HYDRAULIC HYSTERESIS EFFECT ON COMPRESSIBILITY OF UNSATURATED SOILS

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ABSTRACT

An experimental program of laboratory testing on a compacted kaolin in a modified triaxial cell was carried out to investigate the effect of hydraulic hysteresis on a loading collapse curve of unsaturated soils. The test data are presented on a range of constant suction isotropic loading tests along wetting and drying paths. The effect of hydraulic hysteresis on the compression curves at different values of matric suction and the loading collapse curves was observed. The loading collapse curve also indicates a constant value of effective pre-consolidation pressure with decreasing matric suction along the wetting scanning curve.

Keywords: hydraulic hysteresis, unsaturated soils, loading collapse curve, triaxial tests.

INTRODUCTION

Almost 40 percent of natural soils on the earth surface are in an unsaturated state. This type of soils can be found in arid and semi-arid regions and causes severe problems due to expansion and collapse of soils skeleton to several existing buildings worldwide. Moreover, the unsaturated soils are often encountered in civil engineering practice, such as compaction works in construction of roads, dams and other types of embankment.

Most hydro-mechanical models for unsaturated soils have been developed using effective stress approaches (Lewis and Schrefler 1987 Kohgo *et al.* 1993, Sheng *et al.* 2003, Loret and Khalili 2002, Gallipoli *et al.* 2003). The feature of unsaturated soils included in the models is a shift in preconsolidation pressure or yield limit with suction, referred to as the loading collapse (LC) curve. Loret and Khalili (2002) pointed out that the shape of LC curve and the rate of decrease in effective stress control a collapse behavior upon wetting.

Although the LC curve has been included in several models, the effect of hydraulic hysteresis on it is as yet not well understood. As shown in Figure-1, the degree of saturation of two identical soils with the same matric suction, defined as the difference between pore air pressure and pore water pressure, are always different if one is on drying path and another one is on wetting path. Therefore, the areas within the voids affected by matric suction of these two soils are also different. This consequently causes differences in the effective stress, which controls volume changes and LC curve.

The main objective of this research is to investigate the influence of hydraulic hysteresis on the volume changes in unsaturated soils through results from a comprehensive program of laboratory testing on a compacted sample of kaolin in a triaxial cell. The test data are presented on a range of constant suction isotropic loading tests along wetting and drying paths.

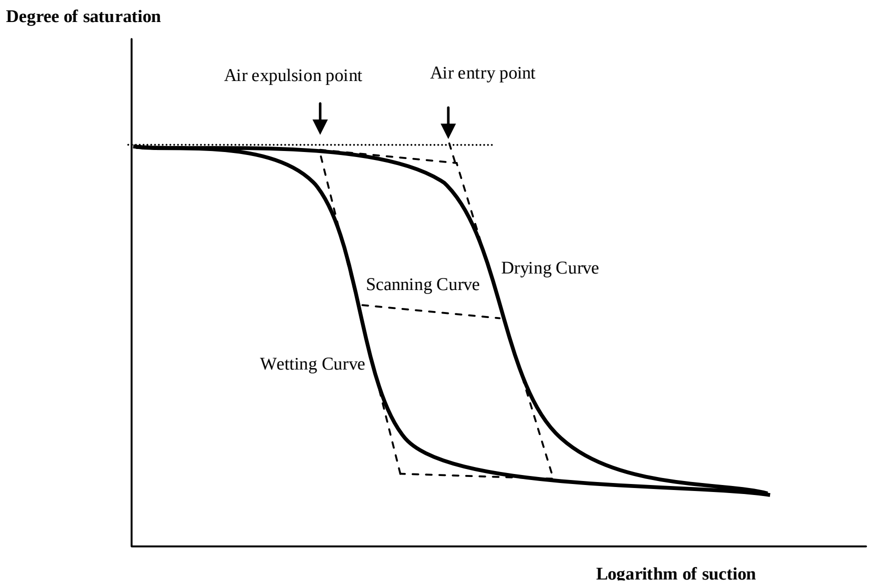

Figure-1. Typical soil water characteristic curve.

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Experimental preparation and test material

Experimental equipment

The tests were performed using a conventional triaxial cell with a few of modifications for testing unsaturated soils as shown in Figure-2. The modified cell was capable of independent measurement and control of pore air pressure and pore water pressure at the top and the bottom boundaries of the specimen. The pore air pressure was controlled through a coarse porous stone placed at the top of the specimen. The pore water was controlled at the bottom of the specimen through a high air entry value ceramic disc. The ceramic disc was attached to the pedestal base using epoxy glue to prevent a flow of air to the water compartment through its surroundings. The suction in the specimen was controlled using axis-translation technique (Hilf 1956).

Prior to each test, the ceramic disc and the pore water control system were saturated using a technique similar to that used by Toll (1988). The empty cell was filled with de-aired water and pressurized to a cell pressure of 600 KPa. The water was allowed to flow through the ceramic disc into the water compartment while maintaining the water pressure at the base of ceramic disc at the atmospheric level. After collecting 200 cm^3 of water flow, the drainage valve was closed for at least 2 hours to dissolve any air trapped within the ceramic disc. The addition flushing process was required to ensure that the ceramic disc was fully saturated.

Volumetric strain measurement

A digital image-processing technique was used for measuring volumetric strains of the specimens. The images of the specimens were taken during testing using digital imaging equipment. A Nikon D50 digital single lens reflex camera with 3008 pixels by 2000 pixels resolution was use to capture the images of specimens. A Nikon AF-Nikkor 85 mm f/1.8D lens was used together with the Nikon D50 camera. To produce clear specimen boundaries on the images, the specimens were lighted to provide sufficient illumination for their shadow areas.

The process of a determination of specimen volume from the digital images was performed using technique similar to that of Macari *et al.* (1997). The specimen height was measured along the vertical axis of specimen appearing in the digital images. For diameter measurement, the specimen was assumed as a series of stacked discs with variation in diameter. The diameter of the specimens was obtained through averaging all assumed discs. Finally, the specimen volume and the volumetric strains were calculated from the measured height and the average diameter.

Test material

The experiments were carried out on a laboratory-compacted-kaolin. The index properties of test soil are given in Table-1.

Table-1. Index properties of kaolin.

Property	**Values**
Liquid limit (%)	52
Plastic limit (%)	31
Specific gravity	2.72
Maximum dry unit weight* (kN/m^3)	14.1
Optimum moisture content (%)	27.5

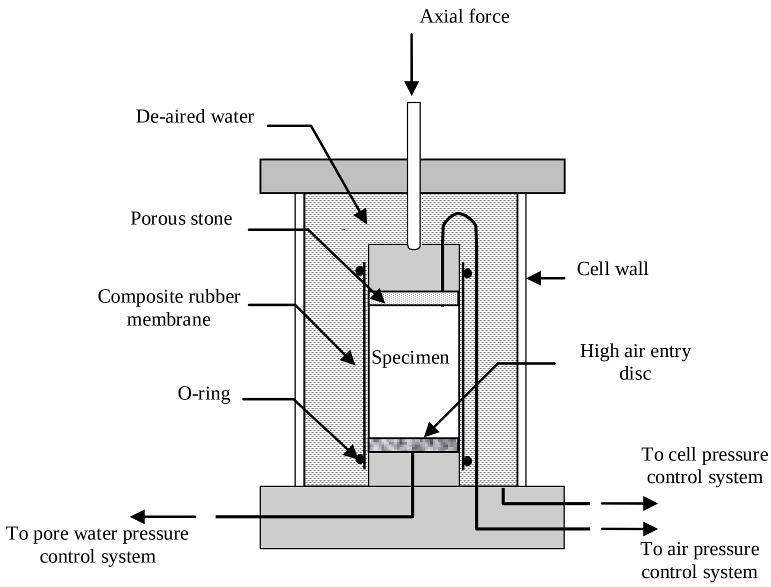

Figure-2. Modified triaxial cell.

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Sample preparation

To make identical specimens with a matrix amenable to stiffening with increasing matric suction, the samples were prepared dry of optimum. The kaolin sample with a water content of 25% was statically compacted to a dry unit weight of approximately 11.8 kN/m^3. Prior to compaction, the kaolin sample was carefully wetted to a water content of 25% and cured for 24 hours in a sealed plastic bag for moisture equalization. The compaction was carried out in nine equal layers in a greased split mold of 38 mm diameter.

The soil-water characteristic curve (SWCC) of the compacted specimens, presented in Figure-3, was obtained by keeping the compacted specimens in the modified triaxial cell at the different values of constant matric suction for 3 days. For wetting portion of the curve, the matric suction was first increased to 300 kPa and then reduced to the target value. The values of air entry (s_{ae}) and air expulsion (s_{ex}) obtained from the SWCC are 80 and 35 kPa respectively.

Specimen set-up

The specimen was covered by two rubber membranes. To minimize diffusion of air through the membranes, the silicon grease was placed between the two membranes. The covered specimen was then placed on the ceramic disc and sealed by fitting O-rings around the base pedestal and the top cap as shown in Figure-2. After assembling the apparatus, the cell was filled with de-aired water and an axial load of about 5 kPa was applied to secure the specimen in place. The free air in the specimen was flushed through the top cap by applying the water pressure of 50 kPa through the cell based while maintaining the pressure at the top at the atmospheric level. To prevent failure of the specimen, a cell pressure of 75 kPa was applied throughout the flushing process. After flushing free air in the specimen for 3 days, the top drainage line was closed for 24 hours to equalize pore water pressure within the specimen.

Test program and procedure

A total of 9 isotropic loading tests were performed using the modified triaxial equipment to investigate the influence of hydraulic hysteresis on compression curve and effective preconsolidation pressure or yield limit at the different values of matric suction.

The isotropic loading tests were performed on both dried and wetted specimens. Prior to each shear test, the specimens were consolidated to an isotropic stress of 200 kPa. Then the specimens were unloaded to the isotopic stress of 50 kPa. Thus, all specimens were subjected to over consolidation ratio (OCR) of 4 and their initial value of effective preconsolidation pressure was 200 kPa. The specimens were then subjected to the different values of matric suction ranged from 0 to 300 kPa. For the dried specimens, the matric suction was increased from 0 kPa (saturated state) to the testing value. For the wetted specimens, the matric suction was first increased to 300 kPa and then reduced to the testing value. The isotropic loading tests were conducted by increasing the cell pressure in increments. For each load increment, dissipation of excess pore water pressure was allowed for at least 3 days to achieve equilibrium.

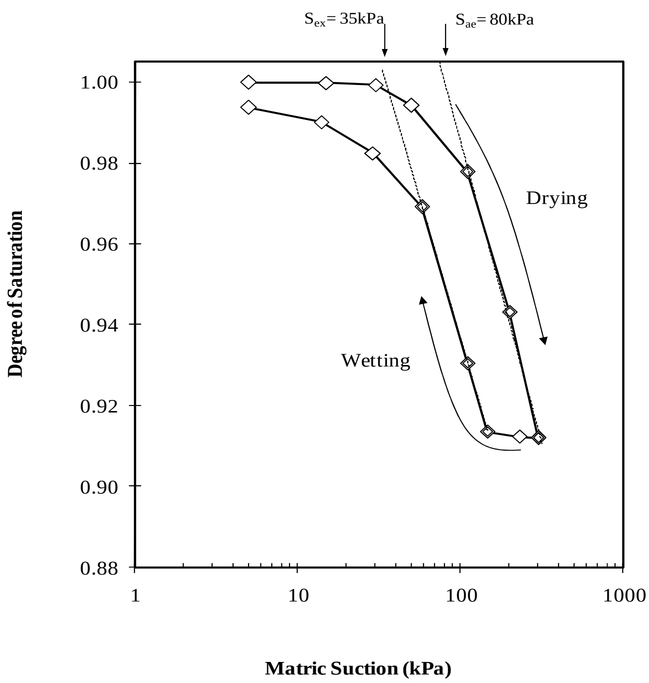

Figure-3. Soil water characteristic curve of compacted kaolin.

Test results

The test results are presented in terms of void ratio against logarithm of isotropic effective stress. The effective stress for unsaturated soils can be expressed as a function of the externally applied stresses and the internal fluid pressures and defined as (Bishop 1959),

$$p' = p_{net} + \chi s \quad (1)$$

where p' is the mean effective stress, p_{net} is the total stress in excess of pore air pressure, referred to as mean total stress, s is the matric suction, and χ is the effective stress parameter attaining a value of unity for a saturated soil and zero for a dry soil. The parameter χ is strongly related to the soil structure (Coleman 1962) and suction ratio, defined as the ration of matric suction over the air entry suction (Khalili *et al.* 2004), and is expressed as,

$$\chi = \begin{cases} [s/s_e]^{-\Omega} & for \quad s \geq s_e \\ 1 & for \quad s \leq s_e \end{cases} \quad (2)$$

in which, s_e is suction value marking the transition between saturated and unsaturated states, and Ω is a material parameter, with a best-fit value of 0.55. For the main wetting path, $s_e = s_{ex}$ and for the main drying path $s_e = s_{ae}$, in which s_{ex} is the air expulsion value and s_{ae} is the air entry value.

The compression curves at different matric suction along drying and wetting paths are given in Figures 4 and 5 respectively. The data shows a shift in normal compression curve to higher effective stresses with increasing matric suction in both cases. Figures 4 and 5 also show that the slope of the normal compression lines, λ and the slope of the unloading lines, κ, are independent of matric suction. The values of λ and κ are 0.054 and 0.019 respectively.

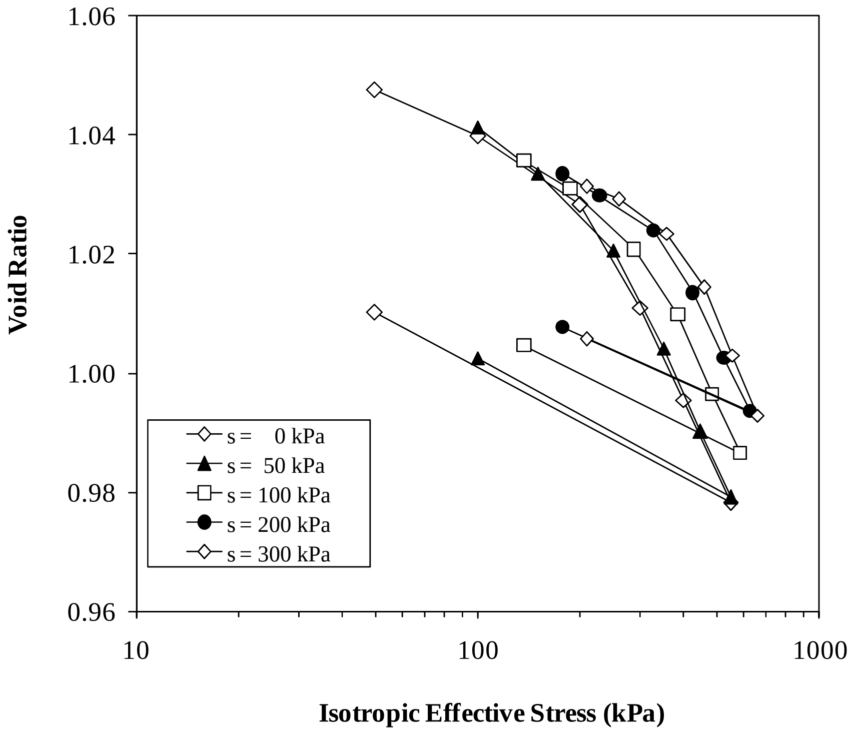

Figure-4. Isotropic loading tests on dried specimens at different matric suctions.

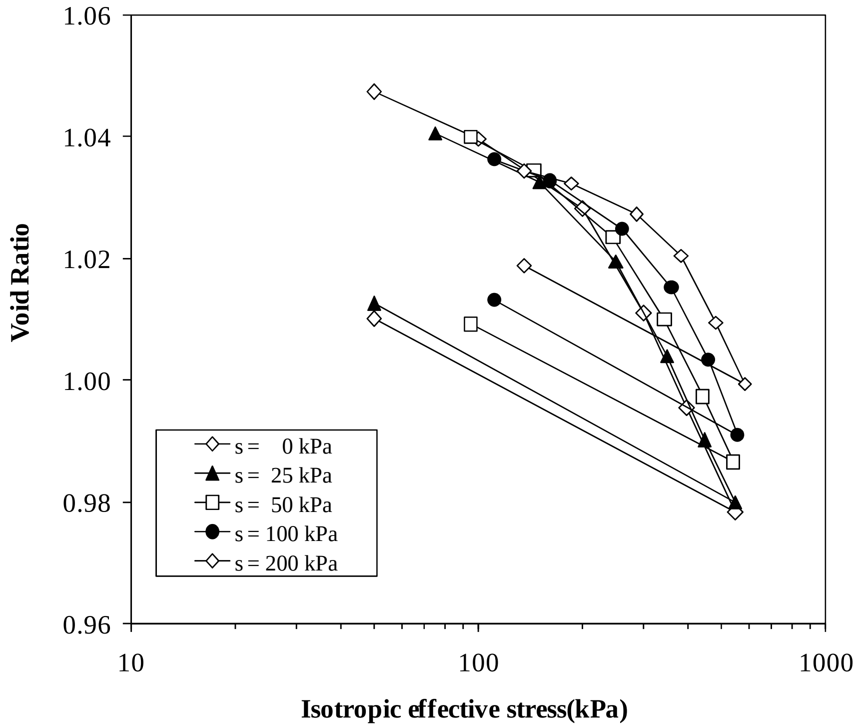

Figure-5. Isotropic loading tests on wetted specimens at different matric suctions.

The variation of the effective preconsolidation pressure or yield limit against matric suction, referred to as the loading collapse (LC) curve is presented in Figure-6. It is obvious that the effect of hydraulic hysteresis on LC curve was observed. The effective preconsoildation pressure is assumed constant at matric suction less than the values of air entry and air expulsion for LC curves along drying and wetting paths respectively. The LC curve along wetting path also indicates that the effective preconsoildation pressure is obviously constant over the range of matric suction along the scanning curve.

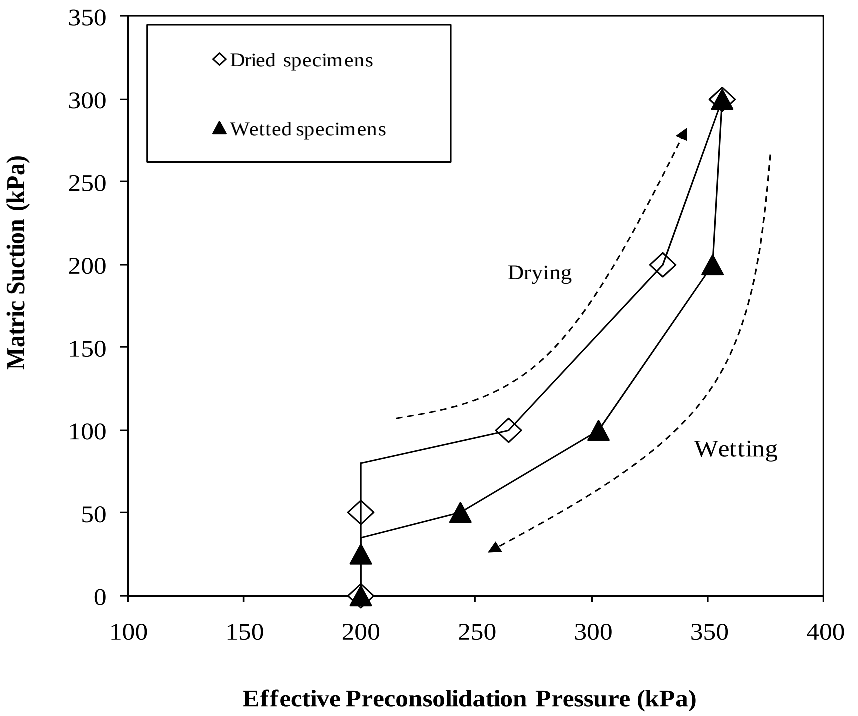

Figure-6. Loading collapse curve of compacted kaolin specimens.

DISCUSSIONS

The compression curve shifts towards higher stress with increasing matric suction for the isotropic tests on both wetted and dried specimens. This causes an increase in the effective preconsolidation pressure or yield limit with matric suction, presented through loading collapse (LC) curve. The saturated response is obtained over the range of rmatric suction less than air entry and air expulsion values for the tests on dried and wetted specimens respectively, agreeable to Blight (1966), Fleureau *et al.* (1993), Khalili *et al.* (2004) and Uchaipichat and Khalili (2009). At the values of matric suction greater than the values of air entry (for dried specimens) and air expulsion (for wetted specimens), except those values along wetting scanning curve, the effective preconsolidation pressure gradually increases with matric suction. A constant value of effective preconsolidation pressure with decreasing matric suction along the scanning curve was observed while the effective stress decreased with decreasing matric suction. This implies that a collapse upon wetting does not occur along the wetting scanning curve, consistent with the observation of Wheeler and Sivakumar (1995) during equalization stage, which was reanalyzed by Loret and Khalili (2002).

CONCLUSIONS

An experimental program of isotropic loading tests was conducted on compacted kaolin using conventional triaxial equipment modified for testing unsaturated soils. The modified triaxial cell was capable of independent measurement and control of pore air pressure and pore water pressure at the top and the bottom boundaries of the specimen. The effect of hydraulic hysteresis on the compression curves at different values of matric suction and the loading collapse curves was observed.

ACKNOWLEDGMENTS

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