Soil Dynamics and Earthquake Engineering 109 (2018) 119–131

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Excess pore pressure generation in sand under non-uniform cyclic strain triaxial testing

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ARTICLE INFO

Keywords:
Triaxial test
Strain-controlled
Non-uniform
Soil liquefaction
Stress path

ABSTRACT

Two sets of strain-controlled cyclic triaxial tests were conducted to investigate soil liquefaction of clean sands. The first set involved conventional uniform strain amplitude cyclic tests, while the second set examined non-uniform strain amplitude cyclic tests. Comparisons were made between the two sets of results with respect to the generation of excess pore pressure and relationship between strain amplitude and stress path. In the case of uniform strain-controlled cyclic tests, larger strain amplitude produced more rapid generation of excess pore pressure. Conversely, for non-uniform strain-controlled tests, larger strain amplitudes may generate lower excess pore pressure instead. Such counter-intuitive phenomenon has design implications if irregular earthquake loadings in the field are incorrectly represented as equivalent uniform loading in the laboratory. Details are described in this paper.

1. Introduction

Saturated fine sands are most susceptible to earthquake-induced liquefaction. Damage caused by soil liquefaction during earthquakes due to loss of shear strength of the soil has been extensively studied with laboratory cyclic tests over the past few decades. The cyclic triaxial test has been widely used to evaluate the liquefaction potential of a soil. When a specimen is subjected to repeated shear loading, the sand particles tend to rearrange their stacking into a denser state. When drainage is prevented, generation of pore pressure and loss of effective stress are resulted.

The induced stresses in soil deposits during earthquakes are considered to be mainly attributed to the vertical propagation of shear waves from bedrock. In the laboratory, cyclic simple shear tests and torsional simple shear tests [7] provide the closest representation of field stress conditions during seismic loading. In a cyclic simple shear test or torsional simple shear test, initial K_0 stress condition is reproduced to simulate field condition, as they have the same stress path during cyclic loading as compared to the field stress path. There are, however, practical problems with both of these types of tests. Cyclic simple shear test apparatus has difficulty in achieving uniform shear strains within the specimen due to stress concentrations at the corners. Torsional simple shear tests suffer from complex sample preparation procedures. Furthermore, the versatility of the apparatus for both types of testing is limited because of their setup.

In contrast, cyclic triaxial testing is capable of accomodating many variations of assessment of soil response across a range of engineering applications. Hence, it is the most widely used laboratory procedure for geotechnical laboratory testing, such as the evaluation of liquefaction potential of saturated sand. Silver et al. [15] showed that cyclic pore pressure and strain development of liquefiable soils from uniform cyclic triaxial tests and simple shear tests on the same soil are comparable. There are two approaches to cyclic triaxial testing of soil specimens: cyclic stress-controlled and cyclic strain-controlled tests. In a cyclic strain-controlled test, one controls the amount of cyclic strain amplitude to be applied per unit time. In the case of stress-controlled test, a uniform cyclic stress amplitude is applied. It was shown experimentally by Silver and Seed [14] that the densification of dry sands are controlled directly by cyclic shear strain, $\gamma_c = \tau_c / G$ (where τ_c is the cyclic shear stress and G is the secant shear modulus) rather than cyclic shear stress. The findings of studies by Martin et al. [11] and Dobry et al. [5] strongly suggest that cyclic shear strain, rather than cyclic shear stress, controls both densification and liquefaction in sands. Further, Silver and Seed [14] performed strain-controlled tests at small strains and showed that strain-controlled tests cause less water content redistribution in soil specimens before liquefaction occurs and provides more realistic predictions of in-situ pore pressures than those obtained from stress-controlled tests. Hence, the induced shear strain, compared to shear stress, was shown to be a better parameter for evaluating the generation of excess pore pressure of saturated sandy materials during undrained cyclic loading.

In the field, cyclic shearing due to earthquake shaking is irregular in

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https://doi.org/10.1016/j.soildyn.2018.03.016
Received 8 August 2017; Received in revised form 11 March 2018; Accepted 13 March 2018
0267-7261/

Table 1
Details of cyclic triaxial tests.

Test ID	Test parameters			
	Soil relative density (%)	Cyclic axial amplitude (mm)	Corresponding cyclic shear strain, γ_c (%)	Effective confining pressure (kPa)
U1	37.8	0.6	0.26	40
U2	38.2	0.6	0.26	60
U3	38.1	0.6	0.26	80
U4	38.5	0.8	0.35	40
U5	38.5	1.0	0.43	40
U6	38.2	1.5	0.65	40
NA1	37.8	0.6/0.8	0.26/0.35	40
NA2	38.6	0.6/1.0	0.26/0.43	40
NA3a	10.9	0.6/1.2	0.26/0.52	40
NA3b	37.7	0.6/1.2	0.26/0.52	40
NA3c	77.5	0.6/1.2	0.26/0.52	40
NA4	37.9	0.6/1.5	0.26/0.65	40
NA5	38.4	0.8/1.0	0.35/0.43	40
NA6a	13.7	0.8/1.2	0.35/0.52	40
NA6b	37.7	0.8/1.2	0.35/0.52	40
NA6c	76.6	0.8/1.2	0.35/0.52	40
NA7	38.2	0.8/1.5	0.35/0.65	40
NB1a	14.2	0.6/0.8/1.0/1.2/1.5	0.26/0.35/0.43/0.52/0.65	40
NB1b	37.8	0.6/0.8/1.0/1.2/1.5	0.26/0.35/0.43/0.52/0.65	40
NB1c	76.3	0.6/0.8/1.0/1.2/1.5	0.26/0.35/0.43/0.52/0.65	40
NB2	38.2	0.6/0.8/1.0/1.2/1.5	0.26/0.35/0.43/0.52/0.65	60
NB3a	11.8	0.6/0.8/1.0/1.2/1.5	0.26/0.35/0.43/0.52/0.65	80
NB3b	37.9	0.6/0.8/1.0/1.2/1.5	0.26/0.35/0.43/0.52/0.65	80
NC1a	13.1	1.5/1.2/1.0/0.8/0.6	0.65/0.52/0.43/0.35/0.26	40
NC1b	37.7	1.5/1.2/1.0/0.8/0.6	0.65/0.52/0.43/0.35/0.26	40
NC1c	75.9	1.5/1.2/1.0/0.8/0.6	0.65/0.52/0.43/0.35/0.26	40
NC2	38.4	1.5/1.2/1.0/0.8/0.6	0.65/0.52/0.43/0.35/0.26	60
NC3a	12.5	1.5/1.2/1.0/0.8/0.6	0.65/0.52/0.43/0.35/0.26	80
NC3b	38.2	1.5/1.2/1.0/0.8/0.6	0.65/0.52/0.43/0.35/0.26	80
NC3c	77.9	1.5/1.2/1.0/0.8/0.6	0.65/0.52/0.43/0.35/0.26	80

magnitude. However, due to experimental difficulties, most cyclic triaxial tests in the past few decades involve applying cyclic loads of uniform amplitude and few investigations were carried out using non-uniform or irregular loading patterns. Seed and Idriss [16] proposed that the effect of irregular earthquake loading can be modelled in the laboratory by a number of uniform shear stress cycles with a magnitude equal to 65% of the maximum shear stress achieved during the field loading sequence. This type of equivalent uniform stress cycle concept has been adopted extensively in practice but lacks thorough verification. Ishihara and Yasuda [8] performed irregular triaxial tests on saturated sand to simulate the more representative loading induced during earthquakes. Two loading patterns were classified in their study: shock type loading (maximum stress builds up in a few cycles) and vibration type loading (maximum stress builds up gradually). Their tests showed that the soil liquefied more easily under shock type loading with the same maximum stress. Hollow cylinder torsion tests with irregular excitation were further carried out by Ishihara and Yasuda [9]. In their study, the electrohydraulic sensor was placed horizontally. As a consequence, torque was induced by the vertical shaft in this equipment onto the hollow cylinder specimen. Similar liquefaction susceptibility was observed in the torsional hollow cylinder test compared to the liquefaction resistance measured from cyclic triaxial test. Later, Wang and Kavazanjian [19] used a modified mini-computer controlled electro-pneumatic cyclic loading system to investigate non-uniform excitation. However, due to apparatus inefficiency, only limited trial tests were conducted. Since then, despite further studies assessing susceptibility of soil liquefaction under non-uniform stress loadings or strain amplitudes in cyclic laboratory tests (e.g., [1,12,13]), difficulty remains in defining what type of cyclic loading responses would best simulate field conditions.

In order to supplement the sparse experimental data on non-uniform cyclic loading, a comparison between conventional uniform and non-uniform strain-controlled cyclic triaxial tests is carried out. Table 1 shows the list of tests presented in this paper. Uniform cyclic amplitude tests are denoted with a “*U*” in the test ID. For non-uniform tests, two different groups of cyclic loading patterns are applied. The first group involves two different shear strain amplitudes alternating every 5 cycles in each tests, as shown in Fig. 1a. Tests in the first group are indicated with “*NA*” The second group involves tests with gradually increasing/decreasing shear strain amplitudes as shown in Fig. 1b and c. They are denoted as “*NB*” and “*NC*” respectively. The relative density (D_r) of the specimen effects the rate of generation of pore pressure as well as shear strength of the soil under cyclic loading. For a strain-controlled test, larger number of loading cycles is required at the same cyclic strain amplitude when the sand's relative density is higher [3]. In this present study, specimens with different relative density were conducted for each of the above types of non-uniform strain-controlled tests, keeping all other testing parameters unchanged, as shown in Table 1.

2. Experimental setup

2.1. Soil properties

Fine grain silica W9 sand supplied by Riversands Pty Ltd at Brisbane, Australia was used. Typically used as a filtration medium, the sand's particle sizes are uniform (poorly graded). A percentage of 95% and above of the sand particles pass through #30 sieve (0.42 mm) and less than 5% of the particles pass through the #200 sieve (0.075 mm) (Fig. 2). Physical properties of the sand are as follow: $\Phi_{crit} = 32°$, $D_{10} = 0.22$ mm, $D_{50} = 0.26$ mm, $D_{60} = 0.3$ mm, $Gs = 2.65$, $e_{max} = 1.02$ and $e_{min} = 0.529$.

2.2. Experimental setup

Cylindrical soil specimens of 38 mm diameter and 76 mm in height are prepared in a watertight rubber membrane with porous stones and