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Centrifuge study into the effect of liquefaction extent on permanent settlement and seismic response of shallow foundations

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Abstract

Centrifuge experiments were conducted to investigate how the liquefaction extent affects the seismic and post-seismic settlement of shallow foundations resting on saturated sand. Two rigid foundations with different bearing pressures were placed on the ground surface in a model container. Multiple input motions were applied to achieve different extents of soil liquefaction. The results indicate that foundation settlement can be divided into three distinct phases: (I) during shaking, (II) during the time period after shaking has ceased and before soil reconsolidation in the shallowest layers has taken place, and (III) during soil reconsolidation. Contrary to the free-field ground, most of the total settlement of the foundations occurred before soil reconsolidation, i.e., during Phases I and II. The volumetric strain during these phases was not significant as opposed to the shear strain produced by the foundation surcharge. It was demonstrated that foundation settlement is not necessarily proportional to the liquefied depth of the sand. The extent of the liquefaction in the sand medium mostly affected the post-seismic settlement of the foundations, while the co-seismic settlement was relatively the same for both foundations. The response of the foundations was significantly influenced by the liquefaction extent, whereas the foundations did not experience large accelerations when the soil profile was entirely liquefied. However, the foundations tolerated large settlement under severe liquefaction conditions. The results of this study highlight the role of the liquefaction extent on co-seismic and post-seismic settlement as well as the seismic response of shallow foundations.

Keywords: Shallow foundation; Liquefaction extent; Settlement mechanism; Centrifuge modeling

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1. Introduction

Soil liquefaction has caused major damage to superstructures resting on shallow foundations during past earthquakes. Soil stiffness is greatly decreased as a result of excess pore water pressure (EPWP) generation and the consequent effective stress reduction. The degree of stiffness degradation and different extents of liquefaction in the soil media around the shallow foundations can produce various levels of damage. Reportedly, this damage is manifested in the forms of a loss in bearing capacity and large settlement.

Field observations and data collected from case histories are useful for identifying the key parameters affecting the seismic mechanism of shallow foundations resting on liquefiable soil. Examples of such damage have been reported during past earthquakes, including the Niigata 1964 earthquake (Seed and Idriss, 1967; Yoshimi and Tokimatsu, 1977; Nagase and Ishihara, 1988), the Luzon

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1990 earthquake (Adachi et al., 1992; Ishihara et al. 1993; Acacio et al. 2001; Tokimatsu et al. 1994), the Adapazari 1999 earthquake (Yoshida et al., 2001; Sancio et al., 2004), the Chile 2010 earthquake (Verdugo and Gonzalez, 2015), and the Tohoku Pacific 2011 earthquake (Tokimatsu et al., 2012; Oka et al., 2012; Koseki et al., 2012). Sand deposits with a depth of 6–10 m were liquefied in the Niigata and Luzon earthquakes. Using the Niigata earthquake data, Yoshimi and Tokimatsu (1977) defined upper and lower bounds for estimating the settlement of a shallow foundation based on its width (B) and liquefaction depth (Z_{liq}). Subsequently, the validity of the bounds for the Luzon earthquake was examined by Adachi et al. (1992). The curves have been widely used in engineering practice and research works. Bertalot et al. (2013) interpreted both new and previously reported case histories, and identified the bearing pressure of the foundation as an additional parameter affecting the settlement of the foundation.

Numerous 1-g shaking table and centrifuge experiments were conducted to interpret the complex mechanism of shallow foundation settlement in liquefiable soil. Yoshimi and Tokimatsu (1977) studied the development of pore water pressure and the settlement of a rigid footing with different bearing pressures. They suggested normalized curves for correlating the settlement, foundation width, and liquefaction depth. Liu and Dobry (1997) conducted several centrifuge tests and reported a significant amount of negative EPWP generated beneath the shallow foundations. Coelho et al. (2004) reported the issue of post-earthquake pore water pressure migration as a key factor. Adalier et al. (2003) discussed the mechanism and effectiveness of stone columns on the seismic performance of shallow footings. Dashti et al. (2010a, 2010b) explained different mechanisms incorporated in shallow foundation settlement using centrifuge studies. They noted the combined role of deviatoric strain and volumetric strain involved in the total settlement and indicated that shear deformation should be considered in the design procedures of shallow foundations resting on liquefiable soils. Dashti et al. (2010a) found that shallow foundation settlement is not proportional to the thickness of the liquefiable layer and that most of the total settlement occurs during the shaking time period. Coelho (2013) and Marques et al. (2012) investigated the liquefaction-induced settlement of rigid shallow foundations with different bearing pressures by centrifuge modeling. They mentioned that the initial static shear stress imparted by a foundation can influence the time history of the EPWP. In contrast to the observations of Dashti et al. (2010a), Marques et al. (2012) and Mehrzad et al. (2016) found that the accumulation of foundation settlement continues even after the shaking stops. Tsukamoto et al. (2012) examined the effects of the duration of seismic shaking and the group effects of closely spaced foundations. Hayden et al. (2015) conducted centrifuge experiments to observe the performance of adjacent structures affected by liquefaction. Bertalot and Brennan (2015) investigated the influence of the initial static stress and the liquefaction extent on the settlement of shallow foundations in their centrifuge studies. They noticed maximum liquefaction-induced settlement for a given bearing stress and its reduction for greater applied stresses. Ishikawa et al. (2015) studied the post-liquefaction progressive failure of shallow foundations using centrifuge modeling. They found that the settlement and the tilting of a shallow foundation will continue as long as the liquefaction state is maintained. Through centrifuge and numerical modeling, Mehrzad et al. (2016) investigated the effect of soil permeability and a foundation's bearing pressure on the seismic response of the soil-foundation system. The entire soil profile was liquefied in the lone centrifuge test reported in that paper. Based on the results of effective-stress numerical analyses, it was found that the total settlement of foundations increases with the increase in soil permeability if other parameters (e.g., shaking intensity, foundation surcharge, etc.) are assumed to be constant. Using three series of centrifuge tests reported in a preceding paper (Jafarian et al., 2017), the authors have investigated the effect of foundation-soil-foundation interaction (FSFI) on the seismic and post-seismic settlement of shallow foundations. They have introduced free and constraint boundaries to explain the asymmetric settlement which was observed in the case of close proximity.

The aim of the present study is to determine how the liquefaction extent affects the settlement mechanism of shallow foundations. Three centrifuge experiments were designed and conducted in which the depth of the soil liquefaction is changed in each experiment with a variety of input motion intensities. In each experiment, two rigid foundations with two different static bearing pressures (representative of light and heavy foundations) are located far enough away from each other to minimize the interaction effects. The experimental setup for each test is discussed in detail. This includes the soil and foundation properties, the model preparation method, the scaling laws, and the instrumentation arrangement. The testing procedure and the results are explained for each test series. The settlement of the foundations, the settlement of the free-field ground, the EPWP at various depths, and the recorded accelerations are reported for the shaking and post-shaking periods.

2. Centrifuge modeling

Geotechnical centrifuge models simulate soil systems at smaller scales and stress levels equivalent to the prototype. In the present study, three centrifuge experiments are performed with the 100*g*-ton centrifuge machine at the National Central University (NCU) of Taiwan. The centrifuge, with a diameter of 3 m, is equipped with an in-flight 1-D servo-hydraulically controlled shaker integrated into a swing basket to impart base dynamic excitation in a high gravity field. The NCU geotechnical centrifuge shaker operates in the frequency range of 0–250 Hz under the centrifugal acceleration of up to 80*g*.

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