Soil Dynamics and Earthquake Engineering 65 (2014) 72–88

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Centrifuge modeling of the seismic responses of sand deposits with an intra-silt layer

Chung-Jung Lee *, Huei-Tsyr Chen, Hon-Chen Lien, Yu-Chen Wei, Wen-Yi Hung

Department of Civil Engineering, National Central University, Jhongli, Taiwan

ARTICLE INFO

Article history:
Received 12 August 2013
Received in revised form
29 May 2014
Accepted 4 June 2014

Keywords:
Intra-silt layer
Liquefaction
Water film
Hydraulic gradient
Centrifuge shaking table test

ABSTRACT

Three dynamic centrifuge model tests were conducted at an acceleration of 80*g* to simulate the seismic responses of level sand deposits: an intra-silt layer was embedded in two of these sand deposits at different depths. The effects of a low-permeability intra-silt layer on the build-up and dissipation of excess pore-water pressure, surface settlement, and the related liquefaction mechanism were investigated. An intra-silt layer modifies the seismic response of the sand deposit, reduces the extent of liquefaction, and thus decreases surface settlement. The depth of the intra-silt layer is one of the factors influencing the seismic responses of the sand deposits. The magnitude of the surface settlement is proportional to the degree of liquefaction in the sand deposit. The high positive hydraulic gradients appearing in both the intra-silt layer and in the sand deposit lying on the intra-silt layer can break a thinner or weaker top layer and result in sand boiling. Our visual animation of the ratio of the excess pore-water pressure and the lateral displacement revealed that the liquefaction front travels upward during shaking and the solidification front travels upward after shaking.

1. Introduction

Recent major seismic events, such as the 1989 Loma Prieta earthquake, the 1999 Taiwan Chi-Chi earthquake, the 1995 Kobe earthquake, and the 2011 Tohoku earthquake, have demonstrated the damaging effects of earthquake-induced soil liquefaction. Soil liquefaction, or the partial loss of soil strength, causes severe damage to geotechnical structure systems (e.g., settling of buildings, slope failures, uplift of light-weight substructures, and pile damage resulting from the lateral spreading of liquefied soils). Typically, natural soil deposits consist of sub-layers with varied grain sizes and varied permeability, such as thin silt or clay layers, which can be continuous horizontally. It is not easy to identify thin silt or clay sub-layers with geotechnical subsoil exploration procedures. If a silt or clay seam is sandwiched in a sand deposit, an upward flow of pore water during and after an earthquake will form a film of water beneath the silt seam [1]. Kokusho [2,3] and Ozener et al. [4] performed a series of 1-*g* (*g*=the earth's gravity) model tests and 1-*g* tube tests to investigate the development of water films (or water interlayers) during and after earthquakes. Kokusho [3] used the consolidation theory to simulate the process of water film growth and decay beneath thin silt seams. The presence of a thin water film with lower shear strength can result in the lateral spreading or slope failure of a gently sloped liquefied ground, which can occur after earthquakes. Thus, the formation of water films beneath stratified layers due to differences in permeability could explain why the steady-state strength of uniform sand specimens obtained from cyclic triaxial tests lead to significantly higher values of residual strength than those estimated in field case studies [5,6].

Fiegel et al. [7] conducted centrifuge model tests that subjected layered soil deposits to base shaking, and described a mechanism for the liquefaction of such soil deposits. Zeghal et al. [8] analyzed and evaluated the degradations of the stiffness and strength of level sand-silt sites at various elevations by performing dynamic centrifuge model tests. Malvick et al. [9] performed centrifuge shake-table tests to investigate the formation of water films and void redistribution beneath silt seams. The effects of silt or clay layers on the emergence of water films are the main differences between the liquefactions observed in field and laboratory element tests. Hence, a detailed investigation of stratified soil deposits subjected to base shaking is necessary, particularly for the effective management of the liquefaction risk of foundations resting on liquefiable deposits.

In situ investigations of the phenomenon of liquefaction are difficult because earthquakes occur infrequently and unpredictably. Small-scale physical modeling is an alternative to geotechnical earthquake engineering that has been used to provide insights into failure mechanisms. Geotechnical modeling requires the reproduction of soil

* Corresponding author.
E-mail addresses: cjleeciv@ncu.edu.tw (C.-J. Lee), chenhtofpadau@seed.net.tw (H.-T. Chen), ycwei@hotmail.com.tw (Y.-C. Wei), wyhung@ncu.edu.tw (W.-Y. Hung).

http://dx.doi.org/10.1016/j.soildyn.2014.06.002
0267-7261/

Table 1
Scaling relationships for dynamic centrifuge modeling.

Parameter	Prototype	Centrifuge modeling (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	$1/N^2$

behaviors in regard to both their strength and their stiffness. Soil behavior is a function of stress level and stress history. Centrifuge modeling can recreate the stress conditions present in full-scale on a reduced scale. If the same soil with the same soil density, ρ, is used in the model and 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.

Earthquake engineering uses centrifuges to model dynamic events at relatively low cost [10]. The key scaling relationships for dynamic events are shown in Table 1. The scaling 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 and subjected to base shaking (where the amplitude of acceleration is $a_m = Na_p$ and the frequency is $f_m = Nf_p$). The scale factors that retain the stress and pressure similarities of the linear dimensions and base acceleration, a, of the centrifuge model and the prototype are 1: N and 1: N^{-1}, respectively. However, in liquefaction problems involving the dissipation of excess pore-water pressure, time scaling is derived from the governing equation of the consolidation problem. The rate of dissipation takes place N^2 times faster in the model than in full scale. Thus there is a conflict between the scaling relating to inertial effects due to shaking and the scaling relating to the dissipation of excess pore-water pressure. In centrifuge modeling, the use of viscous pore fluids, which is N times more viscous than water, to replace the water is a well-established method for satisfying the scaling laws for the movement of pore fluids through the soil during dynamic events [11,12].

A series of 1-D centrifuge shaking table tests were performed to investigate the effects of the presence of one intra-silt layer sandwiched in sand deposits on their seismic responses and the surface settlements, and on the pore-water pressure build-up and dissipation during and after shaking. Two vertical arrays of accelerometers and pore-water pressure transducers were used to monitor the time histories of acceleration and excess pore-water pressure at various depths during and after the subjection of the sand deposits to 1-D base shaking.

2. Geotechnical centrifuge modeling and testing procedures

2.1. Testing equipment

This study was conducted in the Centrifuge at the National Central University (NCU), Taiwan. The NCU Centrifuge has a nominal radius of 3 m and has a 1-D servo-hydraulically controlled shaker integrated into a swing basket [13]. The shaker has a maximum nominal shaking force of 53.4 kN with a maximum table displacement of ± 6.4 mm and operates up to an acceleration of 80g. The nominal operating frequency range of shaking is 0–250 Hz. The table-payload mounting area is 1000 mm $\times$ 546 mm $\times$ 500 mm.

A laminar container with dimensions of 711 mm $\times$ 356 mm $\times$ 353 mm was constructed from 38 light-weight aluminum alloy rings arranged in a stack. Each ring is 8.9 mm in height and is separated from adjacent rings by roller bearings, which are designed to permit translation in the longitudinal direction with minimal frictional resistance [14]. The laminar container is 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. Tested sand and the preparation of the sand beds with an intra-silt layer

Fine quartz sand and silt were used to prepare the three sand beds, two of which contained one intra-silt layer. The characteristics of the quartz sand and silt are shown in Table 2. Fig. 1 shows the grain-size distribution curves of the quartz sand and the silt used in the model tests. The permeabilities of the quartz sand and the silt with a relative density (Dr) of 40% are 6.8×10^{-5} and 7.4×10^{-6} m/s respectively. The ratio of the permeabilities of the silt and the quartz sand is approximately 10^{-1}.

The quartz sand was pluviated in a regular path into the container from a hopper at a constant falling height and a constant flow rate to prepare uniform sand deposits with a relative density of approximately 40%. The pluviation processes were interrupted to embed transducers or to construct silt layers at the specified elevations.

Table 2
Characteristics of fine quartz sand and silt.

	G_s	D_{50} (mm)	D_{10} (mm)	ρ_{max} (g/cm^3)	ρ_{min} (g/cm^3)	Permeability (m/s) in prototype scale
Quartz sand	2.65	0.193	0.147	1.66	1.44	6.8×10^{-5}
Silt	2.65	0.025	0.002	1.53	1.29	7.4×10^{-6}

[1]The maximum and minimum densities of the sand were measured in the dry state, according to the method (JSF T 161-1990) specified by the Japanese Geotechnical Society.

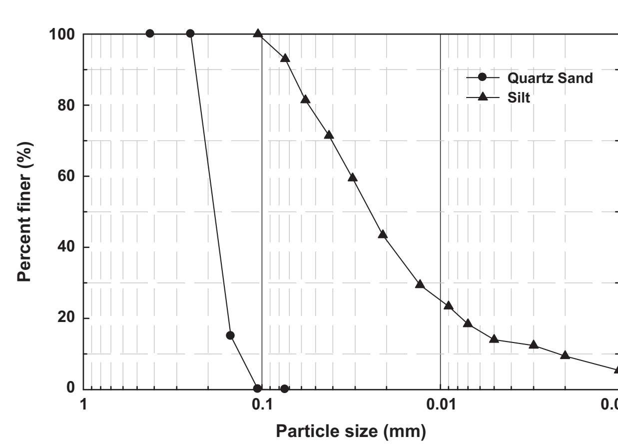

Fig. 1. Grain size distribution curves for the quartz sand and silt used in the tests.