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Influence of air injection on the liquefaction-induced deformation mechanisms beneath shallow foundations

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ABSTRACT

Earthquake-induced liquefaction of soils frequently causes serious damage to structures with shallow foundations. Reducing the degree of saturation of liquefiable soils by air injection is offered as a cost-effective and reliable method of mitigating liquefaction hazards. Nevertheless, very little experimental research is available on the performance of this method. Particularly, the way that air injection influences the deformation mechanisms beneath shallow foundations is not well defined. Gaining a deeper insight into soil displacements during and after air injection can pave the way for developing effective guidelines for the use of this particular technique. For this purpose, a series of dynamic centrifuge tests are presented in this paper. The prevailing deformation mechanisms are identified in a novel way using displacement vector fields. The results indicate that air injection alters the deformation mechanisms that develop underneath and in the ground surrounding a shallow foundation, substantially reducing the average settlements.

1. Introduction

Seismically-induced liquefaction of soils has caused many structures with shallow foundations to suffer severe damage during most moderate to large earthquakes. Some of the prime examples of this are the recent earthquakes in Turkey [1], Chile [2] and Japan [3]. For many years, engineers have conducted several research programmes to develop different types of liquefaction mitigation techniques. A brief list of currently available liquefaction mitigation techniques is given by Seed et al. [4]. These techniques are usually not employed singly, but the combination of two or more is used in practice. The majority of these techniques are often expensive due to their installation costs, and their applications to foundation soils of existing structures are limited. In recent years, many researches have therefore directed their attention towards the development of new liquefaction mitigation techniques that can be implemented beneath the foundation of existing structures as well as at new construction sites.

Natural soils below ground water table are typically considered to be fully or nearly fully saturated [5]. However, partially saturated soils that have formed as a result of biological activities can be also encountered in nature [6]. The degree of saturation, S_r of these soils is relatively low compared to fully saturated soils, and the reduction in the degree of saturation is attributed to the presence of retained air bubbles within the voids of soil. The influence of degree of saturation on the liquefaction resistance of soils has been investigated by several researchers through laboratory tests [7,8]. The test results have demonstrated that the liquefaction potential of saturated soils can be markedly decreased by even a small amount of reduction in the degree of saturation. In the light of these findings, recently attempts have been made to lower the degree of saturation of liquefiable soil deposits by artificially introducing gas bubbles into soils. Several methods have been used for this purpose, including water electrolysis [9], drainage-recharge [9,10], chemical- sodium perborate [11] and biogas [12].

Air injection is another technique that is used for lowering the degree of saturation. This approach basically relies on artificially injecting air into saturated, liquefiable soils without causing significant hydrofracture. Investigations on this particular technique have revealed that injection of air into soil deposits can substantially reduce the degree of saturation [13,14]. The longevity of air bubbles in the soil was studied by Eseller-Bayat et al. [11] and Okamura et al. [15]. It is shown that air bubbles introduced into saturated soil can remain entrapped for a long period of time and do not dissipate easily, which makes this technique reliable. Air injection is a cost-effective and eco-friendly liquefaction mitigation technique since it requires only the use of air, and its impact on the environment is insignificant [16]. These facts have recently led this particular technique to be greatly attractive for researchers and engineers. The application of this technique in practice such as beneath an existing embankment was demonstrated by

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Okamura et al. [17]. The research particularly investigating the response of shallow foundations resting on the liquefiable soils has suggested that the liquefaction potential of soil deposits and relevant foundation settlements significantly decrease with the injection of air [18,19]. The increase in the liquefaction resistance of soils is attributed to the presence of air in the voids of soil. Air in the pores decreases the bulk modulus and increases the compressibility of pore fluid which is air-water mixture. During shaking, the existing air absorbs the generated excess pore pressures by reducing in volume [8].

The previous studies have proven that air injection technique can be an effective way of minimizing the liquefaction-induced foundation settlements. Nevertheless, a comprehensive understanding of the way that air injection affects the seismic response of soils and foundations is still required. In reality, very little experimental research is available as to what the displacement mechanisms beneath and around the edges of shallow foundations resting on partially saturated soils resemble. Therefore, more research is wanting. Gaining a deeper insight into soil displacements can provide better estimation of the extend of liquefaction mitigation needed as well as the potential soil and foundation deformations (e.g., magnitude and rate of settlement and rotations). This eventually can pave the way for developing effective guidelines for air injection technique, and this can allow the engineers to use it in the field more confidently and more often. As part of this research, a spectrum of parameters that influence the soil deformations including degree of saturation and foundation bearing pressure were investigated separately by Zeybek and Madabhushi [20]. The aim of the current paper is to identify the deformation mechanisms that involve in the saturated and partially saturated soils. Of particular interest is the way that the deformation mechanisms which dominate the settlement of shallow foundations supporting typical structures change depending on the presence of air bubbles in the soil deposits. For this purpose, the derived displacement vector fields from the saturated and partially saturated soil layers are presented, and the corresponding results are compared. It is hoped to reinforce and build on the previous research with the findings presented in this paper.

2. Centrifuge testing programme

Geotechnical centrifugal modelling offers an opportunity of testing small-scale models under increased gravitational field and recreating prototype stresses and strains, which in turn replicates the true soil behaviour. A series of five centrifuge experiments were performed on the Turner Beam Centrifuge at the Schofield Centre of the University of Cambridge. More details about the geotechnical centrifuge facilities and instrumentation are provided by Madabhushi [21]. Centrifuge models, representing plain strain problems, were prepared and spun at a nominal centrifugal acceleration of 70*g*. Unless otherwise indicated, all units presented in this paper are in prototype scale. A 3.5 m wide shallow foundation model with a bearing pressure of 135 kPa, representing a strip footing of a heavy structure, was considered. Two benchmark centrifuge experiments were performed in order to investigate the seismic response of nearly fully saturated (unimproved) soils in the free-field and beneath the shallow foundation. It is highlighted that for the remainder of this paper the term ‘*saturated soil*’ is used in direct reference to the nearly fully saturated soil. In a similar way, the seismic behaviour of partially saturated soils (improved by air injection) was studied undertaking three centrifuge tests. Table 1 provides a summary of the centrifuge test parameters and testing programme.

2.1. Model preparation

The choice of model container for this study was dictated by the need to have a transparent side to conduct high speed photogrammetry. Therefore, a rigid container with a Perspex window was used. This type of model container may cause boundary effects due to its rigid walls and therefore affect the model response, particularly when liquefaction is reached. Therefore, a soft putty-like material called Duxseal® was used at the container end walls to minimize the boundary effects in the direction of earthquake loading. Steedman and Madabhushi [22] showed that Duxseal can reduce the stress wave reflections by about two-thirds.

The soil under consideration was Hostun HN31 sand (d_{10}=0.315 mm, 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, AEV of 1.3 kPa). The soil profiles that were tested in this study consisted of homogenous Hostun sand layers prepared at a relative density of about 40%, using air pluviation technique and an automatic sand pourer described in [21]. For the application of air injection in the partially saturated models, a rubber air curtain hose, with several tiny openings of about 0.5 mm diameter and 5 mm spacing, was placed on the centre-bottom of the model container. The sand was dry pluviated to attain 240 mm deep sand deposits, representing 16.8 m soil layers in prototype scale. During the model preparation, arrays of miniature pore pressure transducers (PPTs), piezoelectric and micro-electromechanical system (MEMS) accelerometers were positioned at the desired locations. Linear variable differential transducers (LVDTs) were also used to measure the settlements at different locations. Apart from the free-field centrifuge tests, the foundation was placed on the soil surface in each test. The schematic cross-section of the models is shown in Fig. 1.

In dynamic centrifuge modelling, adjusting the viscosity of the pore fluid by the same value as the gravity level is an accepted procedure to avoid the incompatibility between the dynamic and diffusion time scaling laws [23]. For this purpose, a high viscosity aqueous solution of hydroxypropyl methylcellulose (HPMC) was prepared with a viscosity of 70 cSt. The dry sand models were saturated very slowly with the viscous fluid and using the CAM-Sat system, as described by Stringer and Madabhushi [24]. The conventional mass and volume method was used to determine the degrees of saturation of models. The computed degrees of saturation at the end of the saturation process were consistently above 99%. It is worth noting that the masses, volumes and densities of the pore fluid and solids were determined very carefully. However, certain errors were still expected to happen in the computed saturation ratios due to the sensitivity of the conventional method [25]. The phreatic surface of the saturated models was approximately 0.35 m above the ground surface after spinning.

A stored angular momentum (SAM) actuator device [26] was used to generate sinusoidal pseudo-harmonic input motions. The shakings were parallel to the long side of models. Peak base acceleration of around 0.18g was used for the tests.

2.2. Air injection process

To prepare the partially saturated soils, air was injected into the saturated models at the centrifugal acceleration of 70*g*, prior to each earthquake. Fig. 2 presents typical pressure-time and foundation settlement-time histories recorded during this process in PS-1 and PS-2. It is evident that different approaches were taken in each case. In PS-1, air pressure was increased rapidly until air bubbles became apparent on the ground surface. This resulted in a foundation settlement of 2.57 mm in model scale (180 mm in prototype), which would not be acceptable if this technique was applied to a field structure. In PS-2, a different approach was taken in which air injection pressure was increased gradually, and the response of foundation was monitored very carefully. As seen, the maximum air injection pressure was comparatively lower. The air-induced foundation settlement was only 0.2 mm in model scale (14 mm in prototype), which was quite smaller and tolerable.

In both cases, air began to enter the saturated granular medium when the air pressure reached the sum of hydrostatic pressure at the injection point and air entry value of soil. The ground water level rose due to the volume of pore fluid replaced by the volume of air that entered into the soil. The change in the water level thus pressure was