Stress-dilatancy relationships of an unsaturated soil under various cyclic loading conditions

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1. Introduction

Most of the research works for cyclic loading properties of soils have been conducted for saturated soils. When a soil was subjected to monotonic loading under a drained condition, Rowe (1962) experimentally found that there was unique relationship between the stress ratio: q/p' and dilatancy ratio: $-d\varepsilon_v{}^p/d\gamma^p$, namely strain increment ratio. That is stress-dilatancy relationship. Many studies have been conducted by using triaxial, plane strain and torsional cyclic shear loading tests for saturated soils and obtained the stress-dilatancy relationships (e.g. Rowe, 1962; Pradhan 1989 etc.). Embankments such as, fill dams, roads and railways etc. are usually constructed by unsaturated geo-materials and normally remain unsaturated conditions for in-service period. Then when the stabilities of the embankments against dynamic motions such as earthquakes are evaluated, it is necessary to consider the cyclic properties of unsaturated soils. However, there has been no clear detail report of stress-dilatancy relations for unsaturated soil under cyclic loading conditions. Though Kohgo et al. (1993b, 2007) proposed elastoplastic models for unsaturated soils based on the cyclic plasticity theory, the stress-dilatancy relationships are needed to accomplish more accurate estimations especially for the cyclic hysteresis loops. So, several series of cyclic triaxial shear loading tests were conducted to investigate the stress-dilatancy relationships of unsaturated soil under drained conditions.

2. Materials and Methods

A cyclic triaxial apparatus for unsaturated soils was used. It has a ceramic disc, whose air entry value = 100 kPa, in the pedestal and a porous stone with a water repellent filter in the cap. A silty soil named DL clay was used as the test material under a series of drained cyclic triaxial shear loading tests. DL clay consists of sand, silt and clay, and the percentage of them are 0.1, 90.4 and 9.5 %, respectively. It is also non-plastic. The soil particle density is 2.650 g/cm^3, maximum dry density is 1.538 g/cm^3, optimum water content is 21.2 % and saturated coefficient of permeability is 6.7x10^{-7} m/s.

Table 1. Experimental Conditions

Test Series	Stress Conditions σ_{3net} (kPa)	Stress Conditions s (kPa)	Test Types	Loading conditions	Cyclic No.
CS	100	0, 10, 30, 60, 90	Constant stress ratio (q/p') amplitude	q/p' = 0.7 ～ -1.0	10
CA	100	0, 10, 30, 60, 90	Constant axial strain (ε_a) amplitude	ε_a = ± 1.5%	4
SS	100	0, 10, 30, 60, 90	Shear strain (γ) amplitude increased	γ =±(0.5, 1, 2, 4%)	4

The tests were performed under the single net confining pressure σ_{3net} = 100 kPa and five different values of constant suction s = 0, 10, 30, 60, and 90 kPa. Three different stress conditons, constant stress ratio (CS series), constant axial strain (CA series) and increased shear strain (SS series), were carried out. The details of experimental conditons are shown in Table 1. The soil specimen was compacted with ρ_d= 1.3 g/cm^3 and water content w = 17 %. The dimensions of the specimens are 5 cm in diameter and 10 cm in height. Back pressure 200 kPa were only applied to the saturated specimens. In all the tests, the specimens were isotropically consolidated up to the prescribed pressure and then cyclic shear loadings were applied to the specified stress or strain amplitude under a constant shear axial strain rate of 0.05 %/min. After the cyclic shear loadings finished, processes of shearing were continued until 15 % axial strain in all the tests. During the shearing process, the net confining pressure and suction were kept constant under drained condtions. The effective stresses were evaluated by the effective stress equations for unsaturated soils (Kohgo et al. 1993a, 2007).

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3. Results and Discussions

We will mention here only for shear strain amplitudes increased with cyclic loadings for SS00, SS30 and SS90 (i.e., s = 0, 30 and 90 kPa). Shear strain amplitudes were sequentially increased up to 0.5, 1, 2 and 4 % for the cyclic loadings. The relationships of stress ratio and shear strain obtained from this series of tests are shown in Figures 1 (a - c) for SS00, SS30 and SS90, respectively. The stress ratios increased with the cyclic times in all the cases. It can be seen in these figures that the slopes of the reloading lines become steeper with the cyclic loadings in all the specimens. The hysteresis slopes became also steeper with an increase in suction at the first few cyclic times. Applying higher suction values inhibited the plastic deformations. Namely an increase in suction enhanced stiffnesses of the soil.

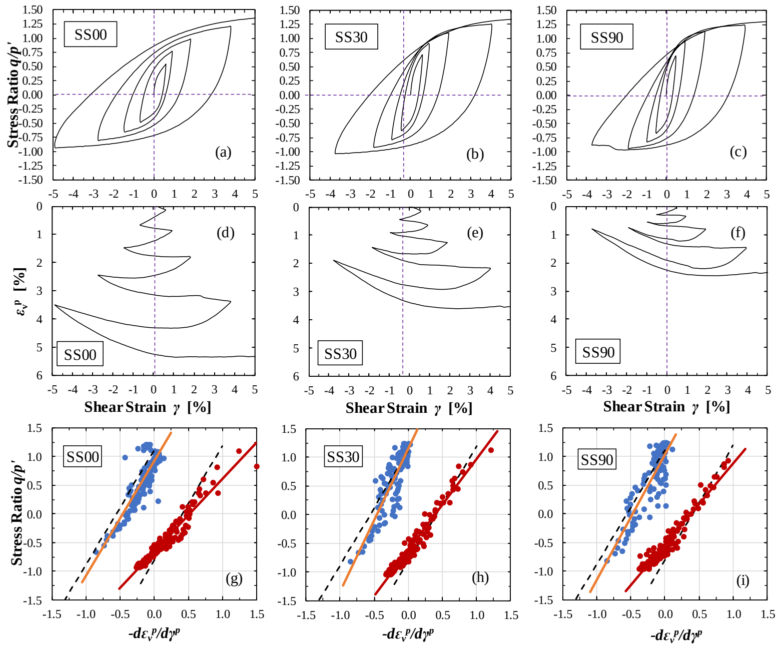

Fig. 1. (a - c) Stress-strain relationship, (d - f) Volume change behavior, (g - i) Stress-dilatancy relationship for increasing shear strain amplitude

The relationships between plastic volumetric strain ε_v^p and shear strain γ^p obtained for SS series are shown in Figures 1 (d - f). Contractive volume change behavior could be seen at the first loading and unloading in all the specimens. The behavior progressively changed to be dilative with the cyclic times. The amounts of compression in each loading and unloading step became larger in all the cases as the shear strain amplitudes increased. The smallest total volume reduction was found in SS90 specimen with the highest suction. The dilative behavior at the unloading stages started from the third unloading stage for SS00, while it started at the second unloading stage for SS30 and SS90 specimens. The behaviors of the specimen with high suction value (SS90) were more dilative than those of the specimen with low suction value (SS00) in all loading cycles.

It is very important to know the stress-dilatancy relationships of the unsaturated soils to evaluate permanent deformations due to cyclic loadings. Figures 1 (g - i) show the relationships of stress ratio and dilatancy ratio, i.e., ratio of plastic volumetric strain increment $d\varepsilon_v^p$ and plastic shear strain increment $d\gamma^p$, for SS00, SS30 and SS90. The blue and red closed circles are the relationships obtained from the loading and unloading cycles, respectively. The stress-dilatancy relationships obtained from all the cycles of loading and unloading appeared to be almost linear in all the cases. The best fitting lines are shown as the solid lines, and the dashed lines were drawn from extended Taylor's theory (Taylor 1948) where the net plastic work is assumed to be only dissipated in friction, and they had the incline = 2 and ϕ'_{pt} = 28 degrees. The estimations by both solid and dashed lines are also reasonable. Each line of stress-dilatancy relationships in loading and unloading may be expressed as a unique one in spite of saturated and unsaturated conditions, if the first suction effect: an increase in suction increases effective stress, is taken into account. The stress-dilatancy relationships for other series (CS and CA series) were also almost linear for all the cases. The plastic potential functions may be consequently derived by using these stress-dilatancy relationships.

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