G Model
PARTIC-942; No. of Pages 11
ARTICLE IN PRESS

Particuology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Particuology

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

Macro- and micromechanical evaluation of cyclic simple shear test by discrete element method

Mozhgan Asadzadeh, Abbas Soroush*

Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form 11 April 2016
Accepted 3 May 2016
Available online xxx

Keywords:
Discrete element method
Direct shear test
Simple shear test
Cyclic loading

ABSTRACT

Direct simple shear tests are considered to be simple laboratory tests that are capable of imposing a cyclic loading that is analogous to that induced by earthquakes. A realistic evaluation of the test results demands a profound micromechanical investigation of specimens. Three-dimensional discrete element method models of a stacked-ring simple shear test were constructed, in which monotonic and cyclic loadings were applied under constant-volume conditions, and good agreement between the monotonic and cyclic macromechanical behaviors was noted. Micromechanical properties of specimens that were subjected to a cyclic loading are discussed in terms of lateral and intermediate principal stress development, fabric anisotropy, and principal stress rotation. The stress and strain states inside the specimen were investigated and it was shown that despite the uniform stress distribution inside the specimen, the volumetric strain distributes non-uniformly during loading and the non-uniformity grows with cycling, which leads to localized zones of dilative and contractive behavior.

Introduction

Soil deposits may be subjected to cyclic loading by earthquakes. Safe building design could be guaranteed by determining the effect of cyclic stress–strain properties of soils as a function of a number of parameters. Cyclic soil properties can be evaluated using several laboratory tests, such as a direct simple shear test (DSST), triaxial test, hollow-cylinder test, and resonant column test (Soroush & Soltani-Jigheh, 2009; Thay, Likitlersuang, & Pipatpongsa, 2013). A DSST is considered to be a simple laboratory test. The test is believed to be capable of simulating a variety of field conditions, in particular, the vertical propagation of seismic shear waves and the rotation of principal stresses. These features have increased the popularity of DSST in evaluating cyclic soil properties (Mao & Fahey, 2003; Porcino, Caridi, & Ghionna, 2008; Wijewickreme, 2010).

Different versions of the DSST have been developed since that was introduced by the Swedish Geotechnical Institute in 1936 (Kjellman, 1951). Commonly used versions include the Norwegian Geotechnical Institute (NGI) type, i.e., a cylindrical specimen that is enclosed by a wire-reinforced membrane as a lateral boundary (Kjellman, 1951), Cambridge type, i.e., a cubic specimen with rigid side boundaries (Roscoe, 1953), and stacked-ring type, i.e., a cubic or cylindrical specimen that is enclosed by a stack of aluminum rings. Peacock and Seed (1968) adapted the DSST to cyclic loading and the test has since been used extensively to test soils that are subjected to cyclic loading, particularly in undrained conditions.

Despite numerous advantages of the apparatus in soil testing, certain specific features of the cyclic simple shear test have remained of concern. When evaluating laboratory soil test results in a liquefaction assessment, it is assumed that stresses and strains distribute uniformly inside the specimen. Some researchers have used laboratory testing and finite element methods (Airey & Wood, 1987; Budhu, 1984, 1985; Wang, Popescu, & Prevost, 2004) and have discussed stress and strain distributions in monotonic and cyclic loading. Among them, Budhu (1984) used NGI- and Cambridge-type simple shear apparatuses and conducted simple shear tests on Leighton Buzzard sand. He used a radiographic technique and showed that by increasing the number of cycles in a cyclic shear-

Abbreviations: PT_{cyc}, cyclic phase transformation; DEM, discrete element method; DSST, direct simple shear test; DSS, direct simple shear; NGI, Norwegian Geotechnical Institute; CV, constant volume; I_{UF}, index of unbalanced force; PT, phase transformation; CS, critical state; τ–σ'_v, stress path; τ–γ, shear stress–shear strain; σ'_v, normal (vertical) effective stress; Cu, coefficient of uniformity; Cc, coefficient of curvature; σ'_{vo} or σ'_{v0}, initial vertical (normal) effective stress; CSR (=τ_{cyc}/σ'_{vo}), cyclic shear stress ratio; φ_{mob}, mobilized friction angle; u (=$\sigma'_{vo} - \sigma'_v$), equivalent pore-water pressure; EPWP, excess pore-water pressure; θ_σ, principal stress direction to the vertical; MS1, a measurement sphere with a radius of 8 mm in the center of the specimen; k (=σ'_x/σ'_z), lateral earth-pressure coefficient; ε_{vol}, volumetric strain; EL, end of the loop; e, void ratio.

* Corresponding author.
E-mail addresses: soroush@aut.ac.ir, abbas958@gmail.com (A. Soroush).

http://dx.doi.org/10.1016/j.partic.2016.05.015

Please cite this article in press as: Asadzadeh, M., & Soroush, A. Macro- and micromechanical evaluation of cyclic simple shear test by discrete element method. *Particuology* (2016), http://dx.doi.org/10.1016/j.partic.2016.05.015

straining test, the shear and volumetric strain become non-uniform along the specimen height in both apparatuses. He also mentioned that loading and unloading cause severe fluctuations in normal stresses at extreme ends of the horizontal boundaries in both specimens.

Non-uniformity in stress and strain distribution inside the specimen may result in non-uniformity in pore-water pressure distribution; however, experimental investigation of the non-uniformity in pore-water pressure distribution is almost impossible. Finite element method that uses a continuum mechanical framework with elastic or elastic–plastic constitutive models is limited by the assumptions made, such as co-axial plasticity. In contrast, the discrete element method (DEM), which was first developed by Cundall and Strack (1979), can model a soil as an assemblage of individual particles. Therefore, fundamental mechanics can be observed and quantified in detail at a microscopic level.

Several researchers have demonstrated the efficiency of the DEM to capture monotonic and cyclic soil properties, including Shafipour and Soroush (2008), and Soroush and Ferdowsi (2011). DEM simulations of cyclic simple shear tests have been conducted by Dabeet, Wijewickreme, and Byrne (2012, 2014). They compared the macromechanical responses of cyclic simple shear test simulations from DEM with those from laboratory tests conducted on glass beads. Close agreement was noted in terms of stress–strain behavior and radial stress development. However, micromechanical properties of the specimens under cyclic loading were not included in their investigation.

A DEM modeling approach was used to investigate micromechanical uncertainties associated with a cyclic simple shear test, such as stress and strain non-uniformity, the stress state inside the specimen, and principal stress rotation during cycling. A specimen was modeled in a stacked-ring simple shear test scheme under constant volume (CV) monotonic and cyclic loading by three-dimensional DEM, using the LIGGGHTS code (LAMMPS Improved for General Granular and Granular Heat Transfer Simulations) (Kloss, Goniva, Hager, Amberger, & Pirker, 2012). The results are discussed micro- and macromechanically, providing good insight into key features of the test.

DEM simulation

The constant volume (CV) test on dry soils, first proposed by Taylor (1948) and then applied in a simple shear test by Pickering (1973), is considered an alternative to the undrained test. In CV tests, pore water is assumed to be incompressible, and any changes in vertical stress that act on the horizontal boundaries are equivalent to a pore-water pressure build up in corresponding saturated undrained tests. Researchers verified experimentally and numerically that the mechanical behavior of granular materials is unaffected by the presence of water, and similar results can be obtained using saturated undrained tests and CV drained tests (Dyvik, Berre, Lacasse, & Raadim, 1987; Shafipour & Soroush, 2008). Therefore, in this study, to avoid fluid-coupled DEM model complexities, cyclic tests were modeled under dry CV conditions.

The stacked-ring-type simple shear test was modeled in this study. To simulate a cylindrical specimen enclosed by stacked rings, ten separate rings with a total height of 20 mm and an inner diameter of 70 mm were modeled by using stacked small rigid walls. Horizontal platens were simulated in a saw-tooth configuration. The saw-tooth configuration was simulated because it is similar to the roughness of horizontal platens in the direct simple shear (DSS) device at the Amirkabir University of Technology.

Fig. 1 shows the particle size distribution curve of the specimens. The interaction of particles was modeled using a simplified

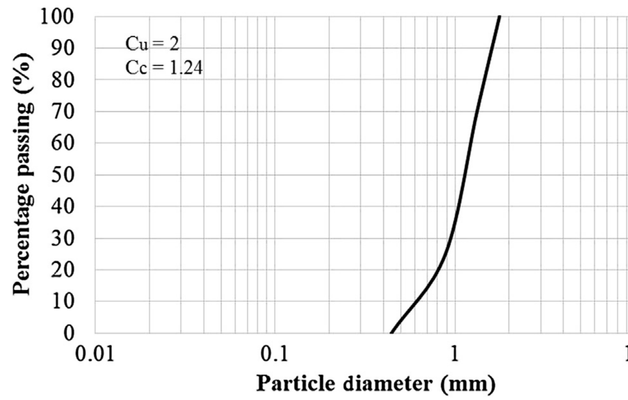

Fig 1. Particle size distribution curve of simulated specimens. C_u: coefficient of uniformity. C_c: coefficient of curvature.

Table 1
Input parameters for numerical simulations.

Parameter	Value
Young's modulus, *E* (MPa)	100
Poisson's ratio, *ν*	0.22
Particle density (kg/m^3)	2550
Coefficient of restitution	0.87
Friction coefficient between particles and horizontal plates	0.6
Friction coefficient between particles	0.24
Friction coefficient between particles and rings	0

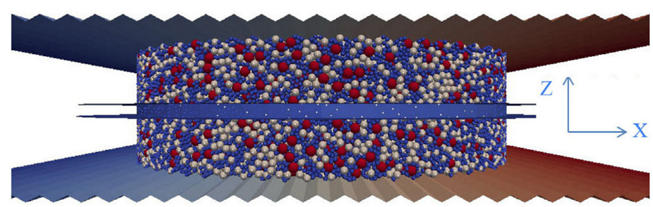

Fig. 2. Modeled stacked-ring simple shear specimen after consolidation.

Hertz–Mindlin contact model with damping (Härtl & Ooi, 2008). The input parameters used in the numerical simulations are listed in Table 1. Parameters were selected based on a parametric study conducted by Asadzadeh and Soroush (2016) to simulate the stress–strain and volumetric strain–shear strain responses of uniformly sized glass beads in drained DSS tests.

In these tests, particles with an initial diameter that was smaller than their final diameter were generated randomly inside the specimen and the radius expansion method was used to achieve the final particle size. The time step was set based on a critical time step and contact properties. To ensure a quasi-static response of the specimens, the index of unbalanced force (I_{UF}) (Ng, 2006) was monitored during the simulations. Ng (2006) suggested using the unbalanced force as an indicator of the state of equilibrium and suggested that $I_{UF} \leq 0.01$ was a reasonable criterion.

Consolidation was modeled by moving the top platen downward at 1 mm/s until the normal stress, which was calculated by averaging forces at the contacts between particles and the top platen, approached the desired value. The modeled specimen that consists of the consolidated specimen, one out of ten modeled rings, and top and bottom platens are illustrated in Fig. 2.

CV tests were simulated by preventing the horizontal boundaries (i.e., top and bottom platens) from moving in the vertical direction. Shearing was applied by moving the bottom and top platens and their adjacent rings at 1 and 0 mm/s, respectively, in the ±*x* direction. The rate of shearing for each of the other rings was set independently to simulate a uniform boundary shear strain.