Soils and Foundations 2015;55(6):1501–1511

HOSTED BY

ELSEVIER

CrossMark

The Japanese Geotechnical Society

Soils and Foundations

www.sciencedirect.com
journal homepage: www.elsevier.com/locate/sandf

SOILS AND FOUNDATIONS

Observation of post-liquefaction progressive failure of shallow foundation in centrifuge model tests

Akira Ishikawa[a,b], Yan-Guo Zhou[b,*,1], Yasuhiro Shamoto[a,b], Hideyuki Mano[a], Yun-Min Chen[b], Dao-Sheng Ling[b]

[a]Institute of Technology, Shimizu Corporation, Tokyo 135-8530, Japan
[b]MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Institute of Geotechnical Engineering, Zhejiang University, Hangzhou 310058, PR China

Received 4 June 2013; received in revised form 15 July 2015; accepted 21 August 2015
Available online 21 November 2015

Abstract

Liquefaction-induced large deformations of shallow foundations were widely observed during strong earthquakes, and one important feature of these is that they occur relatively slowly compared to the duration of earthquake shaking. As most previous model tests used clean sands with high permeability, this type of "delayed" failure mode has not been observed or reproduced realistically in the laboratory to date. In this study, a dynamic centrifuge model test was performed under 30*g* to study the mechanism of post-liquefaction progressive failure of buildings with shallow foundation on relatively thick deposits of liquefiable sandy soils. A two-dimensionally asymmetrical model structure was used to simulate the eccentric loads at the interface between the foundation and the subsoil. A clayey sand model with a relative density of 35% was prepared to have the relatively low permeability and coefficient of consolidation comparable to those of in-situ sandy soils. A prototype 2 Hz, 80 s long sine sweep with peak amplitude of 300 gal was used to simulate an earthquake strong enough to trigger a typical liquefaction state. Seismic responses in the liquefiable deposits and deformations of the structure were monitored during and after shaking. The main finding of this study is that the post-liquefaction progressive failure of shallow foundation was due to the large ground deformation of subsoil where significant shear strain localization had developed during liquefaction. Progressive settlement and tilting of shallow foundation will continue as long as the liquefaction state maintains, and longer durations of liquefaction lead to larger deformations.

Keywords: Liquefaction; Progressive failure; Clayey sand; Permeability; Coefficient of consolidation; Shear strain localization; Shallow foundation; Centrifuge model test

1. Introduction

The liquefaction-induced permanent deformation of buildings with shallow foundation were widely observed during strong earthquakes and caused heavy economic loss especially in urban environments, such as in Niigata of Japan, Dagupan City of Philippines, and Adapazari of Turkey (Tokimatsu et al., 1994; Sancio et al., 2004). Many more recent cases were reported in Urayasu, Japan in the 2011 Tohoku earthquake (Tokimatsu et al., 2012) and in Christchurch area during the 2010–2011 Christchurch earthquakes, New Zealand (Cubrinovski et al., 2012; Zhou et al., 2012).

One important feature of these liquefaction-induced deformations of shallow foundations is that the occur relatively

*Corresponding author. Tel.: +86 571 88208772; fax: +86 571 88208793.
E-mail address: qzking@zju.edu.cn (Y.-G. Zhou).
[1]Postal address: Zhejiang University (Zijingang Campus), Anzhong Building B-404, 866 Yuhangtang Road, Hangzhou 310058, PR China.
Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2015.10.014
0038-0806/

slowly (e.g., several minutes or longer) compared to the duration of earthquake shaking (e.g., several to dozens of seconds), and the damage may continue to accumulate during the period of drainage and redistribution of pore pressures after shaking has ceased, which distinguishes itself from those essentially caused by dynamic effects or inertial forces during the shaking. Take the 16 June 1964 M_w7.5 Niigata earthquake for an example, two-thirds of 340 reinforced concrete buildings in Kawagishi-cho were heavily settled or tilted, with one of them being completely tipped over (see Fig. 1). The testimony shows that the tilting of these apartments developed for at least several minutes after the cease of earthquake. Besides, the direction of permanent settlement and tilting is consistent with the direction of eccentricity of gravity force from the roof structure (Towhata, 2008). Such features were also identified around Tokyo Bay area during 2011 Tohoku earthquake (Yasuda et al., 2012; Cox et al., 2013) and in south Kaiapoi during 2010 Darfield earthquake, New Zealand (Cubrinovski et al., 2010). Therefore a type of gravity-driven progressive failure of liquefied ground under shallow foundations will happen after the termination of ground shaking.

Compared to the flow failure of slopes, dams or caisson type quay walls (Inagaki et al., 1996; Kokusho, 2003; Sento et al., 2004; Malvick et al., 2008; Chiaro et al., 2013), the post-liquefaction progressive failure of buildings with shallow foundation on relatively thick sandy deposit has not been sufficiently addressed. Dashti et al. (2010a,b) performed a series of centrifuge model tests on seismically induced settlement of symmetric buildings and presented various settlement mechanisms. However, as most of previous model tests with structures were conducted on clean sand deposits, hence simulating a coarse sand deposit of high permeability in the prototype at a high centrifugal g-level, foundation settlement occurred essentially during the shaking with the rapid dissipation of excess pore water pressure. As these clean sands could not fully capture the permeability property of in-situ sandy soils (e.g., as low as $k \approx 1 \times 10^{-5}$ m/s of Urayasu sand, Ishikawa and Yasuda, 2012), the "delayed" progressive failure or large deformation of buildings with shallow foundation has not been observed or reproduced realistically in laboratory to date. It should be noted that a number of researchers have studied the effect of prototype permeability on liquefaction behaviors in granular soil deposits, either by using less permeable soils (Liu and Dobry, 1997; Taboada and Dobry, 1998; Dashti et al. 2010b), using higher viscous pore fluid (Okamura et al., 2001; Sharp et al., 2003; Ganainy et al., 2012), or capping the clean sand layer with a thin low permeability layer (Fiegel and Kutter, 1994; Kokusho, 1999), and some have found that post-shaking ground deformations will increase with the decrease of soil permeability. More recently, Abdoun et al. (2013) found that the pore pressure buildup in model of silty sand was in good agreement with the prototype, while other centrifuge deposits of clean Ottawa sand did not develop excess pore pressure. These great efforts shed light on the study of foundation deformations on liquefiable soil deposits.

Fig. 1. Tilted apartment buildings in Niigata (Niigata Nippo Newspaper, 1964).

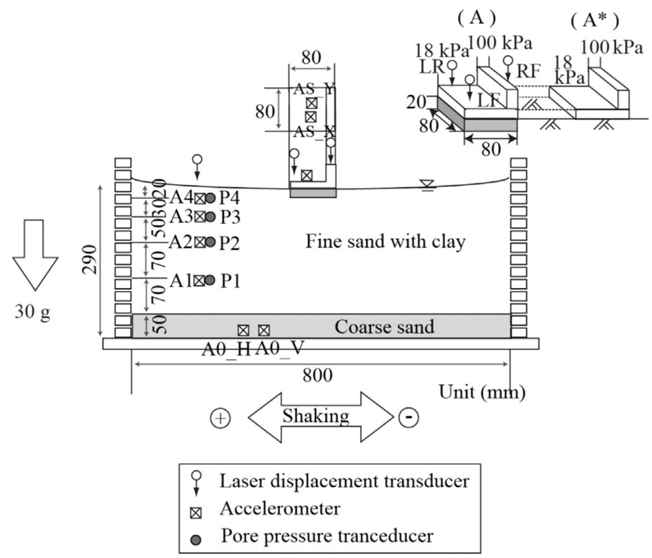

Fig. 2. Schematic of centrifuge model test.

In this study, a centrifuge model test was conducted to study the progressive failure of building with shallow foundation on relatively thick liquefiable deposits. Two-dimensionally (2-D) asymmetric model structure and clayey sand with low permeability and coefficient of consolidation similar to field conditions were used. The test successfully reproduced post-liquefaction progressive failure phenomena of shallow foundation that was quite comparable to prototype behaviors for the first time.

2. Centrifuge testing program

A centrifuge test was conducted in a laminar container with internal dimensions of 80 cm × 47 cm × 37 cm, under a centrifugal acceleration of 30g. The model scale is 1/30. Technical specifications and performance of the centrifuge apparatus could be referred to Mano and Shamoto (2009) and Zhou et al. (2010). Fig. 2 shows the schematic drawing of the model instrumentation. Four laser displacement transducers (LDTs) were used to measure the settlements throughout the tests, with