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Numerical simulation of centrifuge tests to evaluate the performance of desaturation by air injection on liquefiable foundation soil of light structures

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Abstract

Four dynamic centrifuge tests were conducted to study the performance of a newly developed countermeasure technique against soil liquefaction: "desaturation by air injection". In the experiment, liquefiable foundation soils below lightweight structures were desaturated by the air injection technique and base shaking was imparted to the models to obtain a comprehensive set of response data. In this study, numerical simulations of these experiments were conducted by using a two-phase (solid and fluid) fully coupled finite-element code, Coupled Analysis of Liquefaction (LIQCA-2D), to validate the numerical procedures. The mechanical properties of the soil in the saturated and desaturated zones in the models were exactly the same, with the exception of the degree of saturation. The simulation attempted to examine the desaturated models by changing the compressibility of the pore fluid, in which all input parameters for saturated and desaturated models were the same except for the bulk modulus, K^f. Numerical results were comparable with the test results in terms of excess pore pressures and settlement of structures for both saturated and desaturated models. This validates the numerical procedure and further assures the effectiveness of desaturation by the air injection technique as a liquefaction countermeasure.

Keywords: Centrifuge test; Numerical analysis; Liquefaction countermeasure; Degree of saturation; Shallow foundation

1. Introduction

Shallow foundations of residential buildings on liquefiable soil layers have often been damaged during large earthquakes. In recent earthquakes, such as the 2011 Darfield earthquake in New Zealand and the 2011 off the Pacific coast of Tohoku Earthquake, massive destruction of residential buildings occurred, which urgently necessitates reliable and cost-effective countermeasure techniques to remediate liquefiable foundation soils of existing residential houses (The Japanese Geotechnical Society, 2011; Yasuda and Ishikawa, 2012; Orense, 2011; Cubrinovski et al., 2012; Nakai and Sekiguch, 2012). To reduce such damage to existing residential houses, a limited number of remediation methods are available in practice. These methods are primarily based on densification, solidification, and replacement techniques and are excessively expensive.

Because the degree of saturation has a significant effect on the liquefaction resistance of soils, methods of soil desaturation have been studied as remedial measures for liquefaction, which include water electrolysis (Yegian et al., 2006, 2007) and gas

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production in soil by microorganism activity (He et al., 2013). In recent years, an innovative liquefaction countermeasure technique desaturation by air injection has been developed (Okamura et al., 2011, 2012a, 2012b) and has attracted significant interest from engineers because of its extreme affordability and environmental friendliness. It has been reported that injection of air into the ground can substantially lower the degree of saturation of the subsoil (Tokimatsu et al., 1990; Okamura et al., 2003) and this unsaturated condition of the desaturated soils lasts for an extensive time period, typically decades or more (Okamura et al., 2006). Okamura et al. (2011) conducted an in situ air injection test and confirmed that soil in the zone of influence, which is approximately 3.5 m from the injection port, was effectively desaturated. Tomida (2014) conducted a similar test under a road embankment with relatively high air injection pressure and found that the radius of the desaturated zone from the single injector, which increased with increasing air pressure and injection time, extended 9 m in 18 h. Because the material for this technique is free, drilling and installation of injection pipes amounts to the majority of execution costs. A dramatic reduction in estimated execution costs has been achieved by increasing the radius of the desaturated zone.

The effect of degree of saturation on the liquefaction resistance of soils has been studied since the 1960s through undrained cyclic shear tests. The existence of air in pores of soils reduces the bulk modulus of pore fluid (that is, the air–water mixture), which results in increased liquefaction resistance. Changes in the volume of pore fluid during cyclic shearing was found to be the factor dominating this mechanism of enhancing soil resistance to liquefaction (Okamura and Soga, 2006; Unno et al., 2008).

Regarding numerical simulation, limited research has been conducted on this topic. Mitsuji (2008) tried to simulate seismic behavior of unsaturated sand deposits with a one-dimensional effective stress analysis, in which incomplete saturation of the sand was modelled by reducing the bulk modulus of pore fluid. He found that velocity, displacement, and shearing strain of the ground decreased with decreasing the bulk modulus. Gao et al. (2013) developed a computational model based on the Biot's two phase mixture theory and conducted numerical simulations on the behaviors of unsaturated soils under cyclic loadings. They also studied effects of the bulk modulus of the pore fluid on the pore pressure evolution at different initial degree of saturation. Similarly, Yashima et al. (1995) conducted three dimensional liquefaction analysis based on the Biot's theory to observe effects of pore fluid compressibility due to the imperfect saturation of reclaimed soil layers. They found that the strong motion array records of the Port Island observed during the 1995 Hyogoken-Nambu Earthquake were simulated reasonably well. All these numerical analysis mentioned above have dealt with the pore pressure and the acceleration responses of level ground.

Recently, highly instrumented centrifuge tests were conducted to assess the performance of the desaturation technique as a liquefaction countermeasure for soils immediately beneath existing structures (Marasini and Okamura, 2015). The recorded model responses provide an unique opportunity to verify performance of the numerical procedures. In this study an attempt was made to verify the numerical procedure to simulate deformation of locally desaturated soil with structures. This paper presents the results of a computational study based on a comprehensive experimental set of data. The four centrifuge models tested using the geotechnical centrifuge at Ehime University were simulated by using Coupled Analysis of Liquefaction (LIQCA-2D) (Oka et al., 1994, 1999), a finite-element method (FEM)-based effective stress analysis.

2. Overview of centrifuge tests

Marasini and Okamura (2015) performed four centrifuge tests to investigate the effectiveness of desaturation by air injection to mitigate liquefaction-induced settlement of lightweight structures. Schematic illustrations and test conditions of the centrifuge models are presented in Fig. 1 and Table 1, respectively. Models of a structure, with a base contact pressure of either 10 kPa or 35 kPa, resting on either fully saturated or desaturated foundation soils, were prepared at 1:50 scale and tested in the centrifuge at 50g.

The models were prepared in a rigid container with internal dimensions of a 430 mm length, 120 mm width, and 230 mm depth. The soil used for the foundation soil layer was Toyoura sand. A 20-mm-deep dense sand layer was prepared at a relative density of $D_r=90\%$ on the base of the container. For Models M1-2 and M2-2, a two-dimensional air injector with 1-mm-wide orifices on both sides was placed on the dense sand layer. The dry sand was then poured into the container to form a 120-mm-deep uniform sand deposit at $D_r=50\%$. The models were fully saturated in a vacuum environment with an aid of the CO_2 replacement technique. The substituted pore fluid was deaired viscous fluid, with a viscosity 50 times that of water (equivalent to g level).

On completion of the saturation process, the degree of saturation (S_r) of the model was measured by the method developed by Okamura and Inoue (2012). The estimated degree of saturation of all models was very high, in a range between 99.70% and 99.84%.

A mild steel plate, 120 mm wide and either 2.5 mm or 9 mm high, representing the two-dimensional shallow foundation of residential houses, was placed on the surface with two potentiometers for measurement of vertical settlement. The base contact pressures of the lighter and heavier foundations at 50 g were 10 kPa and 35 kPa, respectively, which were equivalent to one- to two-story residential buildings. Each model was then set on the geotechnical centrifuge at Ehime University (http://www.cee.ehime-u.ac.jp/~gm/indexE.html), and centrifugal acceleration was gradually increased to the target level of 50g. The acceleration was kept constant to allow ample time for excess pore fluid to drain through the stand pipes until the height of the water table reached 40 mm below the ground surface.

For Models M1-2 and M2-2, air was injected at 50 g through the injector set on the dense sand layer for simulating in situ air injection to desaturate soil just below the structures. The air