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Effect of shaking strength on the seismic response of liquefiable level ground

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ABSTRACT

Shaking strength is one of the most important parameters that characterize earthquake events. In the past, it was common to apply shaking of different strengths consecutively on a soil model to investigate the effect of shaking level on seismic ground response, without considering the effect of loading history. In this study, a series of dynamic centrifuge tests under different shaking levels was performed on "fresh" saturated sand models with the same initial conditions to investigate the effect of shaking strength on the seismic response of liquefiable level ground. The experimental observations indicate the following effects, (1) Shaking strength has pronounced effect on the excess pore pressure buildup in the saturated sand deposit. The maximum excess pore pressure at the deep part of the deposit increased by 184% and 109% as the peak input acceleration along the *X* direction increased from approximately 0.064 *g* to 0.098 *g* and from 0.098 *g* to 0.189 *g*, respectively. (2) Shaking strength has significant effect on the development of shear strain in soil. However, the permanent settlement is sensitive to the shaking strength at low-shaking level, but the increment rate tends to slow down as the shaking strength becomes stronger. (3) The peak acceleration along the *X* direction at the ground surface was 0.126, 0.079 and 0.087 *g* at peak input accelerations of 0.064, 0.098, and 0.189 *g*, respectively. The peak acceleration at the ground surface under slight shaking was greater than that under strong shaking. (4) The amplification pattern of acceleration varied continuously during shaking. The amplification factor decreased quickly as the excess pore pressure accumulated under strong shaking, but continued to increase at an early stage under low-strength earthquake. The natural frequency of the soil column also evolved with the development of the shaking-induced excess pore pressure, which had adversely affected the wave propagation and ground response. The data presented in this paper enrich the ground response database and can be used to validate the current site-response analysis methods.

1. Introduction

Since the Niigata and Alaska earthquakes in 1964, geotechnical researchers have extensively focused on the dynamic properties of soil. Such properties are pertinent to both the performance of soil deposit and soil structure interaction, especially the liquefaction potential of cohesionless soil under various loading conditions. A typical example of such effort is the collaborated Verification of Liquefaction Analysis by Centrifuge Studies project sponsored by the National Science Foundation (Arulanandan and Scott, 1993). This project has brought together a number of universities to study the effects of earthquake-like loading on a variety of soil models and to acquire data for the validation of numerical analyses. Table 1 summarizes some, but not all, of the dynamic centrifuge tests conducted on uniformly saturated sand models in the past several decades. The test parameters and objectives in these studies are diverse. For example, Arulanandan and Sybico (1992) focused on the variation of soil permeability during shaking and the relationship of soil permeability to post-liquefaction settlement, and Adalier and Elgamal (2005) studied the effect of overconsolidation on the liquefaction potential of sand.

The analysis of the response of level ground subjected to earthquakes, which includes the evaluation of liquefaction potential, settlement, lateral deformation, and ground surface motion, is one of the most important problems in geotechnical engineering practice. Seismic response is greatly influenced by the characteristics of site soils (e.g., Bouckovalas and Kouretzis (2001), Midzi et al. (2003), González et al. (2004), Yalcinkaya and Alptekin (2005), and Berilgen (2007)). Building codes, such as the 2000 International Building Code and the 2005 National Building Code of Canada, require site-specific analysis of the ground response for sites underlain by liquefiable layers. However, practicing engineers have received little guidance on the influence of soil softening and liquefaction on the ground response (Youd and Carter, 2005), which could be caused by the limited observational and experimental data and the lack of full understanding of the mechanism behind the phenomena.

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Table 1
Dynamic centrifuge tests of uniform saturated sand deposit (in the prototype scale).

Researchers	Institution	G-level	Soil	Input motion	Thickness of soil layer, H (m)	Thickness of liquefied soil (m)	Average vertical strain after shaking
Hushmand et al. (1988)	California Institute of Technology	50 g	Nevada sand ($Dr = 54\%$)	Earthquake-like waveform ($a_{max} = 0.6\,g$, $T = 28$ s)	12.7	12.7	3.5%
Arulanandan and Sybico (1992)	University of California, Davis	50 g	Nevada sand ($n = 0.418$)	Earthquake-like waveform ($a_{max} = 0.38\,g$, $T = 28$ s)	9.53	7.15	1.7%
Taboada and Dobry (1993)	Rensselaer Polytechnic Institute	50 g	Nevada sand ($Dr = 40\%$)	Harmonic motion ($a_{max} = 0.24\,g$, $T = 14$ s)	10	3–4	2.0%
Byrne et al. (2004)	Rensselaer Polytechnic Institute	120 g	Nevada sand ($Dr = 55\%$)	Sinusoidal motion ($a_{max} = 0.25\,g$, $T = 36$ s)	38	37	Not reported
Adalier and Elgamal (2005)*	Rensselaer Polytechnic Institute	25 g	Nevada sand ($Dr = 35\%$)	Sinusoidal motion ($a_{max} = 0.1\,g$, $T = 5$ s)	2	1.25	0.35%
			Nevada sand ($Dr = 50\%$)	Sinusoidal motion ($a_{max} = 0.1\,g$, $T = 5$ s)	2	1.25	0.28%
			Nevada sand ($Dr = 70\%$)	Sinusoidal motion ($a_{max} = 0.1\,g$, $T = 5$ s)	2	0.5	0.24%

Note: *, Tests with preloading not listed.

For a specific site, the degree of soil softening and liquefaction depends on the features of earthquake loading, especially the strength of shaking. In the past, shakings of different strengths have been consecutively applied on soil models to investigate the effect of shaking level on seismic ground response (e.g., Adalier and Elgamal (2005)). However, as pointed out by Finn et al. (1970), preshearing influences the liquefaction resistance of saturated sand according to triaxial and simple shear cyclic loading tests. The experimental studies by Zhang et al. (2009) and Wichtmann et al. (2005) also indicated that the cyclic preloading could improve the liquefaction resistance of sand under the condition that liquefaction does not occur during the cyclic preloading. Therefore, the effect of shaking history on seismic ground response cannot be ignored.

In this study, a series of centrifuge tests was initiated on "fresh" models with the same initial conditions to examine the effect of shaking strength on the behavior of the saturated sand deposit under earthquake loading. Soil responses, such as acceleration, excess pore water pressure, vertical settlement, and lateral displacement, were recorded. Experimental observations verify the noticeable influence of shaking strength on the liquefaction potential, deformation of level sand deposits, and acceleration amplification. The influence of the interplay between soil and water during shaking was also demonstrated.

2. Test apparatus

The tests were performed in the Hong Kong University of Science and Technology (HKUST) centrifuge. The centrifuge has a diameter of 9 m with 400 g-ton capacity. A feature of the centrifuge is its capability of simulating dynamic problems in two horizontal directions by using an in-flight biaxial hydraulic shaker, which could operate up to a maximum of 50 g in flight (Shen et al., 1998). The biaxial hydraulic shaker in the HKUST utilizes a pair of servo-actuators for each shaking direction, without rotations in the plane of shaking. The shaker can yield a theoretical maximum acceleration of 40 g in each shaking direction. A shaking duration of 2 s can be achieved for a typical seismic signal.

To simulate the free-field boundary condition, stacked-ring model containers and laminar boxes have been widely used to accommodate the soil column subjected to horizontal one-dimensional earthquake excitation (e.g., Hushmand et al. (1988), Taboada and Dobry (1993)). A laminar box that allows free motion in any horizontal direction was used in this study to minimize the boundary effect of the container on the model behavior under two-dimensional shaking. The laminar container had a polygonal cross-section with 12 sides and 50 lightweight aluminum rings. Each ring was 8.9 mm in height and 58.4 cm in diameter and was separated from the adjacent rings by 24 roller bearings. The translation of each ring in two horizontal directions with minimal friction was permitted, and a relative displacement of up to 2.5 mm between two adjacent rings can be achieved.

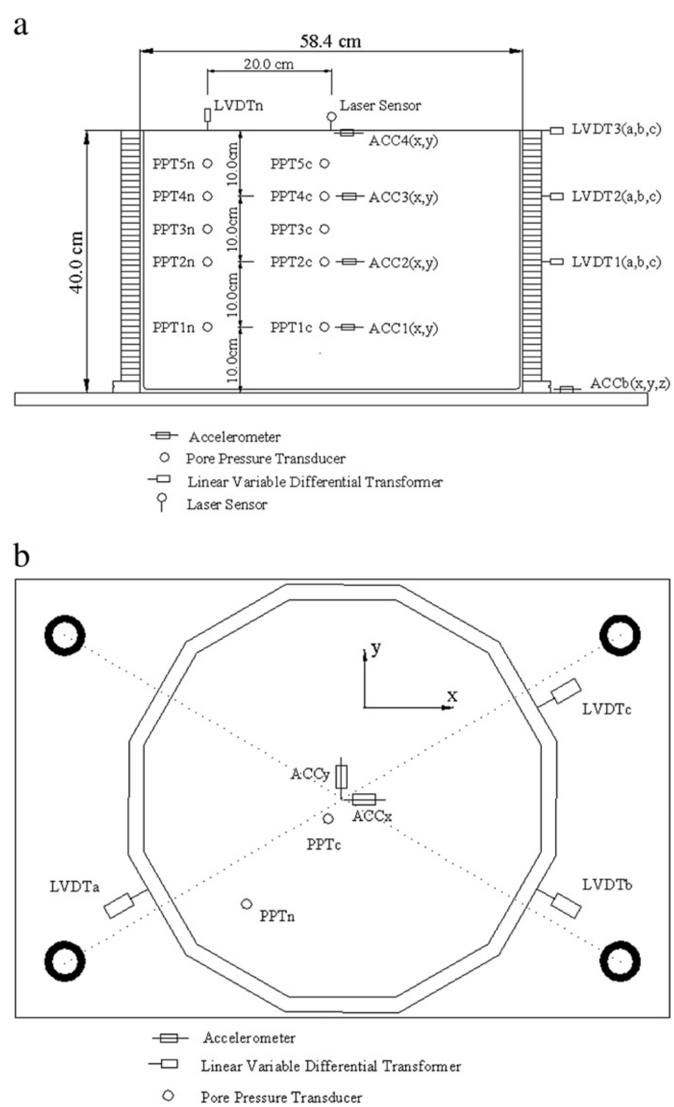

Fig. 1. Layout of instrumentation (a) side view; (b) top view.