Soil Dynamics and Earthquake Engineering 77 (2015) 337–347

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Post-cyclic loading settlement of saturated clean sand

Kenan Hazirbaba [a,*], Maksat Omarow [b]

[a] Department of Civil Infrastructure and Environmental Engineering, Khalifa University, Abu Dhabi, UAE
[b] Former Graduate Student, University of Alaska Fairbanks, USA

ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form
12 June 2015
Accepted 14 June 2015

Keywords:
Cyclic triaxial testing
Strain-controlled test
Excess pore water pressure
Cyclic settlement
Volumetric strain
Threshold shear strain
Liquefaction of sand

ABSTRACT

Saturated sand deposits may experience significant settlement or reconsolidation with the dissipation of excess pore pressure in the post-cyclic loading phase even if liquefaction has not occurred. This paper presents results from an extensive and systematic experimental study on the factors governing the post-cyclic loading settlement of saturated clean sand. Strain-controlled, undrained, triaxial tests were performed on reconstituted specimens of Ottawa (C-109) sand. Effects of excess pore pressure, induced shear strain, consolidation stress, number of loading cycles, and relative density on post-loading settlement were investigated. It was found that the settlement potential during the post-loading phase is strongly correlated to the excess pore pressure; the larger the excess pore pressure the greater the settlement. The potential to develop excess pore pressure, however, decreases considerably with increasing consolidation effective stress in the range between 100 kPa and 400 kPa. Additionally, the level of induced shear strain and the number of loading cycles were confirmed to be important factors in the development of excess pore pressure and post-loading settlement. The results revealed a unique relationship between initial liquefaction and post-loading settlement. Specimens that were loaded up to initial liquefaction were found to experience about the same volumetric strain in the post-loading phase, irrespective of the induced shear strain.

1. Introduction

Loose to medium dense sand deposits tend to densify when subjected to strong ground motion due to particle rearrangement and redistribution of voids within the soil. Dry soil deposits experience densification during shaking while saturated deposits mostly settle and densify after shaking with the dissipation of excess pore water pressure. Depending on the level of generated excess pore pressure, soil index properties, and other factors such as the thickness of soil layer and depth of the ground water table, post-shaking settlement (typically measured by volumetric strain and also referred to as reconsolidation settlement) may cause significant damage to any structure above or within the ground.

The amount of settlement for dry sands depends on the relative density, level of induced shear strain, confining pressure, and number of loading cycles [18]. For saturated sands, however, excess pore pressure generation is the key factor for determining the post-cyclic loading settlement [16]. In cases where large excess pore pressure generation or liquefaction occurs (i.e., $r_u > 0.9$, where $r_u = \Delta u/\sigma_c'$; Δu = excess pore pressure and σ_c' = initial effective confining pressure) significant settlement (i.e., 2% and greater volumetric strain) may be expected with dissipation of excess pore pressure in the post-cyclic loading phase [23]. For smaller excess pore pressure ratios and nonliquefaction cases, the volumetric strain is typically well under 1% [16]. Because the major soil strength and stiffness is preserved at relatively low excess pore pressures, the settlement due to dissipation of such low excess pore pressures is limited [1,16,22].

This study focuses on the generation of excess pore pressure as a key factor governing the post-cyclic loading settlement. The generation of excess pore pressure is controlled mainly by the level of induced shear strains [4]. However, most of the previous experimental studies on cyclic settlement of sands have been typically conducted through stress-controlled tests where the emphasis is on the stresses induced and not necessarily the strains. Further, in stress-controlled testing the induced shear strain can show great variation from cycle to cycle. As a result, the post-cyclic loading volumetric strain is correlated to the maximum induced shear strain. In this study, however, the generation and dissipation of excess pore pressure in clean sand were explored through strain-controlled cyclic tests that allow for more direct evaluation of the characteristics of post-cyclic loading settlement. Specifically, the following effects on the settlement were evaluated: (i) level of induced shear strain, (ii) consolidation effective stress, (iii) number of loading cycles, (iv) initial liquefaction, and (v) relative density.

* Corresponding author. Tel.: +971 2 501 8487; fax: +971 2 447 2442.
E-mail address: kenan.hazirbaba@kustar.ac.ae (K. Hazirbaba).

http://dx.doi.org/10.1016/j.soildyn.2015.06.007
0267-7261/

2. Previous research

Lee and Albaisa [16] studied the settlement of sands caused by the dissipation of excess pore pressure through stress-controlled cyclic triaxial tests. The grain size, relative density, and excess pore pressure were reported as the key factors controlling the amount of the settlement of sand. However, no conclusions were drawn about the possible effect of the induced strains on the post-loading/post-liquefaction settlement.

Tatsuoka et al. [21] studied the influence of various parameters on volumetric strains after initial liquefaction through cyclic stress-controlled, undrained simple shear tests. They found that the amount of settlement significantly depends on the induced maximum shear strain and density of soil. The settlement was found to be relatively insensitive to the overburden pressure.

Tokimatsu and Seed [22] compiled and analyzed previous data from Tatsuoka et al. [21]; Lee and Albaisa [16]; and Yoshimi and Hiroshi [25], and reported that the maximum shear strain is an important factor influencing the settlement after liquefaction. It should be noted that these studies referred to the maximum shear strain that developed in the sample during cyclic stress-controlled testing, and it is unclear whether the influence of the shear strains on settlement was due to the nature of stress-controlled testing (i.e., progressive increase in strain). Liquefaction resistance in stress-controlled testing is typically affected by the method of sample preparation and stress history [17], however Tatsuoka et al. [21] reported that these factors were less significant when dealing with post-liquefaction volumetric strain. They attributed this to the relatively large strains developed during liquefaction and suggested that the settlement behavior of sands is primarily controlled by the relative density and the induced maximum shear strain.

Duku et al. [2] presented results from an experimental study on seismic compression of dry and partially saturated sands. They concluded that seismic compressibility was significantly affected by relative density and confining pressure.

Ueng et al. [23] conducted a study on settlement of a saturated clean sand using a large biaxial laminar shear box. Various one- and multi-directional sinusoidal input motions were imposed by a shaking table at different frequencies and accelerations. They reported that post-liquefaction volumetric strain of the sand decreased with increasing relative density regardless of shaking amplitude, frequency and direction (1-D or 2-D shaking), but increased with shaking duration (i.e., number of loading cycles). Ueng et al. [23] also reported that a surcharge mass of about 1 m thick overlying soil layer did not significantly affect the settlement characteristics for sand; only slightly increased volumetric strains for liquefied specimens.

Few studies [18,26,24,10,11] employed strain controlled simple shear tests in soil settlement tests, but they either referred to the settlement behavior of cohesive materials or concentrated on different aspects of the soil settlement, such as dry soils and threshold values of shear strains, without a direct evaluation of the strain effect on post-cyclic loading settlement of fully saturated sand.

Most relevant previous research efforts and the significant findings of these studies are summarized in Table 1.

3. Experimental program and methodology

Effects of induced shear strain, consolidation stress, number of loading cycles, and relative density on excess pore pressure generation and post-loading settlement of clean sand were investigated in four different groups of testing. The test series are listed in Tables 2–5. The first set includes tests performed on specimens subjected to cyclic loading under effective consolidation stresses of 100 kPa, 300 kPa and 400 kPa (Table 2). The variable parameter in the second group of tests (Table 3) is the number of loading cycles. In this series, specimens with identical properties (relative density, saturation, reconstitution technique) were subjected to different number of loading cycles ranging from 10 to 100 loading cycles. The third series (Table 4) were performed on medium dense sand and terminated with initial liquefaction. Finally, a separate series of tests was conducted on specimens with low relative density to investigate the influence of relative density on reconsolidation characteristics of clean sand (Table 5).

3.1. Soil tested

The soil investigated in this study was Ottawa sand (C-109). Basic index properties of the soil were determined using pertinent ASTM procedures, and are summarized in Table 6. Ottawa sand is commercially produced clean sand with a median grain size D_{50} of 0.42 mm. The particle size distribution of Ottawa sand is shown in Fig. 1. It is classified as poorly graded sand (SP) according to USCS classification.

3.2. Cyclic triaxial testing equipment

A state-of-the-art cyclic triaxial testing equipment was used in this research. The custom-made triaxial apparatus has a tilting frame that allows for in-place specimen preparation. This unique feature helps obtaining high quality specimens and thus more reliable testing results. A photograph and schematic diagram of the system used are shown in Fig. 2. The system is equipped with signal conditioning, servo amplifier, computer interface and data acquisition units. Normal loading, cell pressure application, and back-pressure saturation are controlled through servo valves. The triaxial cell accepts 101.6 mm (or smaller) diameter specimens.

Prior to executing the testing program, the equipment was calibrated and performance of the system was verified by conducting a series of calibration tests and comparing the results with previously published data. This benchmark testing ensured the reliability of the equipment and helped to form a baseline in strain-controlled mode. Undrained cyclic triaxial tests were performed at shear strains varying from 0.003% to 0.5%. It is important to note that the high precision mini LVDTs located outside the triaxial cell (Fig. 2) were calibrated against an internal LVDT placed between the top and bottom platens. This was done to eliminate any possible compliance effect on the strain measurements. Monterey #0/30 sand was used for verification, because no reported data were found in the literature on strain-controlled cyclic loading of Ottawa (C-109) sand. In "Liquefaction of soils during earthquakes" [3], Dobry reported results from several sands including Monterey sand. Thus, the results from this study were compared to those of Dobry, as shown in Fig. 3. The response of Monterey #0/30 was found to be in between the upper and lower bounds of Dobry, indicating quite good agreement. Tests on Ottawa (C-109) sand were also conducted to form a baseline for this study. Interestingly, the results from Ottawa (C-109) sand were found to fall on the upper bound of Dobry. Based on the verification tests, it was concluded that the equipment produced high quality and reliable data through strain-controlled testing.

3.3. Specimen preparation

In this study, the moist undercompaction method [14] was adopted for reconstituting the soil specimens. A predetermined amount of dry soil required to form a 101.6 mm diameter by 205 mm tall specimen was mixed with distilled, de-aired water such that an initial saturation of about 50% was achieved prior to