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Experimental evaluation of mechanical behavior of unsaturated silty sand under constant water content condition

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ABSTRACT

There are very few experimental data on the mechanical behavior of unsaturated soils, particularly in constant water content condition, because of the technical difficulties and time-consuming nature of measuring suction and deformation. This paper presents the results of a series of constant water constant triaxial tests on the specimens of an unsaturated silty sand. Constant water content tests correspond to a field condition where the rate of loading is much quicker than the rate at which the pore water is able to drain out of the unsaturated soil. The axis translation technique and a double-walled triaxial cell have been used to measure the soil matric suction and variation of pore air volume respectively. Test specimens were prepared at two different compaction conditions prior to testing to achieve different initial density. It is found that the mechanical behavior of the soil mainly depends on the initial density, the mean net stress and the initial matric suction. Also the volume and pore water pressure changes are significantly different in specimens with different initial condition. The results of tests indicated that the shearing strength of silty sand increases nonlinearly with matric suction.

1. Introduction

In geotechnical practice most soils are in unsaturated condition, for instance the compacted soils used in several engineering constructions (such as earth dams, highways, embankments, and airport runways). Many of these soil structures often do not attain fully saturated conditions during their design life. Testing of soil in unsaturated conditions is not common in soil mechanics laboratories. The mechanical behavior (i.e. shear strength and volume change) of unsaturated soils is relevant in the design of several geotechnical and geoenvironmental structures. Conventional soil mechanics theory treats soil as either fully saturated or dry. However, a large number of engineering problems involve the presence of unsaturated soil zones where the voids between the soil particles are filled with a mixture of air and water. These zones are usually ignored in practice and the soil is assumed to be either fully saturated or completely dry. This is despite test results indicate significant differences between the mechanical behavior of unsaturated soils and the mechanical behavior of fully saturated or completely dry soils (such as Adams and Wulfsohn, 1998; Miao, 2002; Wang et al., 2002; Chiu and Ng, 2003; Ng and Chiu, 2003; Rahardjo et al., 2004; Kayadelen et al., 2007; Jotisankasa et al., 2009). So far many studies have been conducted on critical state and mechanical behavior of saturated soils (Schofield and Wroth, 1968; Wood, 1991; Maatouk et al., 1995; Newson, 1998) but not unsaturated soils.

In the 1950's, research at Imperial College London, was directed toward a fundamental understanding of unsaturated soil behavior within the classical framework of saturated soil (Bishop et al., 1960). The research involved careful laboratory studies, primarily on the shear strength of unsaturated soil. These studies have provided the catalyst for further studies in various countries of the world. This interest has accelerated during the last 17 years, and has been accompanied by the development of extensive experimental laboratory testing programs leading to the formulation of various constitutive models for unsaturated soils.

It is well known that the mechanical behavior of saturated soils can be interpreted and explained by a single stress state variable, called the effective stress (Terzaghi, 1936). Conversely, unsaturated soils are characterized by the presence of air phase, water phase and air–water interface in voids. Due to the additional pore phase, there are difficulties in applying the same approach to unsaturated soils (Jennings and Burland, 1962) and it is thus difficult to define convenient stress state variables. During the past three decades there has been an increasing use of two independent stress variables to describe the behavior of unsaturated soils (Coleman, 1962; Bishop and Blight, 1963; Burland, 1965; Aitchison, 1967; Matyas and Radhakrishna, 1968; Barden et al., 1969; Brackley, 1971; Fredlund and Morgenstern, 1977).

Critical state frameworks for unsaturated soil mechanics have been proposed and compared with those of saturated soil mechanics (Alonso et al., 1990; Maatouk et al., 1995; Wheeler and Sivakumar, 1995). The smooth transition from the two stress state variables for

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an unsaturated soil, net stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$, (where, σ is the total stress, u_a is the pore air pressure, and u_w is the pore water pressure) to the single stress variable effective stress $(\sigma - u_w)$ for a saturated soil (Fredlund and Morgenstern, 1977), forms the basis for the extension from saturated to unsaturated soil behavior. The concepts of yielding, hardening, and critical state are the key elements comprising the critical state framework for saturated soils. These concepts can be extended using two independent stress state variables, $(\sigma - u_a)$ and $(u_a - u_w)$, to build a critical state framework for unsaturated soils. These variables have been suggested as the critical state variables for unsaturated soils by several researchers (Maatouk et al., 1995; Wheeler and Sivakumar, 1995; Rampino et al., 1998). Given the diversity of results from previous research, more study is required on the behavior of soils with varied values of water content (or matric suction), initial density and net stress to investigate their influence on shear strength and volume change behavior.

This paper presents test data from triaxial tests on an unsaturated silty sand with measurements of matric suction. It summarizes the findings from an experimental program concerning the mechanical behavior of two groups of silty sand with different initial density tested under low mean net stress. Constant water content triaxial tests were carried out on unsaturated specimens. In addition, consolidated undrained tests on saturated samples were performed to study soil behavior in saturated condition. The mechanical behavior of unsaturated specimens is studied and compared with the behavior pattern for saturated specimens and their variation is considered with respect to matric suction.

2. Testing apparatus

The stress–strain behavior of unsaturated soils is often interpreted from results of triaxial or direct shear tests. These tests are generally performed by controlling matric suction (Alonso et al., 1990; Fredlund and Rahardjo, 1993; Aversa and Nicotera, 2002) in the soil specimen by using the axis translation technique. In this technique, the pore-air pressure is artificially raised above atmospheric pressure to increase the pore water pressure by the same amount to a positive value. In this way, the cavitation of water in the measuring system is prevented (Fredlund and Rahardjo, 1993).

In the current study, the triaxial compression apparatus developed at Bu-Ali Sina University is used to study the mechanical behavior of unsaturated soils. The details of the triaxial including its top cap and base plate are presented in Fig. 1. High-air entry ceramic disks, with 500 kPa of air entry values are sealed into the base pedestal and top cap using epoxy resin along their periphery. The two-way water flow (i.e. through ceramic disks in the cap and pedestal) causes a considerable decrease in test time and also create a more uniform distribution of moisture in the specimen. Two ceramic disks connected to the measuring system water compartment. The grooves inside the water compartment run as water channels for flushing air bubbles accumulated due to diffusion. The diffused air volume was measured by using the diffused air volume indicator (DAVI) proposed by Fredlund and Rahardjo (1993), and the measurement of pore-water volume change was corrected accordingly.

3. Testing program and procedures

3.1. Experimental details

In this work two groups of triaxial tests under saturated and unsaturated conditions were carried out for investigating the influence of initial density, matric suction and net confining pressure on soil behavior. The differences between the two groups are the specimen's initial density and compaction water contents. The initial physical properties of specimens are given in Table 1. The values in this table are average values obtained from all specimens in this study. The

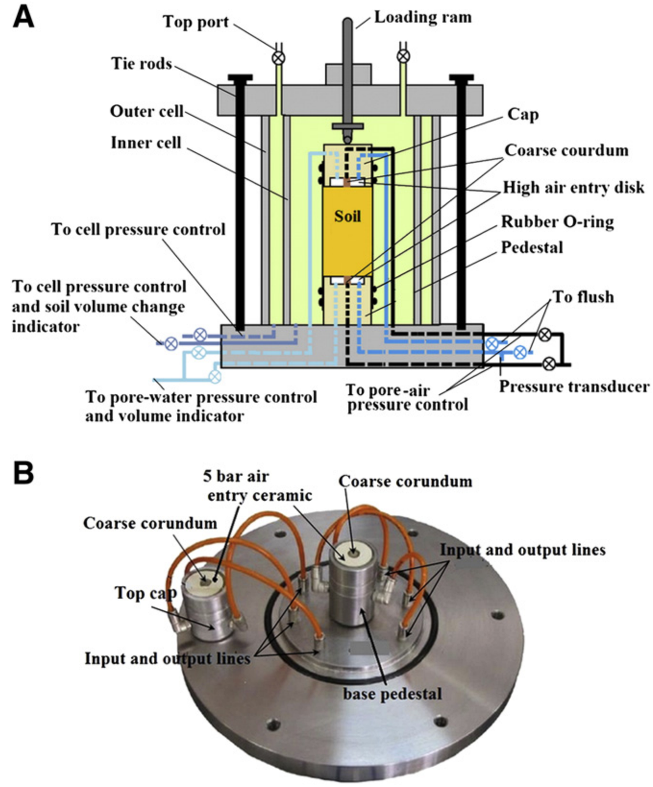

Fig. 1. Details of: (A) used triaxial cell for testing unsaturated soils; (B) base plate of unsaturated triaxial test apparatus.

grain size distribution and compaction test result (ASTM D, 1557, 2002, Method A) obtained by using the Standard Proctor Compaction method are shown in Fig. 2. The soil consists of 51% sand, 20% silt and 29% clay.

Previous investigations have indicated that sample preparation methods affect the behavior of soils (Ladd, 1974; Mulilis et al., 1977) and thus the choice of a suitable sample preparation technique is important in determining the behavior of soils. Current field sampling techniques are not readily able to produce high-quality undisturbed unsaturated soil specimens for laboratory testing at an affordable cost. Accordingly, numerous sample reconstitution methods have been developed and, among these methods, wet compaction has the advantage of providing relatively easy control of specimen density, even for loose specimens (Frost and Park, 2003).

In this work, wet compaction has been used for preparation of samples. Compacted specimens were prepared using a compaction mold specifically designed for static compaction. The purpose of using static compaction as opposed to dynamic compaction is to obtain a more homogenous specimen in terms of density and shear strength.

During sample preparation, dry sand, silt and kaolinite have been mixed at weight ratios of 51, 20 and 29% respectively. A bulk soil sample was prepared by spraying fine droplets of the required quantity of

Table 1
Physical properties of compacted soil specimen.

	Group-1	Group-2
$_{wet}$ $(KN/m^3)\gamma$	19.11	17.24
$_{dry}$ $(KN/m^3)\gamma$	17.94	16.26
$(S_r)_{initial}$ (%)	37.73	26.26
e	0.46	0.61
G_S	2.67	2.67
$(\omega)_{initial}$ (%)	6.5	6