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Centrifuge modeling of seismic foundation-soil-foundation interaction on liquefiable sand

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A R T I C L E I N F O

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A B S T R A C T

Liquefaction-induced settlement and bearing capacity failure have been reported as leading causes of damages in shallow foundations during earthquakes. Previous studies of this problem have mainly focused on the performance of isolated shallow foundations. In urban areas, however, foundations are generally located in close proximity. In this study, three series of centrifuge tests were conducted to investigate the effect of foundation-soil-foundation interaction (FSFI) on the seismic and post-seismic settlement of shallow foundations on saturated sand. Two rigid foundations with different surcharge loads (as heavy and light foundations) were placed with different spacing. Multiple shaking events were applied to achieve different extents of soil liquefaction. The results indicate that significant part of foundation settlement occurred before soil reconsolidation. Furthermore, the time period after shaking, wherein excess pore water pressure sustains, plays an important role in the total settlement of foundations. The acceleration responses experienced by the foundations were significantly larger than those observed in the free-field. The heavy foundation fluctuated more strongly than the light one. Moreover, adjacency considerably affected the seismic response of foundations whereas stronger acceleration response on the ground level was observed for the closer cases. The Clear asymmetric settlement was observed for the adjacent foundations. It is demonstrated that settlement of foundations not only is dependent on foundations' proximity but also is a function of shaking intensity. Influence of foundations' spacing on the generation-dissipation mechanism of excess pore water pressure (EPWP) and liquefaction extent was described by the time-dependent contours plotted by interpolation of the recorded data.

1. Introduction

Numerous catastrophic failures were reported in the past earthquakes in which soil liquefaction caused major damages to the superstructures resting on shallow foundations. Earthquake-induced pore pressure buildup and associated shear strength reduction of liquefied sands may result in bearing capacity degradation and seismic settlement accumulation of shallow foundations. Most of the damaged structures in the past earthquakes were located close to each other in urban areas. Considerable damages have been reported for such foundations which suffered improper design of shallow footing on liquefiable soils. Accordingly, numerous studies have been carried out to assess these complicated mechanisms (e.g., [1–4]).

Approximately 340 reinforced concrete buildings were damaged by excessive settlement and tilting as a result of liquefaction, during the Niigata 1964 earthquake (e.g., [1,5,6]). Remarkable extents of subsoil liquefaction were also observed in the city of Dagupan during the 1990 Luzon Philippines earthquake, wherein many buildings experienced excessive settlement (e.g., [7–9]). Significant settlements were observed in corner buildings, in building without adjacent structures in one or both sides, in buildings surrounded by lightweight structures, and in those part of the area where there was greater separation between adjacent buildings [10]. Tokimatsu et al. [11] reported that structures movements were related to foundation dimensions, confining pressure, and the shear stress imposed by the buildings and their adjacent structures. During the Adapazari, Turkey, 1999 earthquake, many structures were damaged by the liquefaction of shallow and relatively thin layers of saturated sand [12].

In addition to the field studies, numerous experimental efforts including 1g shaking table and centrifuge experiments were conducted for a better understanding of this problem. Yoshimi and Tokimatsu [1] studied the factors such as pore pressure development and structure's width, height and contact pressure which influenced the settlement of the structure. Liu and Dobry [2] focused on soil densification and soil

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permeability on pore pressure buildup and foundation settlement using several centrifuge tests and reported a significant amount of negative excess pore pressure generated beneath the shallow foundations. Partial drainage was shown to occur simultaneously with excess pore pressure buildup, as fast pore water pressure redistribution took place in a three-dimensional pattern in response to transient hydraulic gradients. Coelho et al. [13,14] reported the issue of post-earthquake pore pressure migration as a key factor in bridge foundation settlement during earthquake excitation. Adalier et al. [15] discussed the mechanisms involved in shallow foundation settlement and the influence of stone column as liquefaction countermeasure. Dashti et al. [3,16] centrifuge studies confirm the combined role of the shear strains imparted by the superstructure and the post-liquefaction volumetric strains as dominant mechanisms of total settlement. Coelho [17] and Marques et al. [18] mentioned that the initial static shear stress imparted by rigid foundation influences excess pore pressure history. Mehrzad et al. [19] investigated the effect of soil permeability and contact pressure on foundation response through the centrifuge and numerical models and reported that settlement of foundations increased with the increase of soil permeability. Entire soil profile was liquefied during their centrifuge tests. In contrast to Dashti et al. [3] observation, Marques et al. [18] and Mehrzad et al. [19] found that foundations settlement continues even after shaking is stopped. The mechanism and the amount of post-seismic settlement may be related to the properties of soil, structure, and input motion.

All of the reviewed studies deal with liquefaction-induced settlement of isolated foundations, without adjacent structures. However, in urban areas, structures are located in close proximity which may affect the seismic response of foundations. There are a few studies which address the influence of adjacent structures on settlement mechanism of shallow foundations. Mason et al. [20] examined seismic soil–foundation–structure interaction of framed structures through centrifuge experiments. They found that structure-soil-structure interaction (SSSI) can be beneficial or detrimental, depending on the earthquake motion and the structural system. Tsukamoto et al. [4] conducted two series of seismic 1*g* shaking table tests on rigid circular foundations to examine the effects of shaking duration and the group effects of foundations. Settlements during the shaking time remained almost the same, regardless of the foundations spacing. The post-shaking settlements, however, were different for different spacing. Foundations settled often less when located close to each other. This phenomenon is referred to as site-city effects [21]. Hayden et al. [22] conducted centrifuge experiments to observe the performance of adjacent structures affected by liquefaction. They found that adjacent structures tended to tilt away from one another and settled less than isolated structures. Although, they mentioned that the proximity of foundations would have complex effects, including the tilting of each foundation; they did not discuss factors which influence its mechanisms.

This paper focuses on foundation-soil-foundation interaction (FSFI) in the liquefiable sand. Three centrifuge experiments were designed to examine the effect of foundation proximity on seismic response and liquefaction-induced settlement of foundations. Two rigid foundations with two different static contact pressures (representative of light and heavy foundations) were located in three different spacing from each other. Experimental setups for each test will be discussed in detail. This includes soil and foundation properties, model preparation method, scaling laws, centrifuge boundary effects, and instrumentation arrangement. Testing procedure and the results will be fully explained for each test series. Settlement of the both foundations (in different spacing) and the free-field, excess pore water pressure (EPWP), and recorded accelerations will be reported precisely during shaking and post-shaking periods.

2. Centrifuge shaking table tests

The purpose of geotechnical centrifuge modeling is to simulate soil systems in smaller scales. Centrifuge modeling data provides a basis for calibration of design and computational modeling procedures [23]. Details of the centrifuge modeling in this study are described in the following sections.

2.1. Testing equipment

The experiments were performed in the 100*g*-ton centrifuge at the National Central University (NCU), Taiwan. The NCU Centrifuge has a nominal radius of 3 m and has 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 shaker has a maximum nominal shaking force of 53.4 kN with a maximum table displacement of 76.4 mm and operates up to the acceleration of 80*g*. The nominal operating frequency range of shaking is 0–250 Hz. The table-payload mounting area is 1000×546×500 mm (L×W×H).

A laminar container, with inner dimensions of 711×356×353 mm (Length×Width×Height) and constructed of 38 light-weight aluminum alloy frames, was employed for these experiments. Each frame is 8.9 mm in height, separated from adjacent rings by roller bearings. Roller bearings were specially designed to permit translation in the longitudinal direction with minimal frictional resistance. A relative displacement of up to 2.5 mm between adjacent frames was possible, for a total overall shear strain of up to 15%. Each frame had a high lateral stiffness to maintain overall conditions of zero lateral strain and a constant horizontal cross-section during shaking at 80*g* centrifugal acceleration. The laminar container was designed for dry or saturated soil models and permits the development of stresses and strains associated with 1-D shear wave propagation. A flexible 0.3 mm thick latex membrane bag was used to retain the soil and the pore fluid within the laminar container.

2.2. Similitude laws

The main principle in centrifuge modeling is that a 1/N scale model subjected to a gravitational acceleration of Ng (where g is acceleration of gravity) could experience the same stress as the prototype. If the same soil with the same density, ρ, is used in the model and in the prototype, then for a centrifuge model subjected to an inertial acceleration field N times earth's gravity, the vertical stress at depth h_m (the subscript m denotes the centrifuge model) is identical to that of the corresponding prototype at depth h_p (the subscript p denotes the prototype), where $h_p=Nh_m$ and the scale factor (model: prototype) for linear dimensions is 1: N. This relationship is the scaling law of centrifuge modeling; i.e. stress and pressure similarities are achieved at homologous points. The key scaling relationships for dynamic events are shown in Table 1. In fact, the scaling factors are relationships between a prototype subjected to base shaking (the amplitude of the base acceleration, a_p, and the frequency, f_p) in earth's gravity (1*g*) and the corresponding 1/N centrifuge model tested at an acceleration of Ng. The centrifuge model is subjected to a scaled base shaking with the acceleration amplitude of $a_m=Na_p$ and the frequency of $f_m=Nf_p$. The scale factors retain the stress and pressure similarities of the linear dimensions and base acceleration of the centrifuge model and the prototype are 1: N and 1: N^{-1}, respectively.

Table 1
Scaling relationships for dynamic centrifuge modeling.

Parameter	Prototype	Model (Ng)
Stress and pressure	1	1
Displacement	1	1/N
Velocity	1	1
Acceleration	1	N
Frequency	1	N
Time (dynamic)	1	1/N
Time (consolidation)	1	$1/N^2$