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Consolidation behavior of an unsaturated silty soil during drying and wetting

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Abstract

In this work, the effect of hysteresis phenomenon on the consolidation behavior of an unsaturated silty soil was investigated through a program of experimental tests. Compacted samples were prepared by the slurry method and experimental tests were carried out in a double-walled triaxial cell. Consolidation tests were conducted by the ramping method at suctions of 0, 100, 200, 250 and 300 kPa on drying and wetting paths of the soil water characteristic curve. The results show that the paths of specific water volume and specific volume are not consistent during stabilization in either condition (drying or wetting). In addition, the yield stress for the wetting path is higher than that for drying. The trend of variations of the specific water volume during loading is similar to the consolidation curves for different suction. For both conditions of drying and wetting, the slope and intercept of the virgin line due to variations of specific volume and specific water volume are a function of suction. While their values decrease with increasing suction, these values are higher for the dry path than wetting.

Keywords: Unsaturated soil; Hysteresis; Consolidation; Specific volume; Specific water volume

1. Introduction

Unsaturated soil is a three phase material containing soil particles, water and air. The mechanical behavior of unsaturated soil is strongly influenced by both pore air pressure (u_a) and pore water pressure (u_w). The difference between u_a and u_w is defined as matric suction ($s = u_a - u_w$).

1.1. Drying and wetting

It is possible to obtain an experimental relationship between matric suction and water content (volumetric or gravimetric) or degree of saturation, which is usually represented in a plot in terms of water content or degree of saturation versus matric suction. Such relationships are known as Soil Water Characteristic Curves (SWCC). Physically, this corresponds to a reduction in the thickness of the water envelopes around clay particles, as well as the progressive emptying of the inter-particle pores. As expected, the opposite will be true whenever the matric suction decreases. In a situation of equilibrium, and for a given value of matric suction, the amount of fluid retained within the soil skeleton will be a function of the size and volume of the saturated pores, as well as the amount of adsorption films surrounding the individual clay particles. The exact nature of the relationship between matric suction and water content or degree of saturation is dependent on a number of soil parameters, such as its mineralogical

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composition, particle size distribution, and fabric. The hysteresis phenomenon results from different water content or degree of saturation in the drying and wetting curves at a given value of suction. For two points at the same suction (on wetting and drying curve) the water content or degree of saturation on a drying path is much higher than a wetting path. The hysteresis phenomenon has been attributed to a number of different causes, such as geometrical non-uniformity of pores (known as ink bottle), the effect of the contact angle between the solid and liquid phase and encapsulation of air in pores (Yong and Warkentin, 1966; Fredlund and Rahardjo, 1993 and Dineen, 1997). Wheeler and Karube (1996) stated that hysteresis has an important effect on the mechanical behavior of unsaturated soil. Researchers such as Wheeler et al. (2003), Gallipoli et al. (2003), Phm et al. (2005), Likos and Lu (2004) and Tamagnini (2004) attempted to incorporate the hysteresis effect into constitutive models. Sivakumar et al. (2006) conducted a number of tests on compacted clay soil to investigate the effect of wetting and drying on compression of the soil. They concluded that the yielding of the samples during drying is less than the one during wetting. Khallil and Zargarbashi, 2010 studied the effect of hysteresis on effective stress in unsaturated soil. They presented a simple model for contributing the effect of suction on effective stress during hysteresis. Guan et al. (2010) developed shear strength equations for unsaturated soil by involving the hysteresis phenomenon. Lu et al. (2013) indicted that there is a significant difference between the hydraulic conductivity and porosity of soil due to the hysteresis that influences the properties of soil. Likos et al. (2014) established soil water characteristic curves for different soils and presented an approach to find the parameters needed for estimating wetting path.

1.2. Consolidation

The application of load to an unsaturated soil sample will result in the generation of excess pore-air and pore-water pressures. The excess pore pressures will dissipate with time and will eventually return to their original values before loading. The dissipation process of pore pressure, called consolidation, results in a volume decrease or settlement (Fredlund and Rahardjo, 1993). In saturated soils, instantaneously applied total stress is first supported by the pore water, and the soil skeleton is progressively loaded during pore-pressure dissipation. Researchers such as Barden and Sides (1970), Fredlund and Morgenstern (1977), Fredlund and Rahardjo (1986), Escario and Juca (1989), Rahardjo and Fredlund (1995) and Rahardjo and Fredlund (1996) modified a conventional odometer and conducted consolidation tests on soil samples under different suctions. They used the axis translation technique to create the desired suction in the sample. In this test, the lateral deformation of the sample was confined and the volume change was obtained only in vertical direction. Isotropic consolidation tests were also conducted in triaxial apparatus by researchers such as Wheeler and Sivakumar (1995), Cui and Delage (1996), Estabragh et al. (2004) and Estabragh and Javadi (2015) among others. In isotropic consolidation the sample is compressed isotropically to a normally consolidated condition by increasing the mean net stress, p^{net} ($p^{net} = \frac{\sigma_1+2\sigma_3}{3} - u_a$, where σ_1 and σ_3 are axial and radial stress) with increasing the cell pressure while holding the suction constant. The increasing mean net stress (applied load) is usually carried out by step loading or ramp loading. Cui and Delage (1996) showed that the application of step loading is not suitable for unsaturated soils because this method overestimates the coefficient of compressibility and underestimates the value of the yield stress of the soil.

2. Aim of this work

A review of the literature shows that the majority of the relationships and models for unsaturated soils have been developed based on the study of the mechanical behavior of soils under their drying paths. However, there is remarkably limited information on the mechanical properties of unsaturated soils during their wetting paths and particularly in transition from drying to wetting. In nature, there are also changes in suction from high values to low values due to rainfall, etc (corresponding to the wetting path of SWCC) that may cause the failure of embankments or other structures. In this paper, the investigation focuses on the isotropic consolidation of soil at the same suctions on both the dry and wet paths of the soil water characteristic curve. In what follows, the experimental procedure and the results are presented and discussed. A comparison is made between the consolidation behaviors in the drying and wetting paths.

3. Experimental study

Most practicing geotechnical engineers employ classical (saturated) soil mechanics to analyze geotechnical engineering problems even when unsaturated conditions are involved. This is misguided because some of the fundamental features of unsaturated soil behavior, such as volumetric compression during wetting (often called "collapse compression"), cannot be properly represented without an understanding based on unsaturated soil mechanics. In reality, field applications such as the analysis of slope instabilities, landslides, the underground disposal of radioactive waste, earth dams, embankments and highways all require a proper understanding of the behavior of unsaturated soils, as do foundations and all other geotechnical activities in regions where the natural soil is unsaturated to considerable depth. Therefore, the experimental program in this paper is focused on testing of soils in unsaturated conditions.

3.1. Soil properties

The soil that was used in this experimental work was silt with low plasticity. The soil was composed of 12% clay,