EXPERIMENTAL INSIGHTS INTO INDUCED PARTIAL SATURATION METHODS DEVELOPED FOR LIQUEFACTION MITIGATION: DISTRIBUTION OF GAS BUBBLES

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Abstract

Saturated deposits of sandy soils may liquefy during an earthquake event, causing detrimental effects on the site and structures. Mitigation of liquefaction-induced damage is of the essence when the structures are expected to exceed the acceptable limits of safety and serviceability. Induced Partial Saturation (IPS) has been recently proposed as a novel liquefaction countermeasure. In the present study, several laboratory tests were conducted on partially saturated sand models to offer insights into two IPS methods, paying more attention to the distribution of air/gas bubbles entrapped in pore spaces. For this purpose, loose deposits of partially saturated sand were prepared in transparent plexiglass boxes either injecting air or using a chemical substance. Digital images were recorded at different stages of the tests, which provided an opportunity to visualize the distribution of gas/air bubbles. Furthermore, moisture sensors were placed at different locations of sand models, allowing to capture the variation of the degree of saturation with time. Comprehensive analyses of the test data suggested that oxygen bubbles were generated through a reaction between water and chemical substance, and the distribution of oxygen bubbles was sufficiently uniform across the sand models. This method also allowed the preparation of sand models at the desired degrees of saturation. On the contrary, at 1-g injected air was observed to flow through a path of less resistance, and this technique was comparatively less successful in preparing sand models with uniformly distributed air bubbles and at lower degrees of saturation (i.e., below 90%).

ZEMİN SIVILAŞMASINA KARŞI GELİŞTİRİLEN KISMİ DOYGUNLUĞA İNDİRGEME METOTLARI ÜZERİNE DENEYSEL ÇALIŞMA: GAZ KABARCIKLARININ DAĞILIMI

Anahtar Kelimeler
Sıvılaşma, Kısmi Doygunluk, Hava Enjeksiyonu, Kimyasal Madde, Hidrojen Peroksit

Öz

Doymuş kumlu zeminler, deprem yükleri altında sıvılaşarak serbest saha ve yapılar üzerinde zararlı etkilere neden olabilmektedir. Yapıların güvenliğini ve kullanılabilirliğini sağlamak için zemin sıvılaşmasına bağlı hasarların azaltılması veya önlenmesi gerekmektedir. Son yıllarda ortaya çıkmış olan Kısmi Doygunluğa İndirgeme (IPS) tekniği sıvılaşmanın etkilerini azaltmada kullanılabilecek yeni bir yöntemdir. Bu çalışmada, iki farklı IPS yöntemi kullanılarak kısmi doygun hale getirilmiş kum modelleri üzerinde laboratuvar testleri gerçekleştirilmiş ve özellikle zemin içerisindeki boşluklarda suni olarak oluşturulmuş olan hava/gaz kabarcıklarının dağılımı incelenmiştir. Bu amaç doğrultusunda, hava enjekte ederek veya kimyasal madde kullanarak şeffaf pleksiglas kutu içinde kısmi doygun gevşek kum modelleri hazırlanmıştır. Farklı test aşamalarında kaydedilmiş dijital resimler yardımı ile gaz/hava kabarcıklarının zemin içindeki dağılımı gözlemlenmiştir. Ayrıca, kum modellerinin farklı noktalarına yerleştirilen toprak nem ölçüm sensörleri ile doygunluk derecesinin zamana bağlı değişimi tespit edilmiştir. Test verilerinin kapsamlı analizleri, kullanılan kimyasal maddenin su içinde reaksiyona girmesi ile zemin içinde oksijen kabarcıkları oluşturduğunu ve bu kabarcıkların yeterince üniform olarak dağıldığını göstermiştir. Aynı zamanda bu yöntem ile istenilen

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doygunluk derecelerinde kum modelleri hazırlanabilmiştir. Buna karşılık, zemine enjekte edilen havanın sınırlı bir akış yolunu takip ettiği gözlemlenmiş ve hava enjeksiyon tekniğinin yerçekimi etkisi altında üniform ve düşük doygunluk derecesine (%90 altı) sahip kısmi doygun kum modellerinin hazırlanmasında nispeten daha az başarılı olduğu görülmüştür.

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1. Introduction

Saturated deposits of sandy soils may liquefy during an event of an earthquake, leading to significant loss of shear strength and soil stiffness degradation. Earthquake-induced liquefaction has the potential to cause significant economic losses and casualties. Its detrimental effects have been recurrently observed during past and recent earthquakes, such as in 1995 Kobe (Elgamal et al., 1996), 1999 Izmit (Bray et al., 2004), 2001 Bhuj (Rajendran et al., 2001), 2010 Maule (Bertalot et al., 2013), 2011 Tohoku (Bhattacharya et al., 2011) and 2011 Christchurch (Cubrinovski et al., 2011). A large number of structures in seismically active regions continue to be at extremely high risk of liquefaction-induced damage, and a pressing need exists for the use of countermeasures against liquefaction.

In the aftermath of the 1964 Niigata earthquake, extensive attention has been dedicated to this problem, and different types of liquefaction mitigation methods have been proposed (Seed et al., 2003; Mitchell et al., 1995). Although most of these methods have been proven to be suitable for the new sites, they are less applicable under existing structures and are often very expensive (Gallagher et al., 2007). In recent years, researchers have attempted to resolve this problem and developed a few non-disruptive and cost-effective mitigation methods including passive site remediation (Gallagher and Mitchell, 2002), microbial-induced calcite precipitation (DeJong et al., 2010; Montoya et al., 2013; Choi et al., 2020; Zamani et al., 2021), and induced partial saturation (IPS) methods.

IPS methods can be classified into five major groups: electrolysis (Yegian et al., 2007), drainage-recharge (Yegian et al., 2007), air injection (Okamura et al., 2011; Zeybek and Madabhushi, 2017a), denitrifying bacteria-biogas (He et al., 2013; O'Donnell et al., 2017; Mousavi and Ghayoomi, 2021) and chemical substance as a source of gas bubbles (Eseller-Bayat et al., 2013). The IPS methods rely on the artificial generation of air or gas bubbles in pore spaces, reducing the degree of saturation S_r and markedly increasing the liquefaction resistance of soil (Okamura and Soga, 2006). The IPS methods can be applied both at new sites and beneath existing structures. The material used in their application (i.e., air, sodium percarbonate) is very cheap, significantly reducing the total cost (i.e., Okamura and Tomida, 2015). Moreover, these methods are environmental-friendly as they do not require the use of synthetic materials or chemicals (i.e., epoxy, cement). Several research programs have been undertaken by different research groups around the world to investigate the effectiveness of IPS methods on reducing the liquefaction effects. Cyclic triaxial or dynamic simple shear tests revealed that partially saturated sand specimens prepared with a chemical substance, sodium percarbonate, exhibited greater liquefaction resistance than their saturated counterparts (i.e., Zeybek, 2022a; Eseller-Bayat and Gulen, 2020). Through the dynamic centrifuge tests, generation of high excess pore pressures, associated soil softening, ground surface and/or foundation settlements were shown to substantially decrease as liquefiable sand models were desaturated by injecting pressurized air (i.e., Marasini and Okamura, 2015; Zeybek and Madabhushi, 2017b; Zeybek and Madabhushi, 2019). Through the 1-g shaking table tests, the magnitude of excess pore pressures was shown to decrease as saturated deposits of liquefiable sand were mitigated with electrolysis and drainage recharge techniques (Yegian et al., 2007), a chemical substance containing hydrogen peroxide (Eseller-Bayat et al., 2013; Zeybek, 2022b) and denitrifying bacteria (He et al., 2013). The laboratory and field tests suggested that under different conditions (i.e., horizontal/vertical flow, shaking) air or gas bubbles can remain entrapped within the pore spaces and the IPS techniques offer a reliable solution in the long term (i.e., Okamura et al., 2006; Yegian et al., 2007; Zeybek and Madabhushi, 2017c; Eseller-Bayat et al., 2013; Hu et al. 2020). Few in situ tests were conducted to examine the practicality and efficacy of air injection (Okamura et al., 2011) and chemical methods (Nababan, 2015).

Previous studies established the fundamental principles and highlighted promising features of IPS methods. Despite their virtues, there is a need for further study, targeting the critical factors that control their response. The current study aims to offer experimental insights into two IPS methods, which are expected to enhance the current understanding of these particular mitigation methods and help the geotechnical engineers during their practical applications. Air injection and chemical methods are chosen for this purpose. The performance of these methods is compared with a particular focus on the distribution of air and gas bubbles entrapped in pore spaces.

2. Research Methodology

2.1. Testing Program

In this study, a series of 10 tests were conducted on partially saturated sand models prepared in transparent plexiglass boxes. The main facets of the tests are presented in Table 1.

Five of the sand models were prepared using the air injection method and Hostun sand. The remaining tests involved the use of Şile sand and a chemical substance as a way of generating gas bubbles. In every test, sand models were prepared at a relative density D_r of approximately 40%, saturated with de-aired water, and desaturated with air injection (A) or chemical substance (C). The degree of saturation of air injected and chemically mitigated sand models was in the range of 89.5 to 94.8% and 78.0 to 94.1%, respectively. It is noted that unless otherwise stated, the term '*chemical substance* indicates the '*denture cleanser*' hereafter.

Table 1

Experimental Program

Test No	Test ID	IPS Method	Sand Type	D_r (%)	S_r (%)
1	A1			40.1	94.8
2	A2	Air	Hostun	39.8	90.2
3	A3	Injection	HN31	40.8	91.2
4	A4			41.0	90.3
5	A5			39.1	89.5
6	C1			41.3	94.1
7	C2	Chemical-	AFS	39.5	89.6
8	C3	Efferdent	55/60	38.7	85.0
9	C4		Şile	40.2	80.5
10	C5			40.4	78.0

2.2. Material and Equipment

Two types of sand, namely, Hostun HN31 and AFS 55/60 Şile were used for the preparation of models. Table 2 presents the basic properties of sands. Both are uncrushed clean siliceous sand and are widely used for industrial purposes.

Table 2

Basic properties of sands

Sand Type	Hostun HN31	AFS 55/60 Şile
Average particle size, D_{50} [mm]	0.480	0.296
Uniformity coefficient, C_u	1.67	1.352
Specific gravity, G_s	2.65	2.65
Minimum void ratio, e_{min}	0.555	0.574
Maximum void ratio, e_{max}	1.01	0.885
Soil Classification (USCS)	SP	SP

Based on the analysis of particle size distribution, Hostun sand appears to be coarser than Şile sand (Figure 1). More details regarding the physical and mechanical properties of Hostun and Şile sand can be found in the published literature (i.e., Heron, 2013; Zeybek, 2017; Zeybek, 2022a).

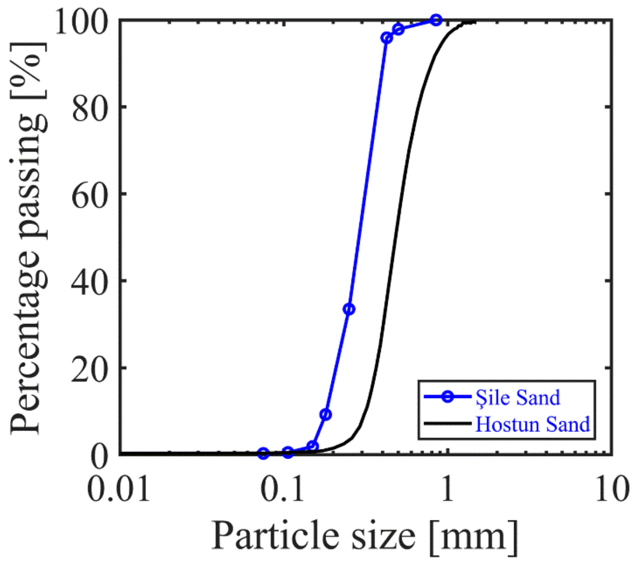

Figure 1. Particle size distribution of HN31 Hostun sand and AFS 55/60 Şile sand

In the tests involving chemical treatment, commercially available denture cleanser tablets, called Efferdent, were used (Figure 2a). It was purchased in tablet form (Figure 2b), and finely powdered (Figure 2c). This type of chemical substance contains hydrogen peroxide and can produce oxygen bubbles through its reaction with water. Further details about the use of Efferdent as a liquefaction mitigation method can be found in the published literature (i.e., Eseller-Bayat et al., 2013).

In some of the tests, VH400 soil moisture sensor probes (manufactured by Vegetronix) were used to measure the variation of the degree of saturation.

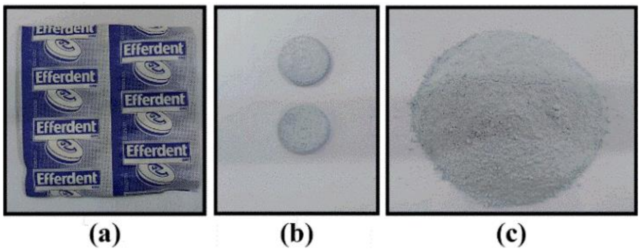

Figure 2. The chemical substance in tablet and powder form

2.3. Preparation of Sand Models

2.3.1. Air Injection Tests

A porous plastic tube and an air diffuser with extremely fine openings were placed on the base of the clear plexiglass model box (Figure 3a). Their inlets were connected to a header tank filled with de-aired water for saturation and an air compressor for air injection. Hostun sand was dry pluviated at a controlled flow rate and drop height. The sand pouring process was halted to install the soil moisture probes at the targeted locations (Figure 3b). Subsequently, reconstituted sand models in a loose condition were saturated by slowly infiltrating the de-aired water from bottom to top (Figure 3c). The saturation process continued until 15 mm of free water was collected above the sand surface (Figure 3d).

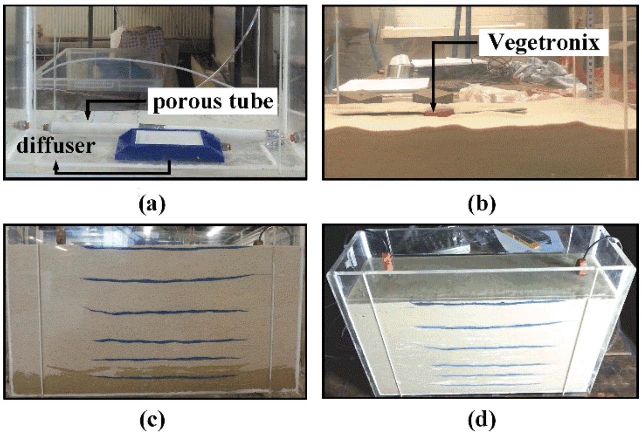

Figure 3. Preparation of partially saturated sand models using the air injection method

This was followed by the desaturation of sand models using the air injection technique. Air was injected in a controlled manner. The flow rate and injection pressure were measured through a flow sensor and pressure gauge (Figure 4).

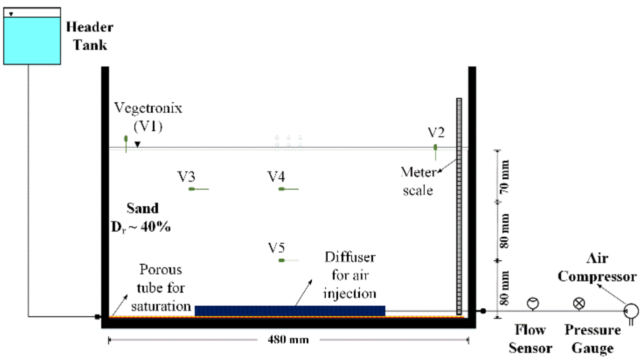

Figure 4. Typical cross-sections of models and test setup

The change in water level was measured through a meter scale on the back window. Similarly, the moisture sensor placed at the sand surface (V1) allowed for continuous measurement of the variation of water level.

2.3.2. Chemical Tests

The chemical tablets were finely powdered, and the chemical powder was mixed with clean Şile sand at different ratios (Figure 5a and Figure 5b). The obtained mixture was poured into the model box through air pluviation (Figure 5c) and subsequently saturated with a specific amount of de-aired water (Figure 5d). After one day of the reaction between the chemical substance and water, oxygen gas bubbles were generated in the pore spaces of the sand model and an increase in the height of free water above the sand surface was observed. It is noteworthy that the top of the sand models was sealed using plastic wrap to minimize the possibility of water loss due to evaporation.

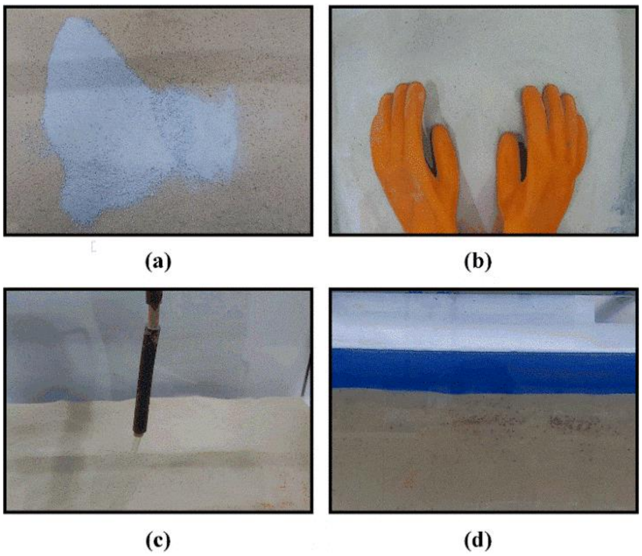

Figure 5. Preparation of partially saturated sand models using chemical powder

3. Results

3.1. Degree of Saturation, S_r

The degree of saturation of sand models was assessed during the saturation and desaturation process by two different approaches, namely, soil phase relations and soil moisture sensors. For the conventional soil phase (mass-volume) method, the weight and/or volume of sand, chemical substance, and water were measured with caution. The average degree of saturation across the sand model was calculated with an assumption of the volume of air or gas bubbles entrapped in pore spaces being equal to the volume of water replaced by air or gas bubbles. In addition, the moisture sensors were used to record the variation of S_r at discrete points of sand models.

Figure 6 depicts an example of the time histories of the degree of saturation recorded during the saturation and desaturation (air injection) process in test A2. The test data corresponds to S_r values obtained based on mass-volume and moisture sensor measurements. It is seen that the degree of saturation of dry sand models increased when saturated with water. The readings of the sensors at the deeper layers (i.e., V5) started to vary earlier than those of the sensors at the shallower layers (i.e., V2) because the saturation started from the bottom and propagated upwards. At the start of the air injection, the average S_r was approximately 97.5%. This was slightly overestimated particularly by the lower sensors. It is also obvious from the figure that S_r of the sand models started to reduce with the inclusion of air bubbles. The average S_r was captured well by the sensor V4. The sensor V5 responded earlier due to its proximity to the air injector, and its measurement was slightly larger than the average S_r. The response of the top sensor V2 was delayed and its readings overestimated the average S_r. It can be deduced from these findings that soil moisture sensors are expected to provide localized and sufficiently accurate measurements, and the results of the mass-volume method were not far off their readings.

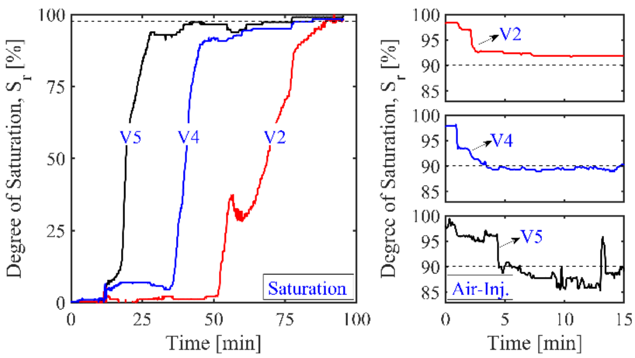

Figure 6. Variation of degree of saturation during saturation and air injection process

3.2. Distribution of Gas Bubbles

Two-dimensional digital images were recorded at different stages of the tests. The visual inspections of the sand models were carried out through the transparent window, showing that sand appeared to be brighter at the end of the desaturation process than at the beginning. The brighter parts in the partially saturated sand models correspond to the presence of air or gas bubbles. The digital images were processed in MATLAB using the image subtraction toolbox. This allowed subtracting the two images recorded before and after the air injection process and offering a rough estimate of the distribution of bubbles across the partially saturated sand models.

Figure 7 displays the distribution of bubbles in the partially saturated sand models involving air injection and chemical treatment. The left-hand two plots are from tests A1 and A4 conducted on Hostun sand with the air injection method. The degrees of saturation of sand models were 94.8 and 90.3%, respectively. The right-hand plots of Figure 7 are for tests C3 and C4 performed on Şile sand with the chemical method. The degrees of saturation of sand models were 85 and 80.5%, respectively. The dark red zones correspond to nearly saturated sand with a small number of bubbles, whereas the light zones (light red or yellow) indicate partially saturated sand with a large number of tiny air or gas bubbles. It can be inferred from the figure that air bubbles were distributed non-uniformly in the sand models prepared with the air injection technique. This may be attributed to the preferential flow pathways where the air tended to flow through the surface along a path of less resistance (indicated by the arrow lines). On the other hand, the distribution of oxygen gas bubbles was comparatively more uniform, and homogeneous partially saturated sand models were achieved in the tests involving chemical treatment. In the comparable condition, this method performed better than the air injection technique, but gas bubbles did not cover the entire sand model in some tests (i.e., TestC3), which can be ascribed to the segregation that occurred during the preparation of models with the sand-chemical mixture.

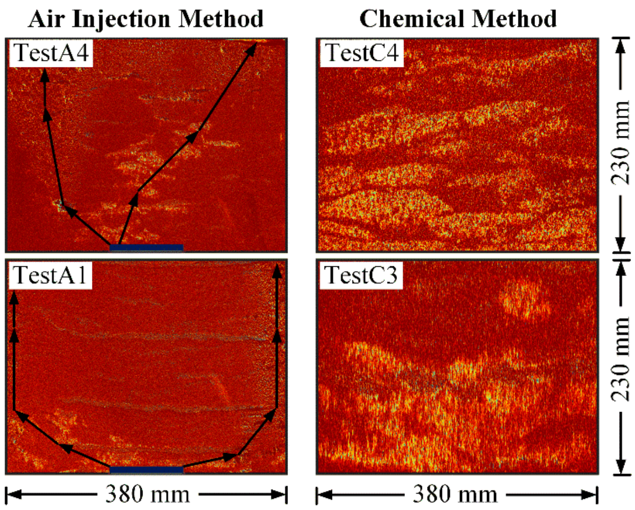

Figure 7. Distribution of air/gas bubbles

Figure 8 shows an example of the time histories of the degree of saturation recorded during the air injection process in TestA1 and TestA4. This data corresponds to the readings of the moisture sensor V5. In TestA4, the moisture sensor appeared to be within a zone where a significant amount of air bubbles was concentrated.

Therefore, the probe of the sensor directly interacted with multiple bubbles, providing a reading lower than the average S_r. On the other hand, in TestA1 the sensor interacted with less amount of air bubbles and measured a higher saturation ratio than the average method. The comparison of the two tests revealed that the distribution of air bubbles was relatively more uniform in sand models with lower S_r (TestA4). The results presented herein were in accordance with the published literature (i.e., Yasuhara et al., 2008; Marasini and Okamura, 2015; Zeybek and Madabhushi, 2018).

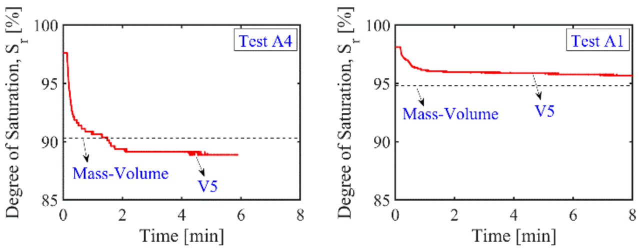

Figure 8. Time histories of the degree of saturation

3.3. Model Disturbance

The desaturation process may affect the structure of sand and cause a substantial model disturbance such as piping or boiling. The sand models were monitored in the front window to obtain a visual indication of this phenomenon. Figure 9 presents typical images of sand models recorded before and after the desaturation process. Experimental observations made after 5 minutes of air injection highlighted that although the air was injected in a slow and controlled manner, many fissures occurred across the sand model.

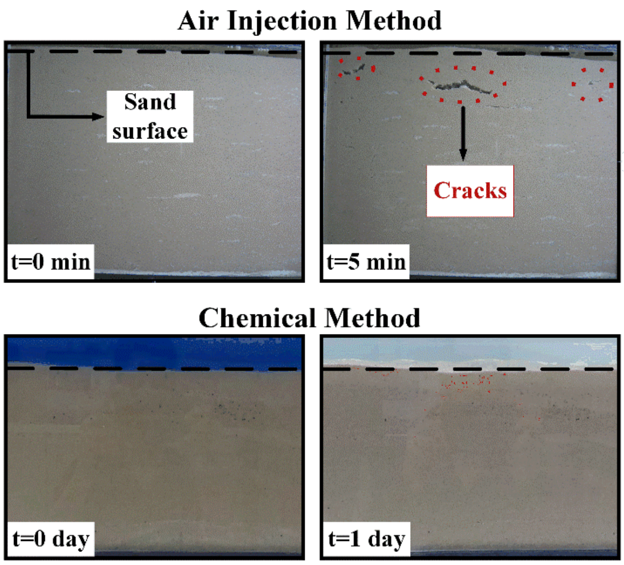

Figure 9. Model disturbance and deformation of the sand structure

Air bubbles caused an uplift of the sand grains at the surface. Moreover, large air-filled cavities and many large cracks were visible in the front window, and they were particularly concentrated at the shallow layers. On the contrary, the reaction of the chemical substance with water in one day led to small fissures. In comparison with the air injector method, the model disturbance was limited during the chemical treatment of the sand model. Zeybek (2022a) suggested that the deformation of sand can be completely prevented by applying a small amount of pressure on the model surface.

5. Discussions

Induced partial saturation (IPS) methods offer an economical, and ecological solution to mitigate the effects of earthquake-induced liquefaction. The performance of the two IPS methods was assessed through a series of laboratory tests conducted at 1-g (Earth's gravity). The particular focus of the tests was placed on the distribution of air/gas bubbles and model disturbance, which were observed in the front window of the transparent box. Detailed analysis of the test results suggested that with a maximum allowable air injection pressure, the degree of saturation of sand models was reduced by about 10% only, and a further reduction in S_r was challenging even with the excessive air pressure. The air bubbles were concentrated in some regions only, which can be attributed to the occurrence of preferential flow pathways. Moreover, an extensive model disturbance was observed particularly at the shallow layers where effective stress was very small. Unlike the 1-g tests presented in the current work, air bubbles were distributed more uniformly in centrifuge models at high-g, and S_r was successfully reduced to the desired level such as below 80%. (Zeybek and Madabhushi, 2018). It can be inferred from these results that at 1-g air injection method is less successful in preparing partially saturated sand models with uniformly distributed air bubbles and at lower saturation ratios. These issues were however resolved by the chemical method. This type of treatment method allowed controlling and reducing the S_r to the desired level. The distribution of air bubbles was also found to be comparatively more uniform in this case, and it caused limited model disturbance (only small fissures). Zeybek (2022a) suggested that small fissures can be prevented by applying a small amount of static load on top of sand models.

6. Conclusions

From this research, the following conclusions can be drawn.

The extent and magnitude of the desaturation and distribution of air/gas bubbles are important design considerations in IPS methods. The air injection method can be effectively implemented at high-stress levels (i.e., field or centrifuge tests). However, its efficacy is limited at low-stress levels (i.e., shaking table or small model tests at 1-g). The air bubbles tend to distribute unevenly because of the preferential flow of air. Therefore, the liquefaction resistance is expected to vary across the air-injected sand models.

The reaction of chemical substances (i.e., efferdent) with water can produce many tiny oxygen bubbles in liquefiable sand models. The magnitude of the desaturation can be controlled by varying the amount of chemical substance, and comparatively more uniform gas bubble distribution can be obtained even at 1-g. Moreover, the model disturbance can be entirely prevented through simple measures (i.e., applying a small pressure on top).

The test results showed that the chemical method can overcome some of the problems and limitations that the air injection method suffers at 1-g tests. This conclusion is however based on the analysis of digital images and five soil moisture sensors, providing only a relatively rough approximation to the distribution of bubbles. Despite its promising feature, further study (i.e., centrifuge or field tests) is needed to elucidate the performance and effectiveness of the chemical method at high-stress levels. The centrifuge models can be combined with several moisture sensors placed at different locations of the sand models to obtain more qualitative results.

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Author Contributions

The author (Abdülhakim ZEYBEK) is responsible for conceptualization, methodology, formal analysis, investigation and discussion of results, writing and reviewing of the manuscript.

Conflict of Interest

The author (Abdülhakim ZEYBEK) has no conflicts of interest to disclose. This study complies with scientific research and publication ethics and principles.

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