Engineering Geology 172 (2014) 1–11

Contents lists available at ScienceDirect

Engineering Geology

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

Residual shear strength of unsaturated soils via suction-controlled ring shear testing

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ARTICLE INFO

Article history:
Received 18 January 2013
Received in revised form 8 January 2014
Accepted 10 January 2014
Available online 24 January 2014

Keywords:
Unsaturated soil
Matric suction
Residual shear strength
Ring shear testing

ABSTRACT

Results from a comprehensive series of suction-controlled ring shear tests, conducted on statically compacted specimens of silty clayey sand and silty sand, are presented. The experiments were accomplished in a newly developed servo/suction-controlled ring shear apparatus suitable for testing unsaturated soils under large deformations and suction-controlled conditions via the axis-translation technique. The present work focuses primarily on two crucial aspects of compacted unsaturated soil behavior, namely, the behavior of silty clayey sand under suction-controlled ring shear testing, and the effects of pre-shearing and suction histories on unsaturated residual shear strength of compacted silty sand. Test results corroborate the important role played by matric suction on residual shear strength properties of unsaturated soils. For the range of net normal stresses and suction states investigated, the increase in residual shear strength with increasing suction was confirmed to be a linear trend for silty sand, but significantly nonlinear for silty clayey sand. Results from multi-stage ring shear tests confirmed that the residual shear strength of unsaturated soils is virtually independent of the pre-shearing and suction histories experienced by the soil.

1. Introduction

A vast majority of the geotechnical infrastructure made of compacted soil, or resting on unsaturated ground, undergoes a wide range of deformations. Calculation of foundation settlement, for instance, requires a good estimation of soil stiffness at relatively small strains. Analysis of slopes, embankments, and soil bearing capacity, on the other hand, requires good estimations of shear strength from peak to residual. To date, however, there is very limited experimental evidence of unsaturated soil behavior under large deformations, and the corresponding residual shear strength properties, while the soil is being subjected to controlled-suction states. This type of research has been deterred in the past by the lack of suitable testing tools and techniques. It is, therefore, in this context that a suction-controlled ring shear (RS) apparatus would play a fundamental role in the thorough characterization of this type of geomaterials.

Only a short handful of researchers have recently begun experimental trials with new test methodologies, including Vaunat et al. (2006, 2007), Infante Sedano et al. (2007) and Merchán et al. (2011). The main focus of these pioneering efforts has been on adapting and expanding the capabilities of existing Bromhead-type devices for soil testing under controlled-suction states via vapor-transfer or axis-translation techniques. Despite the crucial findings of these dedicated few, highlighting the key role played by matric suction, a comprehensive experimental effort has yet to be undertaken to produce a thorough set of suction-dependent residual failure envelopes for soils tested at a relatively wide range of low suction states (i.e., from 0 to 100 kPa); and to investigate the effects that both pre-shearing and suction histories may have on the residual shear strength properties of unsaturated soils. The present work is motivated by these research needs.

A comprehensive series of suction-controlled RS tests, performed on statically compacted specimens of silty clayey sand and silty sand, has been undertaken. The work focuses primarily on two crucial aspects of compacted unsaturated soil behavior: (1) behavior of silty clayey sand under suction-controlled ring shear testing, and (2) effects of pre-shearing and suction histories on unsaturated residual shear strength of silty sand. The experiments were conducted in a newly developed servo/suction-controlled RS apparatus that is suitable for testing unsaturated soils under large deformations and suction-controlled conditions via the axis-translation technique. A detailed description of its full development, including main components and a thorough performance verification against the original Bromhead device (Bromhead, 1979), is reported by Hoyos et al. (2011).

The RS unit is suitable for testing both fully-softened shear strength and residual shear strength parameters that can be used for slope stability assessments of various scenarios (ASTM Standard D6467-06a, 2006; ASTM Standard D7608-10, 2010). The main focus of the current work is on unsaturated residual shear strength at large displacements, which will transpire, for instance, in unsaturated earth slopes experiencing seismic events, or shallow and relatively deep foundation soils above ground water table. On the other hand, accurate assessments of unsaturated residual strength parameters is of extreme importance in natural

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http://dx.doi.org/10.1016/j.enggeo.2014.01.001

slopes in fissured rocks with unsaturated clayey and silty fills that can undergo significant shear strength changes upon wetting, or shallow fissured landslides that can also be activated by wetting. Unsaturated residual shear strength can also be used as a macroscopic indicator of the nature of micro-structural changes experienced by the soils when subjected to drying (Merchán et al., 2011).

Silty clayey sand and silty sand were selected as the test materials for the present work mainly because of their poor gradation and low plasticity, which minimize the effects of particle size and shape on menisci formation in the pore-water phase, hence considerably reducing the time needed for pore-fluid (air and water) equalization during suction-controlled RS testing. On the other hand, the relatively significant content of fine-grained soil in both test materials is expected to minimize the potential for wall-friction effects between the specimen and the concentric rings of the RS device. Had the authors chosen to investigate residual shear strength of a purely clayey soil, a crucial topic in its own right, the time frame would have been prohibitively long, particularly the multi-stage RS testing program undertaken to study the effects of pre-shearing and suction histories. In the present work, low plasticity silty clay has been tested only under saturated conditions with the sole intent of verifying the suitability of the newly developed RS apparatus to reproduce typical residual shear strength properties of clayey soils under these conditions.

2. Servo/suction-controlled RS apparatus: basic features

2.1. General assembly

The RS apparatus allows for the application of vertical loads up to 8 kN, monotonic torque up to 113 N-m, and unlimited angular rotation. It consists of three main modules: (1) Main cell with rotational shear system, including pneumatic actuator for application of normal loads and an electromechanical rotary actuator for application of torque loads; (2) Data acquisition and process control (DA/PC) system, with performance and data reduction software for real-time calculation of normal and shear stresses and average linear and angular displacements; and (3) PCP-15U suction control panel for implementation of axis-translation technique (Hoyos et al., 2011). In the present work, an orderly step-by-step setting-up procedure was established as follows:

1. All actuators and the DA/PC system are switched on to allow the instruments to come into equilibrium and minimize the influence of temperature offsets.
2. A small piece of wet filter paper is placed over the top of each high-air-entry (HAE) ceramic disk, prior to specimen compaction, to ensure phase continuity between the pore-water in the soil and the water in the saturated disk: Fig. 1(a).
3. The 15 mm (0.59 in. thick specimen is then statically compacted into the bottom annular platen, having 152.4 mm (6 in.) OD and 96.5 mm (3.8 in.) ID: Fig. 1(b). The specimen is quickly transferred to the RS frame and the platen tightly fixed onto the bottom base plate: Fig. 1(c).
4. The vertical load shaft is brought up through a servo controller and the upper annular platen affixed to the top of the piston shaft: Fig. 1(c). A light vertical seating load of 25 N is applied in order to bring the upper annular platen in full contact with the specimen.
5. All drainage and flushing lines are filled with de-aired water and flushed several times to avoid any trapped air in the whole system.
6. The main RS cell is installed and the top cover plate affixed to the cell: Fig. 1(d). A pore-air pressure line from the PCP-15U panel is connected to the cover plate via a quick connector.
7. Readings of the load-torque transducer are reset, and the LVDT and angular deformation sensors are re-zeroed, prior to RS testing.
8. The specimen is then subject either to a suction-controlled single-stage or multi-stage RS test using the $s = u_a$ testing concept (i.e., $u_w = 0$).
9. When the test is finished, all pressures are gradually reduced back to atmospheric pressure, the main cell and top annular platen gently removed, and the soil failure surface thoroughly examined via microscopic digital imaging (Velosa, 2011).

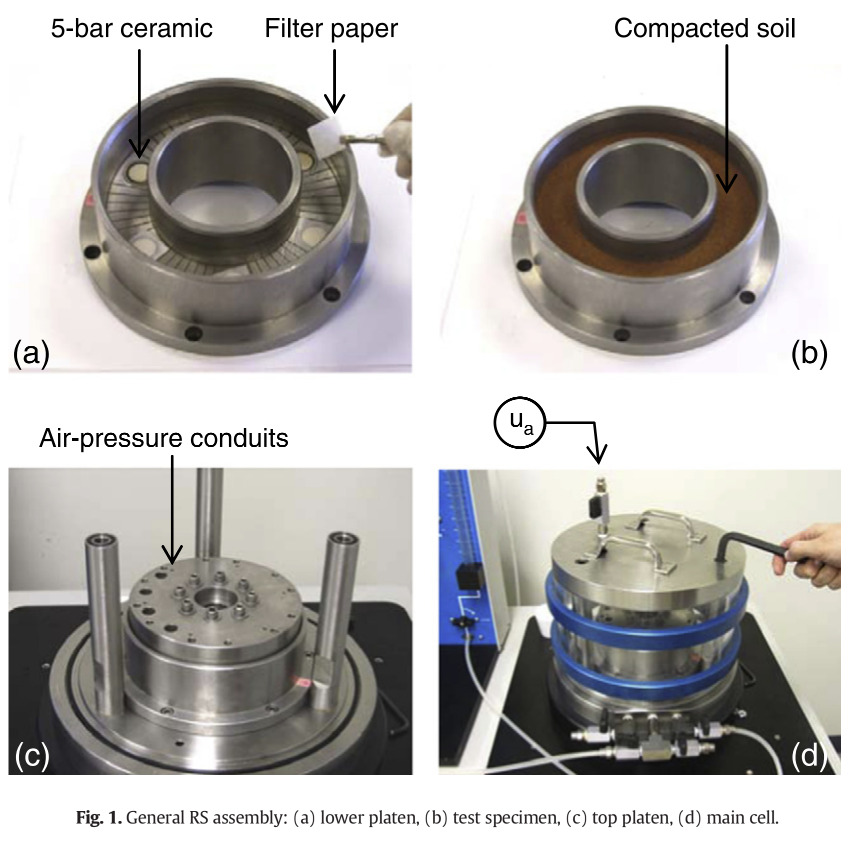

Fig. 1. General RS assembly: (a) lower platen, (b) test specimen, (c) top platen, (d) main cell.