral hydraulic gradients of 0.05 to 0.8 using large scale constant head flow test setup (Fig. 11). Air remained entrapped in the partially saturated specimen even under gradients as high as 0.8.

Thus, it is a definitive conclusion that regardless of the flow regime, air remains entrapped in the partially saturated specimens.

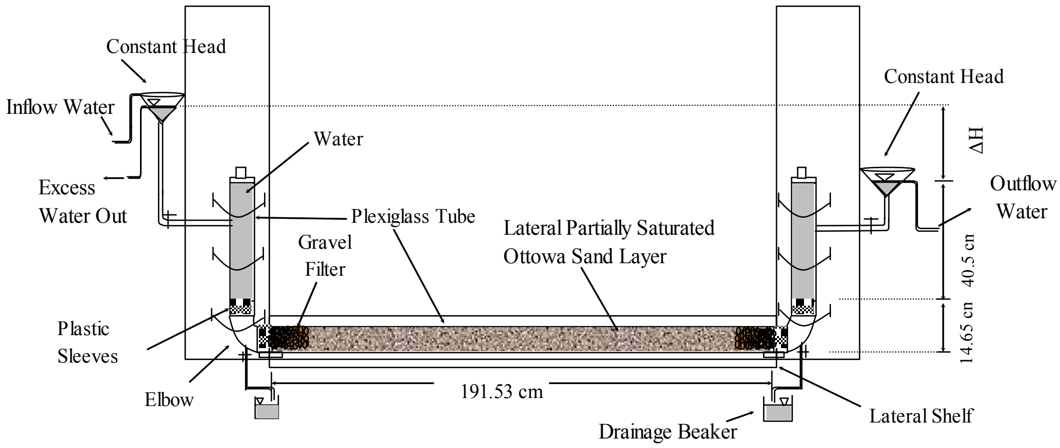


Fig.11 Partially saturated sand column tested under lateral gradients

Summary and Conclusion

Induced partial saturation (IPS) was introduced as a new cost effective liquefaction mitigation measure which can be applicable for new as well as existing structures. Gas generation through electrolysis and air entrapment by drainage-recharge (D-R) were developed as the induced partial saturation techniques to prepare large partially saturated specimens in the laboratory.

A liquefaction box that permitted the application of cyclic simple shear strains in large loose sand specimens using a shaking table was designed and manufactured. Fully and partially saturated sand specimens were tested under constant cyclic simple shear strains. 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, hence increases the liquefaction strength.

Furthermore, large scale constant head flow tests were performed on large soil columns in vertical and lateral directions to investigate the endurance of air/gas bubbles in the voids. The test results led to the observation that air bubbles remained entrapped in the sand without any significant indication of diffusion.

The experimental results reported in this paper demonstrated that induced-partial saturation (IPS) holds promise as a liquefaction mitigation measure. Further research is ongoing in evaluation of liquefaction strength of partially saturated sands experimentally with a more advanced integrated sensors and setup, in development of a methodology for predicting liquefaction strength of partially saturated sands and in exploration of the practical techniques for the field application.

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