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Experimental investigation on loading collapse curve of unsaturated soils under wetting and drying processes

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Abstract. An experimental program of isotropic loading tests on a compacted kaolin using a conventional triaxial equipment modified for testing unsaturated soils was perform to investigate a loading collapse curve of unsaturated soils along wetting and drying paths. The test data are presented in terms of effective stress on a range of constant suction. The suction hardening behavior was observed for both wetted and dried samples. With the use of an appropriate effective stress parameter, the unique relationship for loading collapse curve for wetting and drying processes was obtained.

Keywords: wetting-drying processes; unsaturated soils; loading collapse curve; triaxial tests.

1. Introduction

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.

However, the LC curve under wetting and drying processes is as yet not well understood. As shown in Fig. 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 LC curve 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.

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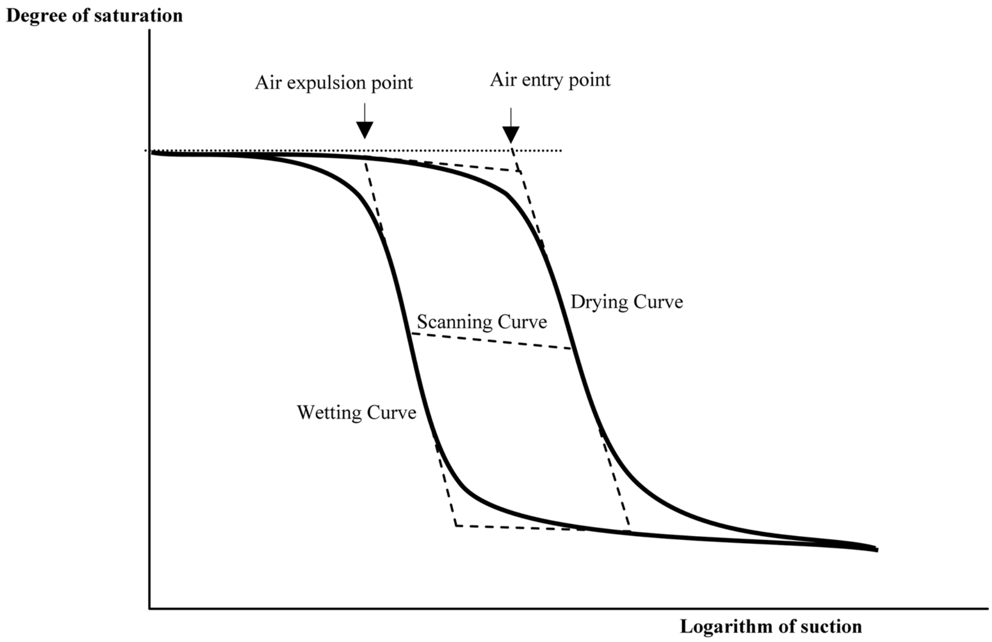

Fig. 1 Typical soil water characteristic curve

2. Experimental preparation and test material

2.1 Experimental equipment

The tests were performed using a conventional triaxial cell with a few of modifications for testing unsaturated soils as shown in Fig. 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.

2.2 Specimen volumetric strain measurement

A digital image-processing technique was used for measuring volumetric strains of the specimens.

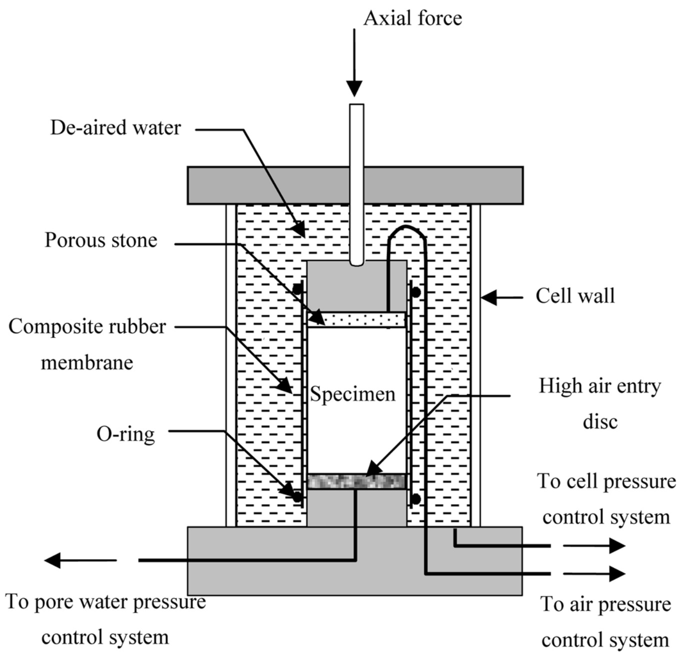

Fig. 2 Modified triaxial cell

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.

2.3 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

*Obtained using standard Proctor test.

2.4 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 Fig. 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.

2.5 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

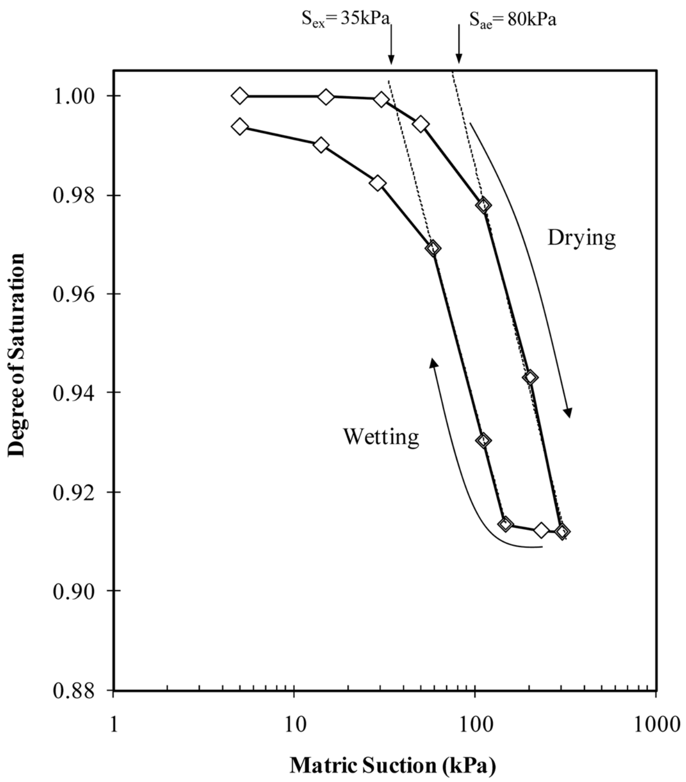

Fig. 3 Soil water characteristic curve of compacted kaolin

cap as shown in Fig. 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.

3. 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 overconsolidation 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.

4. 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)

$$p' = p_{net} + \chi s \tag{1}$$

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. Fredlund *et al.* (1996) suggest that the parameter χ is a function of degree of saturation (S_r) and can be expressed as

$$\chi = (S_r)^n \tag{2}$$

in which, n is a fitting parameter and $n = 1$ is assumed in this paper.

The parameter χ is also related to suction ratio, defined as the ratio of matric suction over the air entry suction (Khalili *et al.* 2004), and is expressed as

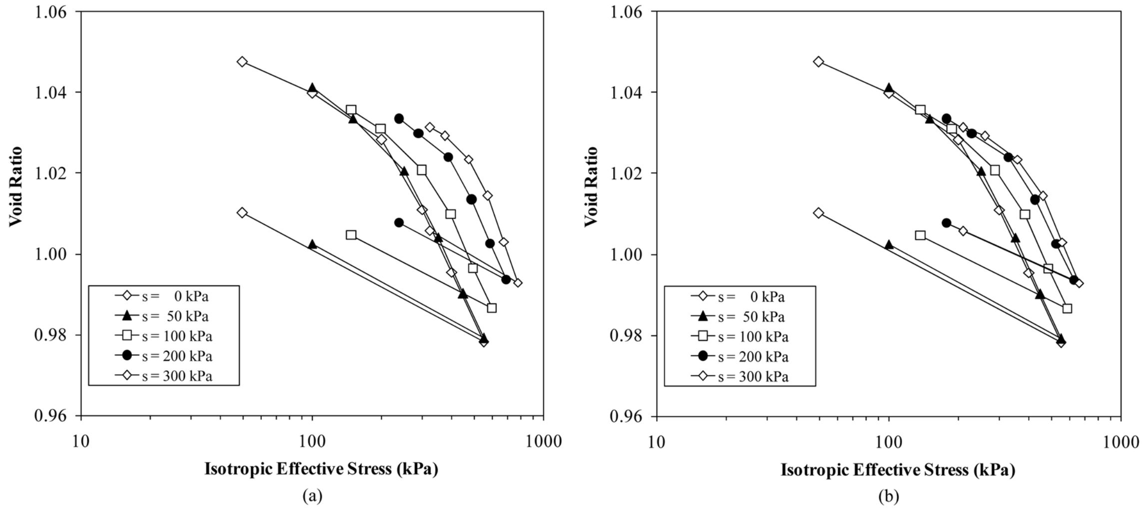

Fig. 4 Isotropic loading tests on dried specimens at different matric suctions : (a) using χ proposed by Fredlund *et al.* (1996), (b) using χ proposed by Khalili *et al.* (2004)

$$\chi = \begin{cases} [s/s_e]^{-\Omega} & \text{for } s \geq s_e \\ 1 & \text{for } s \leq s_e \end{cases} \tag{3}$$

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 Figs. 4 and 5 respectively. The data shows a shift in normal compression curve to higher effective stresses with increasing matric suction in both cases. Figs. 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.

The variation of the effective preconsolidation pressure or yield limit for dried and wetted specimens against matric suction, referred to as the loading collapse (LC) curve is presented in Fig. 6. For the results presented using the parameter χ proposed by Fredlund *et al.* (1996), it is obvious that a unique relationship for LC curve was obtained. The small suction hardening was found for the suction value less than 80 kPa and becomes greater for the portion of curve above this point. Moreover, the stress path corresponding to wetting under constant net mean stress is also presented in Fig. 6. It can be seen that the stress path for wetting under constant net mean stress of 215 kPa, on which the initial state before wetting is on the LC curve at matric suction of 300 kPa, lies inside the LC curve for its portion with the matric suction greater than 100 kPa.

However, the effect of hydraulic hysteresis on LC curve was observed for the results presented using the parameter χ proposed by Khalili *et al.* (2004). In this plot, 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

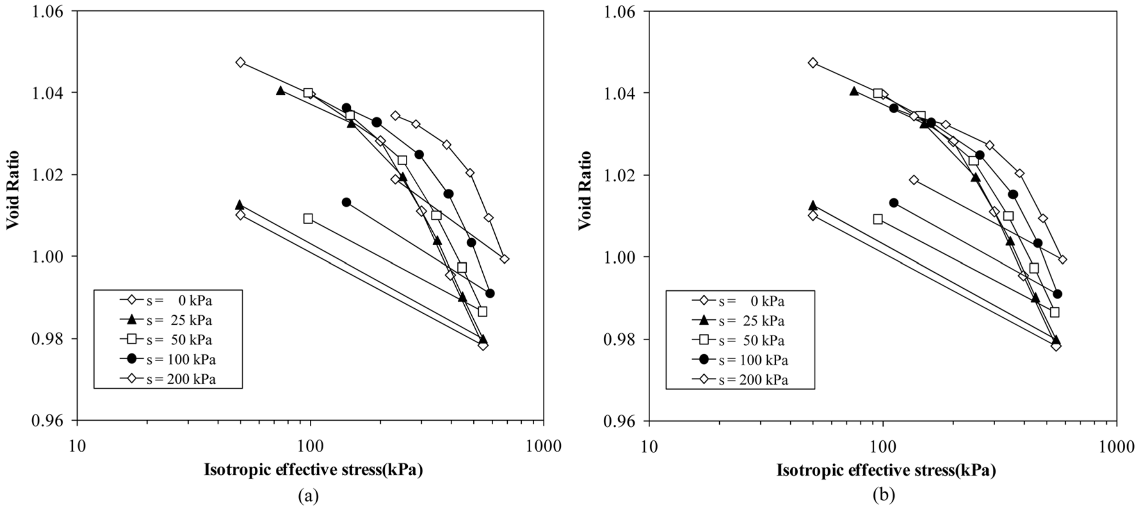

Fig. 5 Isotropic loading tests on wetted specimens at different matric suctions: (a) using χ proposed by Fredlund *et al.* (1996), (b) using χ proposed by Khalili *et al.* (2004)

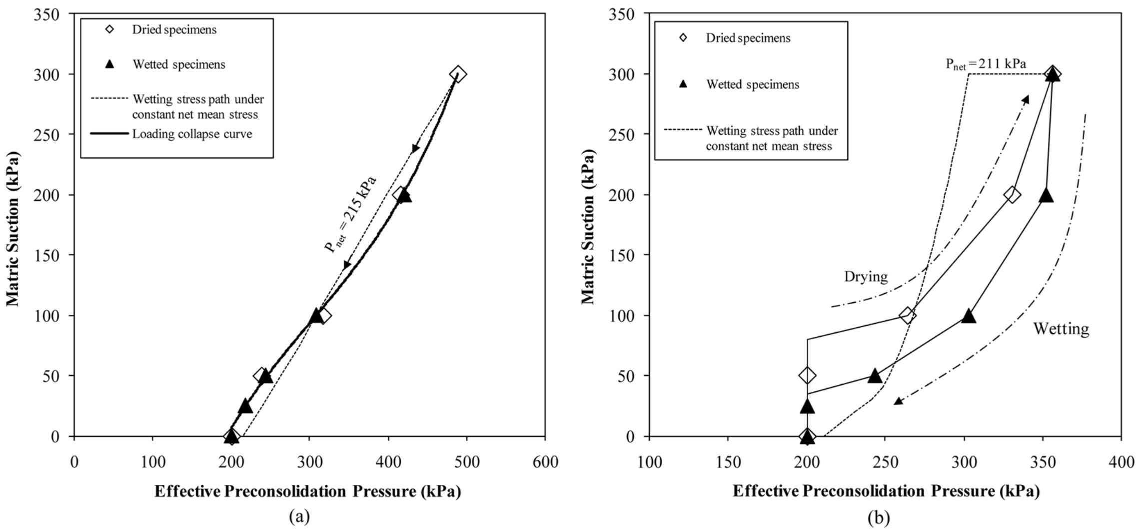

Fig. 6 Loading collapse curve of compacted kaolin specimens: (a) using χ proposed by Fredlund *et al.* (1996), (b) using χ proposed by Khalili *et al.* (2004)

indicates that the effective preconsoildation pressure is obviously constant over the range of matric suction along the scanning curve. For the stress path corresponding to wetting under constant net mean stress, the effective stress instantly shifts as the stress path is reversed, due to the bi-valued parameter s_e. The stress path lies inside the LC curve for its portion with the matric suction greater than 60 kPa.

5. Discussion

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. This study also shows that with the use of an appropriate effective stress equation, the constitutive model for unsaturated soils contains only single relationship for LC curve or yield surface for both wetting and drying processes. For the results presented using the parameter χ proposed by Fredlund *et al.* (1996), the small suction hardening was observed for the suction below the air entry value (80 kPa), which is the transition between saturated and unsaturated state for both wetting and drying processes as shown in SWCC in Fig. 3. Furthermore, the plot of stress path corresponding to wetting under constant net mean stress, on which the initial state before wetting is on the LC curve, shows that elastic deformation initially occurs before wetting-induced collapse phenomenon, consistent with the observation of Wheeler and Sivakumar (1995) during equalization stage, which was reanalyzed by Loret and Khalili (2002).

6. Conclusions

An experimental program of isotropic loading tests was conducted on a compacted kaolin using a 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 results were presented in terms of effective stress. The suction hardening behavior was observed for both wetted and dried samples. The unique relationship for loading collapse curve for wetting and drying processes was obtained.

Acknowledgments

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Notations

χ	: effective stress parameter
κ	: slope of the unloading line
λ	: slope of the normal compression line
p'	: mean effective stress
p_{net}	: mean total stress
s	: matric suction
s_{ex}	: air expulsion value
s_{ae}	: air entry value