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Suction stress and its application on unsaturated direct shear test under constant volume condition

B.S. Kim [a,1], S. Shibuya [a,2], S.W. Park [b,3], S. Kato [a,*]

[a] Dept. of Civil Eng., Kobe University, Rokko-daicho 1-1, Nada-gu, Kobe City, Hyogo 657-8501, Japan
[b] Dept. of Civil & Environmental Eng., Dankook University, Jukjeon-dong 126, Suji-gu, Yongin City, Gyeonggi-do, Republic of Korea

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ABSTRACT

This paper examined the application of suction stress on the results of the direct shear test under constant volume condition for unsaturated soil as a subsequent study carried previously out under a constant pressure condition. In particular, the direct shear apparatus used was a modified type for unsaturated soil, and the opening between the upper and the lower shear boxes was applied with Teflon sheets. The suction stresses of each test were derived by means of the Suction stress-SWRC Method (SSM). As a result, it was found that the stress paths for unsaturated soil agreed well with the maximum volumetric compression point (M.C.P.) line, which was obtained under saturation and constant pressure conditions, through applying the suction stress in the (σ_{net},τ) plane. These results therefore showed that the suction stress derived from the application of the SSM can be considered to explain the mechanical behavior in saturated and unsaturated soils regardless of the two test conditions in the direct shear test.

1. Introduction

It is recognized that the direct shear test (DST) has several inherent defects such as the principal stress rotation due to the moment, stress non-uniformity (the stress concentration on the shear plane), and the failure plane definition during shearing. Despite these problems, the DST has still been used as one of the testing methods to evaluate the shear strength of soils under two different conditions: i) the constant pressure condition, and ii) the constant volume condition (ASTM, 2011).

In the former case, the vertical stress for the specimen is kept constant during the shear process. The excessive pore water pressure is not induced during shearing because it diminishes quickly in the case where the height of the specimen is low or the shearing rate is slow. Thus, this testing method can be classified as the consolidated drained (i.e. CD) condition compared with the triaxial test. Many studies for saturated soil under a constant pressure condition have been carried out in order to examine the mechanical behavior of soils using the direct shear box apparatus (e.g., Skempton and Bishop, 1950; Jewell and Wroth, 1987; Jewell, 1989; Shibuya et al., 1997; Hight and Leroueil, 2003; Guo, 2008). On the other hand, owing to its advantages, the laboratory testing for unsaturated soil in particular has been carried out applying the axis translation technique and controlling the pore air and pore water pressure independently with the direct shear apparatus. The advantages include: the shorter drainage distance, the testing time, and the simple testing operation compared with that of the triaxial test. Most of these studies have attempted to explain the apparent cohesion due to soil suction by applying the shear strength theory based on the triaxial test results (e.g., Donald, 1956; Satija, 1978; Escario, 1980; Escario and Saez, 1986; Gan et al., 1988; Kim et al., 2010; Likos et al., 2010).

In the latter case, the vertical displacement of the specimen is kept constant during the shear process. Because the volume of the specimen does not change during shearing, this test can be identified with that under the consolidated undrained (i.e. CU) condition, compared with the triaxial test. Although several studies using the direct shear apparatus under constant volume condition for saturated soil have been reported (e.g., Bjerrum and Landva, 1966; Dyvik et al., 1987; Garga and Sedano, 2002), very few studies have been reported for unsaturated soil. Thus, the relationship of the mechanical behavior between saturated and unsaturated soils under the constant volume condition in the DST is still controversial.

In this paper, a series of direct shear tests under a constant volume condition were therefore carried out in order to examine the relationship of the shear behaviors between saturated and unsaturated soils. As an interpretation method of test results, the suctions stress, as a subsequent study against the constant pressure condition of Kim et al. (2010), was also applied to the test results for unsaturated soil. Additional tests under a constant pressure condition were also conducted in order to examine the effect of the shearing rate on the application of the SSM (Suction stress-soil water retention curve Method) proposed by Kim et al. (2010). Through applying the suction stress to the test

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* Corresponding author. Tel./fax: +81 78 803 6030.
E-mail addresses: bskim@person.kobe-u.ac.jp (B.S. Kim), sshibuya@kobe-u.ac.jp (S. Shibuya), spark@dankook.ac.kr (S.W. Park), skato@kobe-u.ac.jp (S. Kato).
[1] Tel./fax: +81 78 803 6030.
[2] Tel./fax: +81 78 803 6023.
[3] Tel.: +82 31 8005 3472; fax: +82 31 8005 3496.

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results obtained under the two conditions, the relationship of the mechanical behavior between saturated and unsaturated soils under the two conditions was discussed respectively.

2. Suction stress and suction stress-SWRC Method (SSM)

2.1. Definition of suction stress

Many studies have been carried out in order to examine the shear strength and deformation behaviors for unsaturated soil based on the extended Mohr–Coulomb criterion for saturated soil (e.g., Bishop, 1959; Coleman, 1962; Bishop and Blight, 1963; Fredlund and Morgenstern, 1977; Fredlund et al., 1978; Alonso et al., 1990; Kohgo et al., 1993; Gens, 1996; Karube et al., 1996; Vanapalli et al., 1996; Khalili and Khabbaz, 1998; Gens et al., 2006). Several studies have attempted to explain effectively the increment of the shear strength, that is, the apparent cohesion (Δc) due to the matric suction in unsaturated soil. The notion of the suction stress can be classified as one method of these attempts.

$$\tau = c' + (\sigma - u_a)\tan\varphi' + \Delta c \tag{1}$$

where τ is the shear strength on the failure plane, c' is the effective cohesion, and φ' is the effective angle of internal friction.

Karube and Kato (1994) proposed the concept of ‘Meniscus water’ and ‘Bulk water’ from a microscopic point of view. The bulk water is the pore water which occupies the pore volume between soil particles, and meniscus water exists at the contact point between soil particles. The proportion of bulk water in the soil water increases with the degree of saturation. On the contrary, the proportion of meniscus water increases with the decrease of the degree of saturation. Thus, the proportions of bulk water and meniscus water would be affected by matric suction. The meniscus water increases the intergranular adhesive force acting perpendicularly on the contact plane between soil particles, and it causes an increase in the stiffness of the soil skeleton. On the other hand, bulk water not only increases the stiffness of the soil skeleton, but also decreases the volume of soil mass due to an induced slippage at the contact points between soil particles.

Karube et al. (1996) and Karube and Kawai (2001) presumed the proportions of the bulk water and meniscus water by the calculation using the driest curve in the relationship between matric suction and degree of saturation as shown in Fig. 1. That is, the driest curve is a wetting path of the assumptive pore water distribution whereby only the meniscus water exists at contact points until the entire void of soils fills with the pore water, while the bulk water does not exist. From such an assumption, they proposed the stress components caused by the influence of meniscus water and bulk water as the meniscus stress (p_m) and the bulk stress (p_b), respectively. It could be assumed that the meniscus stress and the bulk stress are related to the pore size distribution rather than to the degree of saturation. The suction stress (p_s) was defined as the summation of the two stress components. Furthermore, the suction stress (p_s) in terms of the relation of matric suction ($u_a - u_w$) can be defined by the relationship between the residual degree of saturation (S_{r0}) and the degree of saturation (S_r) through the relation of the driest curve as follows:

$$p_s = p_m + p_b = \frac{S_r - S_{r0}}{100 - S_{r0}} \times (u_a - u_w) \tag{2}$$

where u_a and u_w are the pore air pressure and the pore water pressure, respectively.

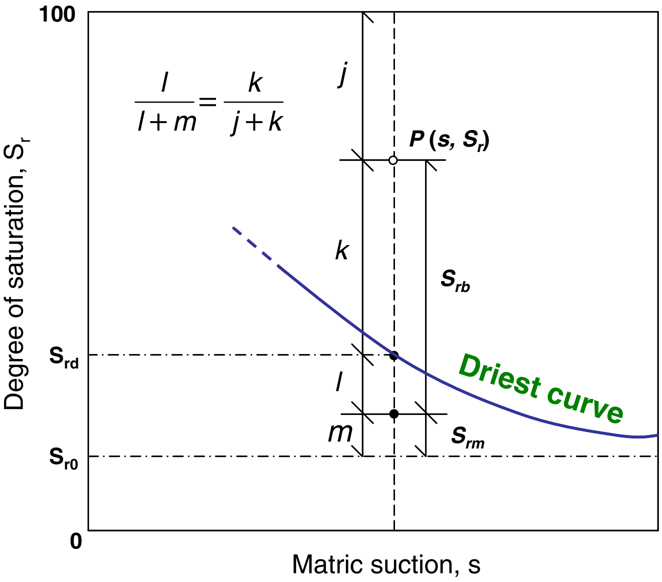

Fig. 1. Notion of the direst curve.
After Karube et al. (1996).

As another approach of the suction stress, Lu and Likos (2006) introduced an expression for the intergranular stress (σ_c) in unsaturated soil considering the microscopic interparticle force and stress analyses, and reported that the suction stress can be conceptualized as the resultant of interparticle physicochemical stresses attributable to cementation, van der Waals attraction, double-layer repulsion, capillary stress arising from surface tension, and negative pore–water pressure. Because each of the interparticle stress components comprising suction stress is a function of water content, degree of saturation or matric suction, they introduced the suction stress as follows:

$$\sigma_c = \sigma_t - u_a + \sigma'_s + \sigma_{C0} \tag{3}$$

$$\sigma'_s = \frac{\theta - \theta_r}{\theta_s - \theta_r} \times (u_a - u_w) \tag{4}$$

where $\sigma_t - u_a$ is the net skeletal stress, σ'_s is the suction stress, σ_{C0} is the physicochemical stress at the saturated state, θ is the volumetric water content, θ_s is the volumetric water content at the saturate state, and θ_r is the volumetric water content at residual state.

2.2. Suction stress-SWRC Method (SSM)

Kim et al. (2010) proposed the Suction stress-SWRC Method (SSM) in order to examine the relationship of the shear strength and deformation between saturated and unsaturated soils under a constant pressure condition in the DST. Here, the SWRC is an abbreviation of the soil–water retention curve. The SSM is a methodology used to determine the values of the matric suction and suction stress in any stress state on the failure plane based on the volumetric water content. In the DST, the water content is measured through the drained water volume from the specimen, and the matric suction value can be determined by means of the volumetric water content for the SWRC. The suction stress is then calculated with the obtained matric suction value and the measured degree of saturation using the following equation.

$$p_s = \frac{S_r - S_{r0}}{1 - S_{r0}} \cdot s* \tag{5}$$

where s^* denotes the matric suction obtained using the SSM.

Kim et al. (2010) showed test results whereby the failure stress states for unsaturated soil can be arranged on the failure line for saturated soil by applying the suction stress obtained from the SSM as a confining stress component. This result confirms that the increment