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Effect of hydraulic hysteresis on shear strength of unsaturated clay and its prediction using a water retention surface

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ABSTRACT

A vadose zone may exist within man-made or natural slopes under the condition of a deep water table. During repeated cyclic infiltration (wetting) and evaporation (drying), the suction and degree of saturation may change within this regime. Thus, it is crucial to have a thorough understanding of the effects of a cycle of wetting and drying on the shear strength of unsaturated soils to assess the long term stability of these slopes. Three series of laboratory tests are presented in this paper, from which the water retention and shear behaviors of an unsaturated clay are studied. A three-dimensional main wetting surface is proposed and a unique failure envelope expressed in terms of Bishop's stress can be used to characterize the shear strength of unsaturated soil subjected to different hydraulic histories. The measured shear strengths are compared with those predicted by the proposed main wetting surface and the drying curve under no confining stress. It is found that a better prediction is obtained by using the main wetting surface for unsaturated specimens subjected to different hydraulic histories.

1. Introduction

A vadose zone may exist within man-made or natural slopes under the condition of a deep water table. This partially saturated regime can be subjected to variation because of the seasonal changes in weather leading to repeated cycles of infiltration and evaporation. Many landslides that occurred in these slopes are triggered by rainfall infiltration. In assessing the long-term stability of these slopes, the fundamental understanding of the effect of hydraulic history on the mechanical behavior of unsaturated soils is needed (Sorbino and Nicotera, 2013). Matric suction (hereafter referred to as "suction") defined as the difference between pore–air pressure (u_a) and pore–water pressure (u_w), is generally recognized as one of the key variables that governs the mechanical behavior of unsaturated soils. Shear strength is a key focus area for past studies on unsaturated soils (Bishop and Blight, 1963; Fredlund et al., 1978; Escario and Saez, 1986; Nam et al., 2011; Maleki and Bayat, 2012). It is found that shear strength increases nonlinearly with suction, but the trends at high suctions are still not well understood. Furthermore, some recent studies (Wheeler et al., 2003; Melinda et al., 2004; Rahardjo et al., 2004; Ng et al., 2009; Guan et al., 2010; Khalili and Zagarbashi, 2010; Khosravi and McCartney, 2012; Khoury and Miller, 2012) have shown that the hydraulic history also influences the shear strength and stiffness of unsaturated soils. Melinda et al. (2004) found that the shear strength envelope is not unique for unsaturated specimens subjected to drying and wetting paths. Rahardjo et al. (2004) postulated that this difference in shear strength may be due to the difference in degree of saturation S_r (or the contact area of pore–water with soil particles) resulting from the hydraulic history. Thus, both suction and S_r are required to characterize the shear strength of unsaturated soils.

Recently, Khoury and Miller (2012) reported that specimens subjected to wetting path after drying exhibit higher shear strength than those subjected to only drying path. They proposed that other than S_r, the suction history is also another factor that may control the shear strength of unsaturated soils. Furthermore, recent laboratory studies on the small strain shear modulus (Ng et al., 2009; Khosravi and McCartney, 2012) also showed that specimens subjected to a cycle of drying and wetting are stiffer than those subjected to only drying. Khosravi and McCartney (2012) proposed an empirical model that incorporates the concepts of effective stress and hardening mechanism due to suction to model this observed phenomenon of hydraulic hysteresis. It should be noted that these reported laboratory evidences are limited to the testing conditions under which the specimens are loaded before the application of a cycle of drying and wetting. Thus, additional research into the role of hydraulic hysteresis in the mechanical response of unsaturated soils is a subject that deserves further study, especially under different loading paths.

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As shear tests carried out on unsaturated soils are very time consuming, a number of empirical equations have been proposed to predict the shear strength of unsaturated soils based on the water retention curve, WRC (Fredlund et al., 1996; Vanapalli et al., 1996; Oberg and Sallfors, 1997; Toll and Ong, 2003). WRC refers to the relationship between water content (or S_r) and suction, which is measured conventionally by drying saturated specimens in successive increments of suction. It is generally known as the main drying curve. However, the relationship between S_r and suction is not unique. A main wetting curve can be obtained by wetting dried specimens in successive decrements of suction. The hydraulic hysteresis refers to the difference in S_r for a given suction due to the wetting and drying paths. It should be noted that WRC is measured conventionally without any loading. Recent studies have shown that its shape depends on the stress level and stress path (Vanapalli et al., 1999; Ng and Pang, 2000a,b; Romero and Vaunat, 2000; Wheeler et al., 2003; Chiu and Ng, 2012). The effect of stress level can be considered as the dependency of WRC on void ratio or volumetric strain (Gallipoli et al., 2003; Tarantino and Tombolato, 2005; Sun et al., 2007; Nuth and Laloui, 2008; Masin, 2010). Then, the WRC should be extended to a three-dimensional surface in the space of suction – degree of saturation – void ratio (Tarantino and Tombolato, 2005; Salager et al., 2010; Tsiampousi et al., 2013). Furthermore, Tarantino and Tombolato (2005) founded that a unique main wetting surface for a compacted kaolin in the space of suction – degree of saturation – void ratio can be obtained from “hydraulic wetting” (i.e. adding water) and “mechanical wetting” (i.e. constant water content) tests. In other words, it appears that the main wetting surface is path independent.

Some recent efforts (Guan et al., 2010; Infante Sedano and Vanapalli, 2010) have attempted to predict the shear strength of unsaturated soils using WRC measured under a confining pressure. Guan et al. (2010) used the main wetting curve to predict the shear strength of an unsaturated sand–kaolin mixture on the wetting path. However, the main wetting path was measured without any loading. On the other hand, Infante Sedano and Vanapalli (2010) showed that the WRC obtained with an applied stress gives a better prediction on shear strength than the one under no confining stress. However, the test specimens followed the drying path. Hence, past laboratory studies have rarely reported the coupling effects of hydraulic history on shear strength and of stress level on main wetting surface. In this study, it is attempted to study the coupled hydro-mechanical behavior of unsaturated soil, namely the effect of stress level on WRC and the effect of hydraulic history on shear strength. Based on the water retention test results, a three-dimensional main wetting surface is proposed and its predictions of shear strength due to different hydraulic histories are discussed.

2. Laboratory study

2.1. Basic soil properties and specimen preparation

A clay of low plasticity was used in the study. The basic physical properties of the tested soil were determined in accordance with the procedures given in GB/T 50123-1999 (Ministry of Construction of P.R. China, 1999). The fractions of sand, silt and clay are 20, 77 and 3%, respectively. The plastic and liquid limits are 16 and 34, respectively. The maximum dry density and optimum water content determined from the standard Proctor test are 1810 kg/m^3 and 16%, respectively. The tested soil is classified as CL according to the Unified Soil Classification System. The soil specimens were prepared by the moist-tamping method. The specimens were compacted to an initial dry density of 1650 kg/m^3 (or a void ratio of 0.62) at a water content of 16%.

2.2. Test program and procedures

The test program and conditions are summarized in Table 1. Table 1 reports the confining pressure, suction and void ratio after isotropic compression for each specimen. The program consists of three test series: *W*, *T-W* and *T-DW*. The *W*-series is to study the effect of stress level on WRC. WRCs were measured by a twin-cell triaxial test apparatus (Chiu et al., 2010) using axis translation technique for suction below 400 kPa and contact filter paper method for suction above 400 kPa (ASTM, 2010). Fig. 1 depicts the paths of WRCs. Point O_1 refers to the initial suction of unsaturated specimens after compaction, which is around 300 kPa. The specimens were saturated in deaired water inside a desiccator for 48 h following path O_1O. Thereafter, the saturated specimens were isotropically compressed to a stress level ranging from 50 to 100 kPa (path *OA*). Finally a cycle of drying and wetting (path *AB* and *BA*, respectively) was applied to each specimen. For a given suction, the equilibrium was reached when the rate of change in water content was smaller than 0.1%/day. Typically, 2–7 days were required to achieve the equilibrium condition for a given suction. Besides, the conventional WRC was also measured without loading as a control test (path OO_2 and O_2O).

Table 1
Test program and conditions of water retention and triaxial tests.

Test series	Specimen ID	Target suction before compression (kPa)	Confining pressure (kPa)	Void ratio after compression
W	*W*-0-0	0	0	0.620[a]
	W-0-50	0	50	0.538
	W-0-100	0	100	0.514
T-W	*T-W*-0-50	0	50	0.532
	T-W-0-100	0	100	0.498
	T-W-0-200	0	200	0.448
	T-W-50-100	50	100	0.647
	T-W-100-50	100	50	0.651
	T-W-100-100	100	100	0.641
	T-W-100-200	100	200	0.630
	T-W-150-50	150	50	0.644
	T-W-150-100	150	100	0.637
	T-W-150-200	150	200	0.626
T-DW	*T-DW*-100-50	100	50	0.661
	T-DW-100-100	100	100	0.642
	T-DW-100-200	100	200	0.632
	T-DW-150-50	150	50	0.654
	T-DW-150-100	150	100	0.642
	T-DW-150-200	150	200	0.630

[a] Initial void ratio of specimen.

The *T-W* and *T-DW* series are triaxial drained test carried out under constant suction and the objective is to study the effect of cycle of drying and wetting (i.e. hydraulic history) on shear strength envelope of unsaturated clay. Thirteen suction-controlled tests were conducted on unsaturated specimens. Three additional tests were conducted on saturated specimens as the control tests. The unsaturated and saturated tests were carried out in the twin-cell and conventional triaxial test apparatus, respectively. The stress paths of triaxial tests are depicted in Fig. 1. *T-W* series consists of seven suction-controlled triaxial tests conducted on unsaturated specimens subjected to wetting before loading (paths O_1X). On the other hand, there are six triaxial tests in *T-DW* series conducted on unsaturated specimens subjected to a cycle of drying and wetting before loading (path O_1O_2 and O_2X). The specimens of *T-DW* series were dried to a maximum suction of 600 kPa (point O_2) before wetting to the target suctions specified in Table 1. Hence, the maximum past suction for specimens of *T-W* and *T-DW* series are 300 and 600 kPa, respectively.

The suction equalization was conducted at a confining pressure of 20 kPa and was terminated when the rate of change in volumetric water content of the specimens was smaller than 0.1%/day. For a given suction, around 7 and 14 days were required to achieve the equilibrium condition for the drying and wetting paths, respectively. After the suction equalization, the unsaturated specimens were isotropically compressed at a loading rate of 5 kPa/h (path *XB*). The ramped loading rate was similar to that of 6 kPa/h used by Cui and Delage (1996) and