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CENTRIFUGE TESTING TO STUDY THE EFFECTS OF AIR INJECTION ON THE LIQUEFACTION-INDUCED SHALLOW FOUNDATION SETTLEMENTS

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Abstract

In recent years, air injection has been proposed as a cost-effective liquefaction mitigation technique that can be implemented underneath existing structures as well as at new construction sites. The effective application of this particular technique however requires a clear identification of the most critical mechanisms of liquefaction-induced deformations and their mitigation through it. In this study, a series of centrifuge tests were conducted on the shallow foundation. The dominant mechanisms of settlements in the fully and air injected-partially saturated soils were identified, and the performance of air injection in minimizing their respective contributions were evaluated. The test results indicate that artificially injecting air bubbles into the liquefiable soil deposits changes the dominant deformation mechanisms. The foundation settlements are dominated by the deviatoric deformation mechanisms in the fully saturated soils, whereas the volumetric deformation mechanisms are more pronounced in the air-injected partially saturated soils. Injection of air bubbles into the liquefiable soil deposit markedly minimizes the deviatoric soil deformations underneath the shallow foundation and reduces the overall structural settlements. The majority of the settlements in these soils happen due to volumetric deformations mechanisms.

Keywords: Geotechnical centrifuge; Liquefaction mitigation; Shallow foundations; Settlements; Partially saturated soils

1. Introduction

The devastating effects of liquefaction on the built environment have been repeatedly observed in many moderate to large size earthquakes. Based on the observations of structure performance on the liquefied sites, it has been recognized that the structures with shallow foundations are particularly vulnerable to liquefaction-induced deformations. The recent earthquakes of the 1999 Kocaeli, Turkey, the 2010 Maule, Chile and the 2011 Christchurch, New Zealand are the prime examples of this situation. When the loose, saturated soils beneath the shallow foundations liquefy, a decrease in the effective stress and the associated shear strength occurs. In the case of full liquefaction (near-zero effective stress state), significant structural deformations occur, including such as excessive settlement and tilting as well as shifting of structures. Within the years, several research programmes have been performed to develop different types of liquefaction mitigation techniques to encounter liquefaction-induced deformations.

The influence of degree of saturation on the liquefaction resistance of soils has been investigated by several researchers, and the relevant test results have shown that the liquefaction resistance of saturated soils significantly increases by even a small amount of reduction in the degree of saturation [1-2]. Considering the positive effect of reducing the saturation ratio on the liquefaction resistance, in the recent years some researchers have been exploring the liquefaction mitigation techniques that involve the artificial introduction of gas bubbles and creating partially saturation zones in the liquefiable soil deposits. One of these techniques is the air injection. This technique basically involves the injection of pressurized air into the liquefiable soil layer in a controlled fashion, and artificially reducing the degree of saturation. It can be implemented both at new construction sites and beneath the foundation of existing structures (see Fig.1). The research performed on this particular technique has shown that the injection of air into soil deposits can substantially reduce the degree of saturation [3]. It has been also indicated that the injected air bubbles can remain entrapped in soils and do not dissipate easily. The partially saturated condition can therefore last for long period, which makes this technique reliable [4]. In addition, its use is very advantageous since it is a cost-effective and eco-friendly liquefaction mitigation technique [5].

Several parameters regarding the air injection technique including its application in the field [6] and its performance on reducing structural movements [7] have been investigated. These studies have helped establishing the significant parameters for the particular technique. Nonetheless, the influence of air injection on the response of soil deposits improved with this technique and performance of shallow foundations sitting on these soil deposits have not been understood adequately. Zeybek and Madabhushi [8] have studied in a quantitative fashion the deformation mechanisms under the shallow foundation of a typical '*heavy*' structure sitting on the air-injected partially saturated soils. It has been shown that the dominant deformation mechanisms alter going from fully saturated to partially saturated case. In the experimental research presented here, the deformation mechanisms beneath the shallow foundation of a typical '*light*' structure sitting on the air-injected partially saturated soils are studied, and the dominant deformation mechanisms in these soils are identified. The obtained results have confirmed the deformation mechanisms identified in the case of heavy foundation. Moreover, as different from this research the influences of some critical parameters on the response of several deformation mechanisms and relative contributions to the overall foundation and free-field settlements are discussed briefly.

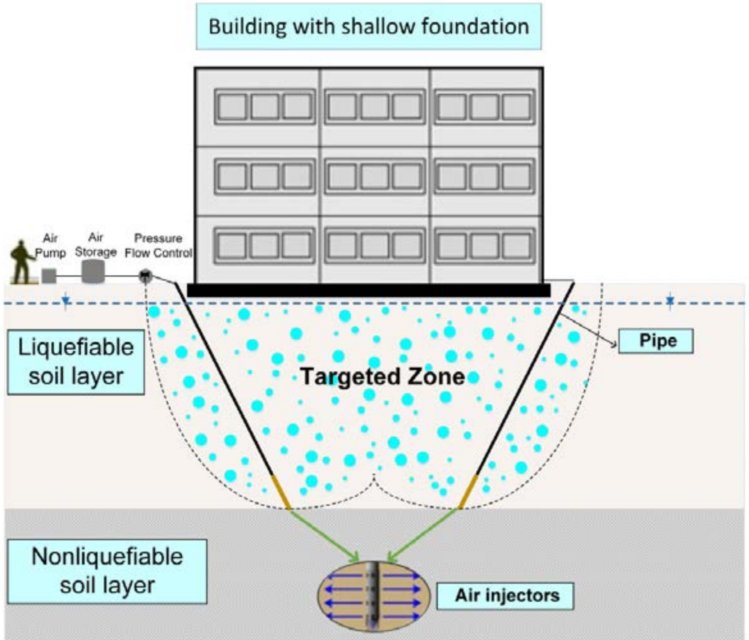

Fig. 1 –Schematic illustration of liquefaction mitigation through air injection technique underneath an existing building with shallow foundation

2. Methodology

A series of three centrifuge experiments were performed on the shallow foundation at the Schofield Centre of Cambridge University. The centrifuge models were prepared and spun at a nominal acceleration of 70g. The programme followed during the tests is summarized in Table 1. The units presented in this paper are in prototype scale, unless otherwise indicated. The soil used in the experiments was Hostun HN31 sand (d_{50}=0.480 mm, U_c= 1.67, e_{min}=0.555, e_{max}=1.01, G_s= 2.65 and air entry value= 1.3 kPa). Hostun HN31 sand was dry pluviated in a Perspex window box to attain 240 mm (model scale) deep homogenous, liquefiable soil beds at a relative density of 40%. A rubber tube with several tiny openings was placed at the bottom of sand beds to inject air bubbles and perform liquefaction mitigation. Arrays of piezo-electric accelerometers, micro-electromechanical system (MEMS) accelerometers and pore pressure transducers were positioned at the desired locations to measure the soil and foundation accelerations as well as pore pressure response in the soil. Linear variable differential transducers (LVDT) were also used to measure the foundation and free-field settlements at different locations. The schematic illustration of centrifuge models was shown in Fig.2. The free-field responses were recorded at Section 1 and Section 3, whereas the responses underneath the foundation were achieved at Section 2. Ideally, the free-surface responses should be recorded at locations away from the foundations and container end walls to ensure that the soil-structure and boundary effects are negligible. A soft putty-like material called Duxseal® was used at the container end walls to minimize the boundary effects, such as the stress wave reflections, in the direction of earthquake shaking. Moreover, the free-field measurements were performed sufficiently distant from the foundation.

Table 1 – Centrifuge testing programme

Test ID	Model identification	Input motion characteristics	Test conditions		
			Initial relative density %)	**Initial degree of saturation (%)**	**Final degree of saturation after air injection (%)**
FSL-1	Fully saturated	Frequency: 0.72 Hz			99.0
PSL-1	Partially saturated	Peak input acceleration: 0.18g	40.0	99.0	93.1
PSL-2	Partially saturated				79.5

The dry sand models were then saturated using CAM-Sat system, as described by Stringer and Madabhushi [9]. During the saturation process, aqueous solutions of hydroxypropyl methylcellulose (HPMC) with a viscosity of 70 times that of water were used as the pore fluid to avoid any incompatibility between dynamic and diffusion time scaling laws. The degree of saturation of models was around 99% after the saturation process was completed, and the phreatic surface of the saturated models was 0.35 m above the ground surface. Following the saturation of models, they were placed on the Turner beam centrifuge carefully. A shallow foundation model was positioned on the ground surface. The foundation model used in the experiments had a 3.5 m width and 1.75 m height. It was made of duralumin and applying a bearing pressure 50 kPa. After the all, the centrifugal acceleration was increased in steps of 10 g to the targeted g (65g at the foundation level and 70g at the base of the model). In the fully saturated, unimproved soil test (FSL-1), the earthquake was straightaway applied. However, in the partially saturated, improved soil tests (PSL-1 and PSL-2), air was injected to mitigate the liquefiable soil before earthquake being applied. The injection of air into the soil was performed in a controlled fashion, and more details about this process was given by Zeybek and Madabhushi [8]. The shakings were applied using a stored angular momentum (SAM) actuator device [10], and the shakings were parallel to the long side of models. Although the amplitude and frequency of earthquakes were same, and the peak base acceleration of around 0.18g was used for all tests, the duration of shakings was much longer in tests PSL-1 and PSL-2 to investigate the behavior of improved soil zones during the longer shakings. During the tests, digital images were acquired using a high speed camera (see Fig.3) to investigate the soil deformations through particle image velocimetry (PIV) technique [11].

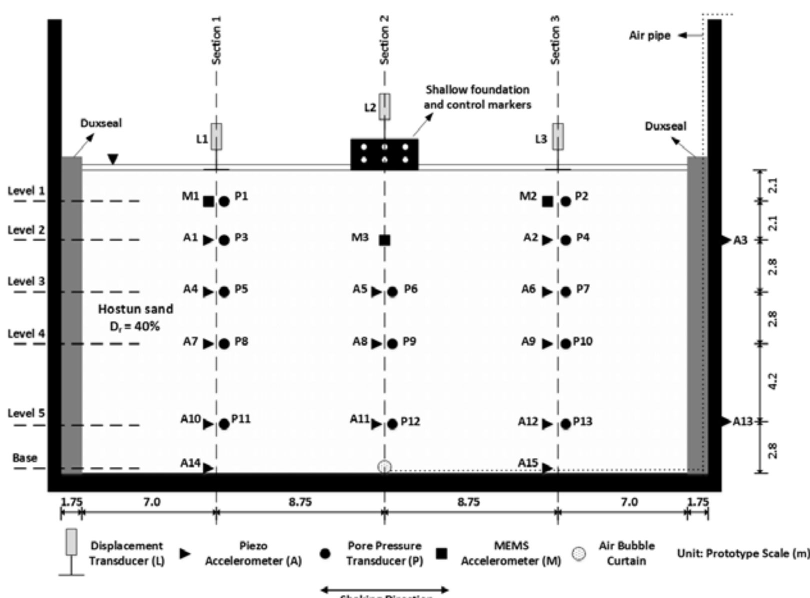

Fig. 2 – Centrifuge model layout in experiments

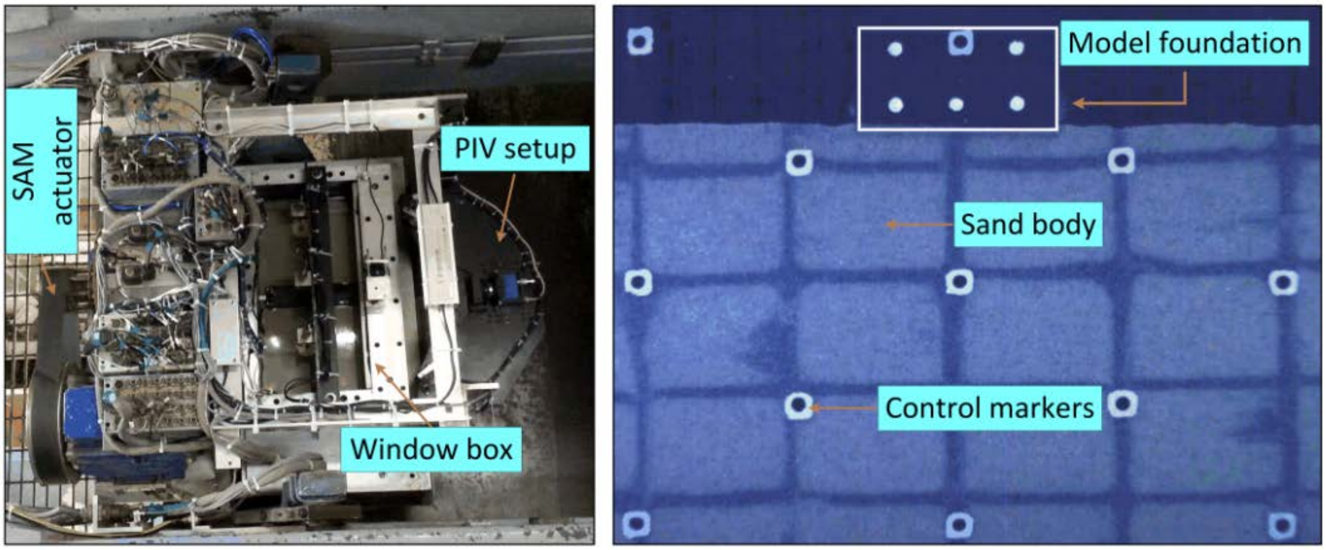

Fig. 3 – Centrifuge test and PIV setup

3. Typical experimental results and findings

3.1 Settlement response

The average foundation settlement-time histories measured in all experiments and the input acceleration-time histories recorded during test FSL-1 are shown in Fig.4. The settlements that occurred during air injection process in the partially saturated models are indicated by horizontal dashed lines. It is clear that foundation began settling after one significant loading cycle in all cases, however the rate of settlement was significantly smaller in the partially saturated soils. Although the duration of the shakings was much longer in the partially saturated soil tests, the foundation settled significantly less, compared to test with no remediation (FSL-1). Comparing the settlements after the same number of acceleration cycles (17), the total structural settlements, including the air injection-induced settlements were reduced by almost 48% and 75% by air injection in tests PSL-1 and PSL-2.

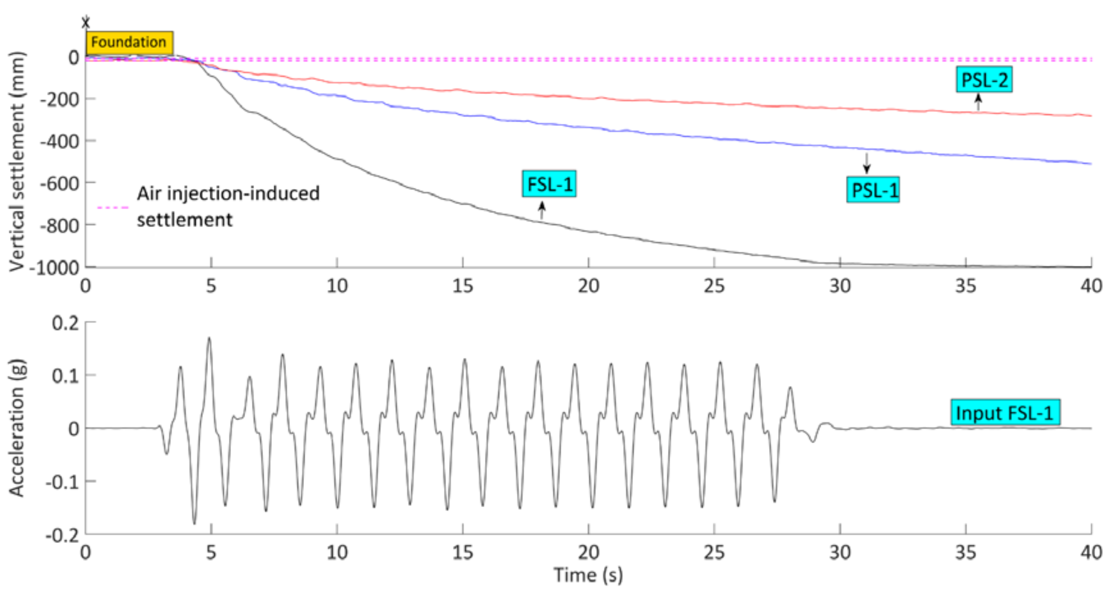

Fig. 4 – Average foundation vertical settlement-time histories recorded in all tests

The total air-induced, co-seismic and post seismic settlements that developed in the free field (Section 1 and 3) and underneath the foundation (Section 2) are presented for all tests in Fig.5. As shown in this figure, some settlement of free surface and shallow foundation occurred during the air injection process. The deformations taking place during this process and the way they can be minimized were explained by Zeybek and Madabhushi [8]. As explained in this paper, some volume of pore fluid was replaced by some volume of air bubbles that entered into the soil, and an upward migration of pore fluid took place. When this process occurred very rapidly, seepage-induced liquefaction in the upper part of soil with low confining stress took place, and this resulted in a decrease in the effective stresses. Moreover, the introduction of air bubbles increased the compressibility of soil matrix. All of these eventually increased the local positive volumetric strains that occurred in the air-injected partially saturated soils. In addition to this, the foundation imposed static shear stresses caused localised bearing failure deformations, resulting in a small punching of settlement of foundation. However, as observed in the current paper the air-induced settlements were notably small, and therefore its effect on the seismic response was assumed to be negligible.

The comparison of the co-seismic and post-seismic settlements in the fully and air-injected partially saturated soils in Fig.5 shows that post seismic settlements in the latter case were significantly smaller, compared to the former case, but co-seismic settlements were larger. The reason behind this trend was explained by the quicker dissipation of excess pore pressures in the air-injected partially saturated soils [12]. The presence of pockets of air bubbles within the soil formed artificial drainage boundaries and shortened the drainage paths, leading the faster drainage to occur. The possible explanation for the increased co-seismic free-field settlements in the partially saturated soils might be this stronger tendency for drainage as well as increased compressibility of soil matrix. The increased potential for drainage during cyclic loading further increased cyclic shear-induced localised volumetric strains. This finding indicates that reducing the degree of saturation of soils through air injection can be an effective approach to reduce the post-liquefaction volumetric settlements due to re-consolidation, which is relatively consistent with the finding of Sawada et al. [13].

The observations made during the partially saturated soil experiments suggested that after earthquakes stopped small amount of entrapped air bubbles tried to escape from the soil medium. As the excess pore pressures were built up, the increased pore fluid pressures increased the buoyancy forces acting on the bubbles, and moved some of them up. The moving air bubbles slightly pushed the upper particles of partially saturated soils on top where the confining stresses are almost zero. This eventually led to volumetric expansion in these regions. However, it is clear that the volumetric settlements that occurred due to the consolidation associated with the excess pore pressure dissipation and localised volumetric strains associated with increased drainage tendency surpass this volumetric expansion in the air-injected partially saturated soils.

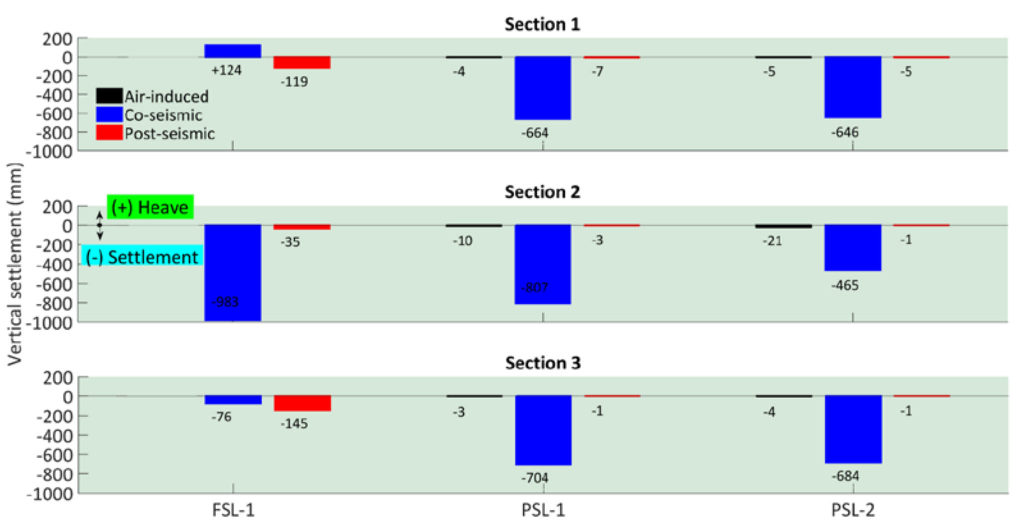

Fig. 5 – Total air-induced, co-seismic and post seismic settlements in the free field (Section 1 and 3) and under foundation (Section 2)

3.2 Deformation mechanisms

The surface settlement trough (profile) in the fully saturated soil (FSL-1) in Fig.6 shows that foundations settled more than the adjacent ground, and the ground adjacent to the foundations settled more than the free field. The larger settlements observed adjacent to the foundation relative to the free field were associated with the localised volumetric settlements caused by the partial drainage near the perimeter of foundation, as suggested by Dashi et al. [14]. However, the comparison of the foundation settlement relative to the free field settlement in the partially saturated soils (PSL-1 and PSL-2) showed that the difference between foundation and free field settlement was significantly smaller, when comparing to the fully saturated case. The differences in these observed trends suggest that the deformation mechanisms dominating the settlement of shallow foundation and free field are different in the case of fully and partially saturated soils. As observed on these images, very deep layer of deformation and very large lateral movements of the coloured sand columns which are evenly distributed throughout the liquefiable layer are apparent in the fully saturated soils. These are indicative of deviatoric deformations indeed. However, in the partially saturated soils, only shallow layer of soil deformation is the case. The horizontal soil movements are concentrated only at the shallow soil layer, and their magnitude is very small, relative to the fully saturated soil. This shows that volumetric, rather than deviatoric, mechanisms of settlements are responsible for the majority of the foundation settlement.

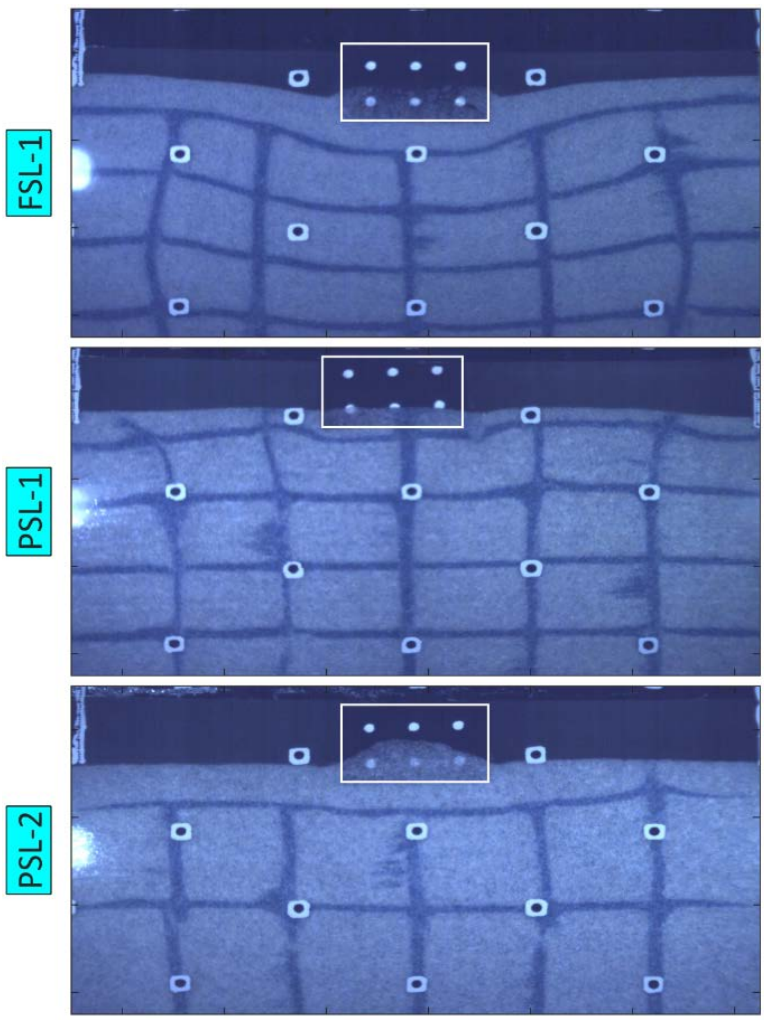

Fig. 6 – The shape of deformation after the end of the shakings (FSL-1: 28; PSL-1: 190 and PSL-2: 330 seconds)

The altering effect of air injection into the saturated liquefiable medium on the dominant deformation mechanisms was shown in the case of a heavy shallow foundation with a bearing pressure of 135 kPa [8]. In this paper, this phenomenon was investigated underneath a relatively light foundation with a bearing pressure of 50 kPa. Fig.7 presents the accumulated displacements occurring through an equal number of acceleration cycles (17) beneath foundation. The displacements illustrated at the same scale in Fig.7- (a-c) clearly show that the deformations in the partially saturated soils (PSL-1 and PSL-2) were comparatively very small. For the better illustration of deformation mechanisms, the magnitude of displacements during PSL-1 and PSL-2 are magnified by 5 times and shown in Fig.7- (e-f). It is clear that the deviatoric and volumetric soil strains and the consequent soil displacements were both apparent, but the deviatoric strains were more dominant to the foundation settlement in the fully saturated soil. There was a strong tendency for horizontal soil movements. The depth of liquefaction increased to a level where a bearing shear mechanism formed. However, in the partially saturated soils the deviatoric shear strains and consequent horizontal movement of foundation soil were significantly reduced. The positive volumetric strains, associated with the increased compressibility of the air-injected soil and stronger drainage tendency, increased, which led to vertical soil deformations. However, even with this increase the overall deformations were still much smaller, compared to those observed in the fully saturated soil. The lateral soil movements into the free-field were significantly reduced, and they were concentrated only at the shallow layers of partially saturated soils.

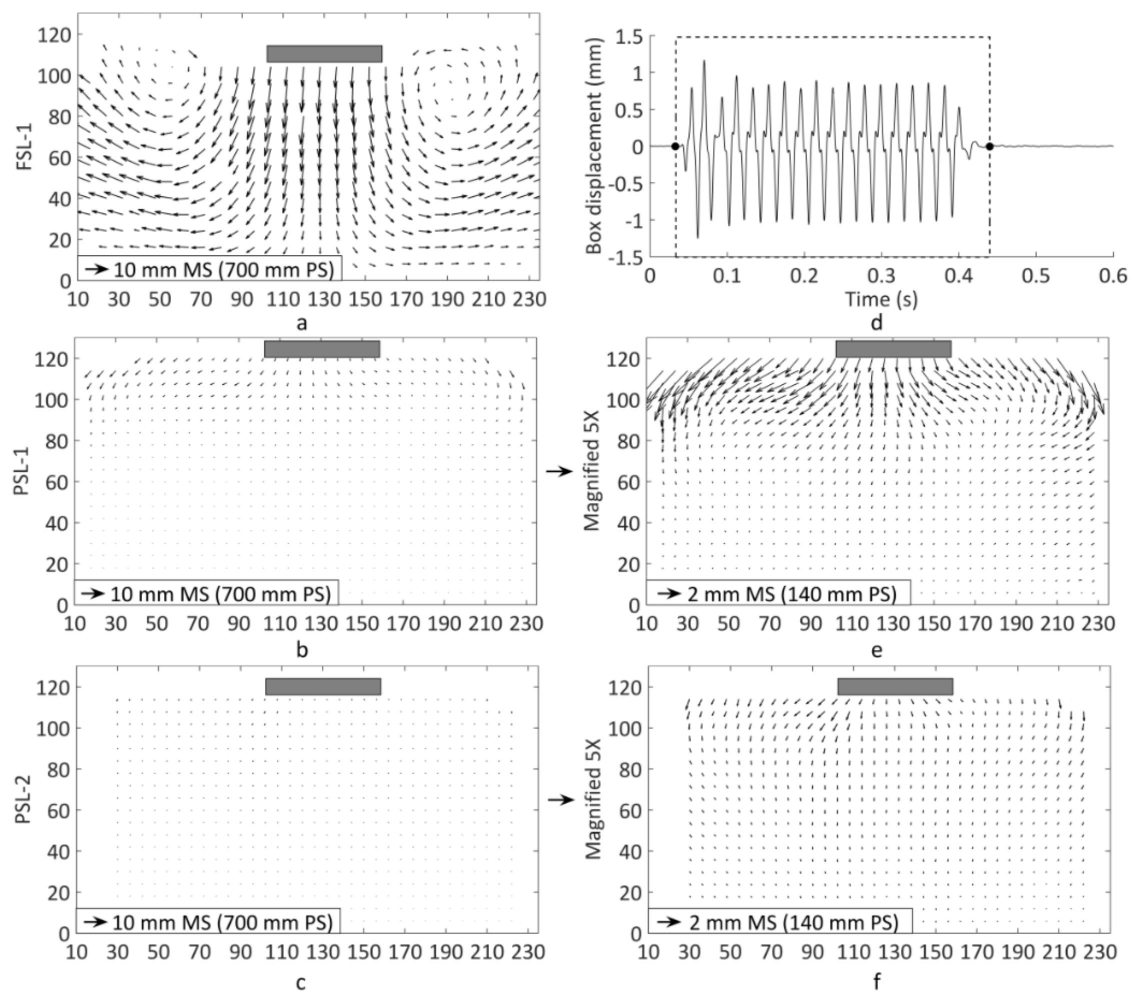

Fig. 7 – Accumulated soil deformations during the earthquake events (Zeybek and Madabhushi [12])

4. Discussions on deformation mechanisms of the air-injected partially saturated soils

The application of air injection as a liquefaction mitigation technique on the buildings with shallow foundations can be more effectively performed when the most critical liquefaction-induced deformation mechanisms and their subsequent contributions to the overall foundation settlements are clearly identified for the unimproved, fully saturated soil deposits. Then, the performance of air injection in minimizing these deformations can be successfully evaluated. Based on the centrifuge experiments on the buildings with shallow foundations, Dashti et al. [14] identified the dominant mechanisms of liquefaction-induced building settlements, and they classified these as volumetric and deviatoric settlement mechanisms. In the current study, based on the observations and results obtained from fully saturated soil test (FSL-1), the majority of the settlement mechanisms they identified were confirmed. The volumetric strains and more dominantly deviatoric strains led to large foundation settlements in the fully saturated soil. In addition, the deformation mechanisms that involve in the air-injected partially saturated soils were determined here, and similarly grouped into two as 'volumetric' and 'deviatoric' (see Table 2). Although some deviatoric type of deformations were present, the majority of the settlements were caused by the volumetric type of deformation mechanisms in the air-injected partially saturated soils (PSL-1 and PSL-2).

Table 2 – Mechanisms of ground and foundation deformations

Mechanisms of deformations in the air-injected partially saturated soils		
Type of deformation	**Mechanisms of deformation**	
	During air injection	**During and after earthquake**
Volumetric	Positive volumetric strains due to the seepage-induced liquefaction	Localised volumetric strains due to the increased potential for drainage
	Positive volumetric strains due to the increased compressibility of soil matrix	Positive volumetric strains due to the increased compressibility of soil matrix
		Volumetric strains due to the consolidation during excess pore pressures dissipation
		Negative volumetric strains (expansion) due to upward air bubble movement
Deviatoric	Localised and partial bearing failure due to the strength loss in the foundation soil during upward-seepage	Limited bearing capacity failure
		Limited cumulative foundation settlements due to SSI-induced cyclic loading

The influence of each deformation mechanism is evaluated here. It is found that the injection of air bubbles into the saturated, liquefiable soil layer reduced the lateral soil movements, the depth of liquefaction, the post-earthquake reconsolidation settlements, and the cumulative foundation settlements due to soil-structure interaction cyclic loading. The presence of air bubbles provided a lateral confinement for the foundation soil, and the lateral movement of this soil into the free field was significantly prevented. The depth of liquefaction was also reduced significantly, and bearing shear mechanism under the shallow foundation did not form. The volumetric deformation mechanisms became dominant to the overall foundation settlement. Air injection allowed for reducing the shear strains, and limited the deviatoric type of deformations under the static and dynamic stresses induced by foundation.

The air injection on the other hand intensified the majority of volumetric settlement mechanisms. The localised volumetric strains due to the partial drainage increased as a result of the increased potential for drainage. The pockets of air bubbles created artificial drainage boundaries and shortened the drainage paths in the partially saturated soils, and this resulted in larger volumetric strains during earthquakes. The presence of air bubbles inside the pore fluid also increased the compressibility of pore fluid and therefore overall soil matrix, leading to more positive volumetric strains.

Air injection decreases the deviatoric type of deformations, increases the stiffness and shear resistance of soil beneath the foundation. The partially saturated soil with greater stiffness and larger resistance to soil softening reduces the probability of bearing capacity failure. However, this might have an adverse effect by amplifying the soil and structural accelerations. Zeybek and Madabhushi [12] indicated that the use of air-injection as a liquefaction mitigation measure does reduce structural settlements, but will have the consequence of larger structural accelerations. This effect was more notable under an unliquefied and much stiffer soil zone beneath a heavy shallow foundation, as expected. Balakrishnan and Kutter [15] explained how the natural period of the soil deposits changes when the stiffness of the soil alters. This may increase the ground motion amplification depending on the predominant period of ground motion. It is therefore suggested that the use of air injection might have an amplifying effect on the SSI-induced structural settlements, depending on the type of structures, natural periods of ground and structures.

5. Conclusions

A series of centrifuge tests on the shallow foundation were performed in this study to investigate the efficacy of air injection on reducing shallow foundation settlements. Moreover, based on the PIV analysis of images the dominant deformation mechanisms in the fully (unimproved soil deposit) and partially saturated soils (improved soil deposits with air injection) were identified. The results obtained are expected to provide a thorough understanding of the air injection technique as a liquefaction mitigation technique, and allow for more efficient application of this technique in the field.

It has been shown, based on the centrifuge tests on the shallow foundation, that the air injection technique is very successful reducing the liquefaction-induced settlements of shallow foundation. The deformation mechanisms, based on the PIV analysis images, also demonstrate that the settlement of foundation was mostly controlled by the volumetric deformation mechanisms in the air-injected partially saturated soils. The deviatoric shear strains were significantly reduced, and the overall foundation settlement was reduced by up to at least 48%. The subsequent contribution of each deformation mechanism to the overall foundation settlements was identified. Minimising shear-induced deformations and limiting the lateral flow of foundation soil was possible with this particular mitigation technique. Moreover, it was successful to reduce the post-earthquake volumetric settlements due to re-consolidation. On the other hand, it has an intensifying impact on the co-seismic localised volumetric strains and positive volumetric strains that occurred due to increased drainage tendency and volume compressibility.

7. Copyrights

7. References

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