Shear Strength Behaviour of Unsaturated Silty Soil

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Summary. This paper presents results of an experimental study on shear strength behaviour of an unsaturated silty soil. A comprehensive set of laboratory experiments have been undertaken in a double-walled triaxial cell (and a conventional cell for saturated samples) on samples of a compacted silty soil. In the experiments the soil samples were subjected to isotropic consolidation followed by unloading and subsequent anisotropic reloading (shearing) under constant suctions. Volume change and shear strength data for the samples were monitored continuously during the experiments. In this paper, the results of the experimental study will be presented and the effects of suction on the shear strength and volume change of unsaturated soil will be discussed in detail.

Key words: unsaturated soils, suction, shear strength, overconsolidation ratio, volume change

1 Introduction

There are vast areas of the world, particularly in tropical and subtropical regions, where the soils are generally unsaturated. In addition, even in many temperate regions, the soil above the water table remains unsaturated. Geotechnical engineers need to be able to assess the shear strength of unsaturated soils for safe and cost effective design of structures founded on unsaturated soils.

The first attempt to explain the shear behaviour of unsaturated soil was presented by Bishop (1959). The use of Bishop's equation for unsaturated soils was criticised by Jennings and Burland (1962) and Burland (1964). They pointed out that Bishop's equation, while appearing to explain shear strength behaviour, could not fully explain volume change behaviour. The importance of separating the stress state variables $(\sigma - u_a)$ and $(s = u_a - u_w)$ has been emphasized (where σ is total stress s is suction u_a is pore air pressure and u_w is pore water pressure) by many researchers such as Fredlund et al. (1978), Matyas and Radhakrishna (1968) and Wheeler and Karube (1995). Fredlund et al. (1978) and Fredlund (1979) put forward concepts for unsaturated soil based on independent stress state variables, giving the shear strength relationship as:

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (1)$$

where τ is shear strength, c' is the effective cohesion, ϕ' is the angle of friction and ϕ^b is the angle of friction for changes in $u_a - u_w$. In this method ϕ^b is assumed to be constant for all values of matric suction $(u_a - u_w)$. This approach has been widely used in interpreting shearing behaviour of unsaturated soils. Fredlund et al. (1978) suggested that ϕ^b could be assumed to be equal to the effective stress angle of friction measured in saturated condition (ϕ'). This would suggest that it is constant for all values of matric suction. The use of a linear relationship between $u_a - u_w$ and ϕ^b (i.e., a constant value of ϕ^b) was shown to be in error by Escario and Saez (1986). This non-linearity was confirmed by Fredlund et al. (1978) who assumed ϕ^b varied as a function of suction. In what follows the results of an experimental study on the shearing behaviour of an unsaturated soil will be presented and the effect of suction on the shear strength of unsaturated soils will be discussed.

2 Test Procedure and Program

2.1 Preparation of Compacted Specimens

The soil used in the testing program was a silty soil with low plasticity. The soil comprised 5% sand, 90% silt and 5% clay and had a liquid limit of 29% and plasticity index of 19%. The results of the standard proctor compaction test indicated a maximum dry density of $1.74\,\mathrm{Mg/m^3}$ at an optimum water content of 14.5%. Compacted specimens were prepared using a compaction mould designed specially for static compaction. The purpose of using static compaction as opposed to dynamic compaction was to obtain a more homogenous specimen in terms of density and shear strength throughout the volume of the specimen. The soil mass was mixed at a water content of 10% (4% less than optimum from standard compaction test). The specimens were 76 mm high and 38 mm in diameter. Compaction was done in nine layers with each layer being compacted to a maximum vertical total stress of 1600 kPa. The specimens produced by this method were found to be very uniform and the interface between the layers was barely apparent.

2.2 Test Procedure and Program

A series of triaxial tests were conducted using a conventional triaxial cell for saturated and a modified cell for unsaturated soil testing Estabragh et al. (2004). Both triaxial cells were connected to GDS controllers for applying the cell pressures, pore water pressure (u_w) and axial strain. All the experimental data were recorded continuously by a computer. The triaxial test program consisted of several stages as follows:

3.2.1 Equalisation

After setting the apparatus, the first step of each test was equalisation. At this stage by applying the required air and water pressures, the specimen was brought to the desired suction.

3.2.2 Ramp consolidation and unloading

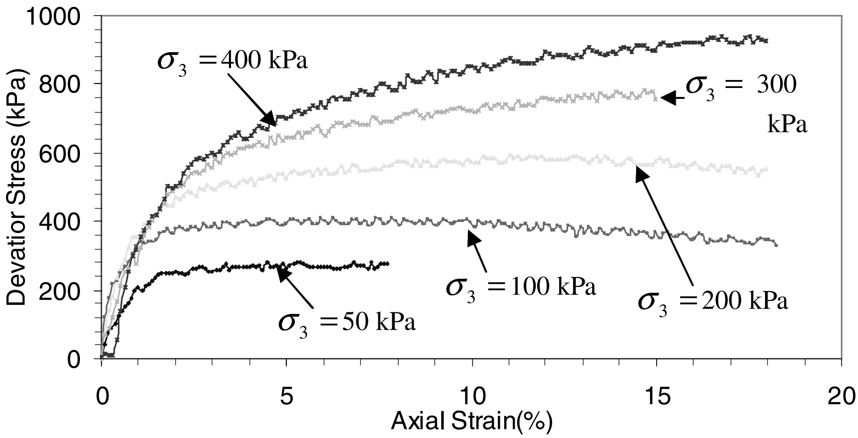
After the equalisation stage each specimen was consolidated isotropically to the selected value of mean net stress (p') by ramp consolidation. The sample was then unloaded isotropically to a predefined lower value of mean net stress. Suction was maintained constant during loading and unloading.

3.2.3 Shearing

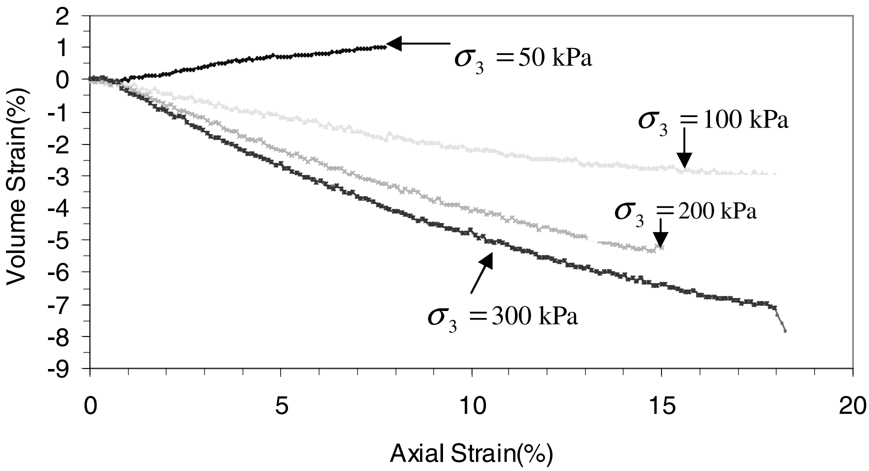
After the unloading stage, each specimen, with pre-defined overconsolidation ratio (OCR), was sheared by applying an axial load at a constant compressive strain rate Estabragh and Javadi (2006).

3 Results and Discussion

Typical results of the triaxial tests are presented in Figs. 1 and 2. The triaxial shear tests were performed under controlled suctions (0, 100, 200 or 300 kPa) and constant cell pressures (50, 100, 200, 300 or 400 kPa). Each series of tests was carried out at a specified overconsolidation ratio (OCR = 11, 5.5, 2.75, 1.38 and 1.1). Compression of a specimen during shearing is expressed using a negative sign, and a positive sign is used for dilation of the specimen in the graphs of volumetric strain versus axial strain. Figs. 1**a** and 2**a** show that in the shear tests the deviator stress increased with increasing cell pressure until a peak value and then remained nearly constant. Figs. 1**b** and 2**b** show that, generally, the volume of the samples decreased during shearing except for the samples with high overconsolidation ratios. For tests with $\sigma_3 = 50$ and 100 kPa at suctions of 100 and 200 kPa the deviator stress first increased and then slightly decreased. During shearing, the volume of these samples increased after a slight initial contraction. However, it is concluded from these results that the stiffness of the soil specimens generally increased with increasing confining pressure and decreasing the value of OCR. In the tests conducted on specimens with high OCR values of 11 and 5.5, the specimens exhibited a relatively brittle behaviour and during shearing, a slight increase



(a) Deviator stress with axial strain

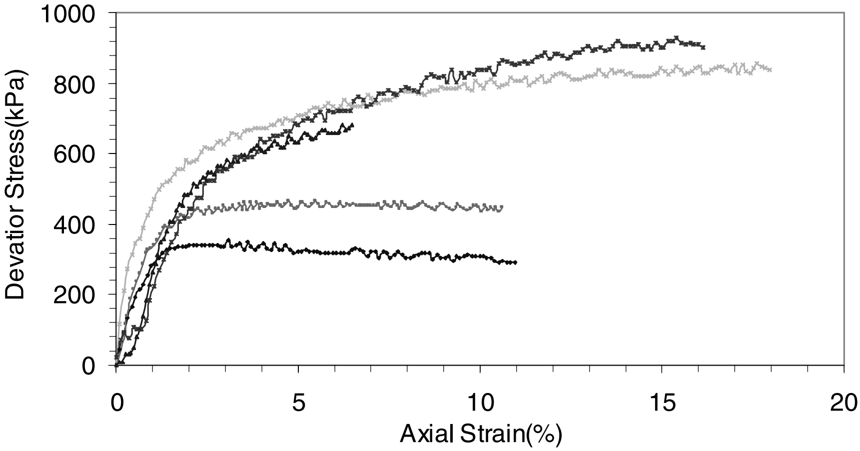


(b) Volumetric strain-axial strain curves

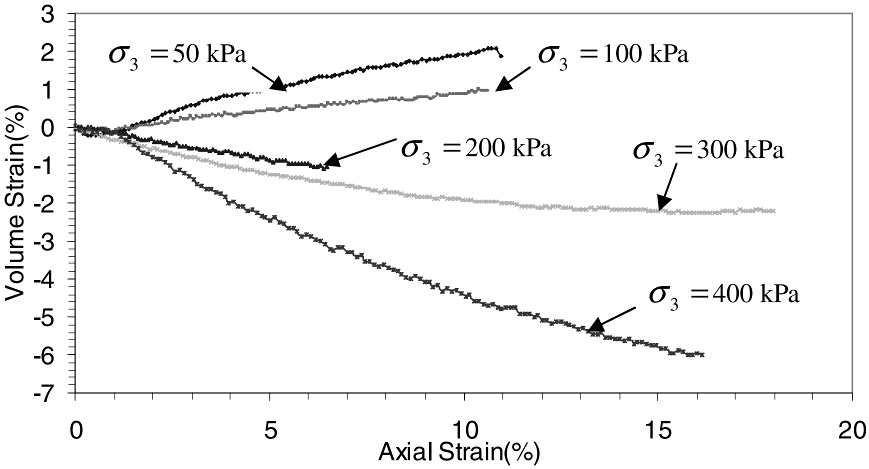
Fig. 1. (**a**) Stress-strain curves, (**b**) Volumetric strain-axial strain curves for samples tested at $s = 100\,\mathrm{kPa}$ under various cell pressures

in total volume was observed after an initial compression. This behaviour can be attributed to the influence of matric suction on the stiffness, brittleness and dilatancy of the soil specimens, especially at low confining pressures. The exhibition of post softening behaviour is commonly observed in heavily over consolidated specimens.

Figure 3 shows typical results of variation of maximum deviator stress with suction at constant cell pressure. This figure shows that the deviator



(a) Deviator stress-axial strain curves



(b) Volumetric strain-axial strain curves

Fig. 2. (**a**) Stress-strain curves, (**b**) Volumetric strain-axial strain curves for samples tested at $s = 200\,\text{kPa}$ under various cell pressures

stress increased with increasing suction. Also, Figs. 1 and 2 show that the brittleness of the soil decreased with increasing confining pressure. It can be concluded that the strength of soil specimens increases with increasing suction but its variation is not linear. The increase in cell pressure causes a progressive evolution from dilatancy to compression behaviour until the dilatancy completely disappears.

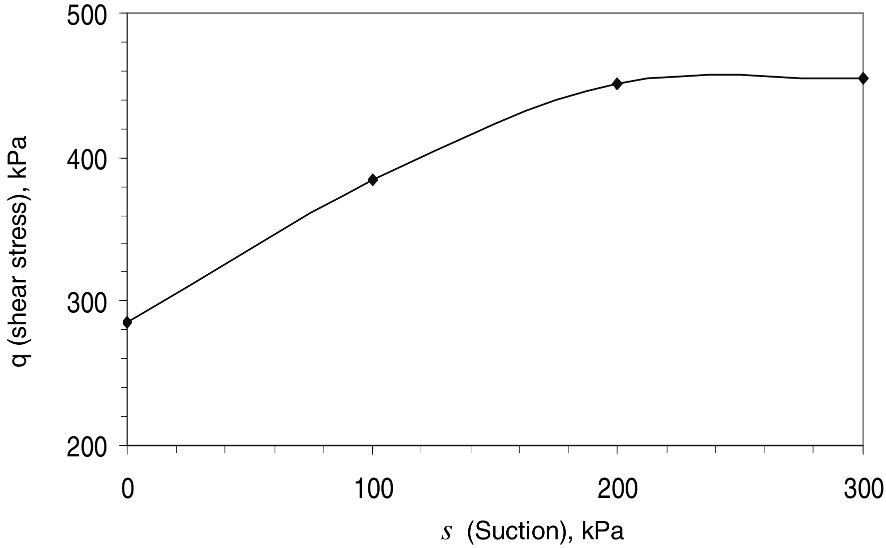


Fig. 3. Variation of maximum deviator stress with suction

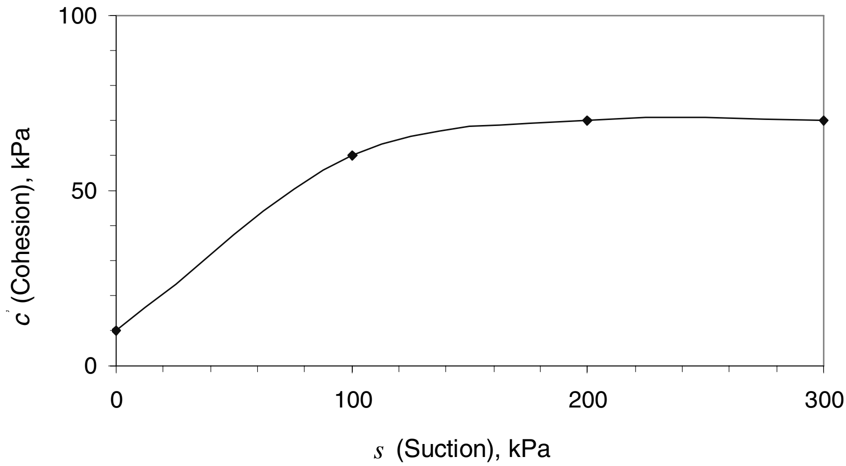


Fig. 4. Variation of c' with s

Figure 4 indicates a similar pattern of increase in cohesion intercept with increase in matric suction at the peak shear stress for all specimens tested under different confining pressures.

4 Conclusion

The experimental program on the saturated and unsaturated specimens provided some information on the shear strength behaviour of unsaturated compacted silty soils. The following conclusions are drawn.

Both confining pressure and suction affect the shear strength behaviour of unsaturated soil.

Softening and increasing the stiffness (hardening) of specimens for a given cell pressure depend on the value of suction.

Dilatancy or compression may occur during shearing; suction and OCR are important factors affecting dilatancy and compression.

The cohesion of soil is a function of suction and the relationship is nonlinear.

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