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Experimental approach to estimate strength for compacted geomaterials at low confining pressure

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Abstract. It is important to estimate the shear strength of shallow compacted soils as a construction material. A series of constant water content triaxial compression (CWCC) tests under low confining state in this study were performed on compacted geomaterials. For establishing a relationship of the shear strengths between saturated and unsaturated states on compacted geomaterials, the suction stresses were derived by two methods: the conventional suction-measured method and the Suction stress-SWRC Method (SSM). Considering the suction stress as an equivalent confining stress component in the (σ_{net}, τ) plane, it was found that the peak deviator stress states agree well with the failure line of the saturated state from the triaxial compression test when the SSM is applied to obtain the suction stress. On the other hand, the cavitation phenomenon on the measurement of suction affected the results of the conventional suction-measured method. These results mean that the SSM is distinctly favorable for obtaining the suction value in the CWCC test because the SSM is not restricted by the cavitation phenomenon. It is expected that the application of the SSM would reduce the time required, and the projected cost with the additional equipment such as a pore water measuring device in the CWCC test.

Keywords: compacted geomaterials; suction stress-SWRC Method (SSM); suction stress; soil-water retention curve; shear strength

1. Introduction

Low-rise buildings and shallow foundations like pavements are always located on soils above water table and under fully saturated conditions. If these structures become wetter or drier, this may change the shear strength of underneath compacted soils, and thus cause the shallow structure to deteriorate rapidly. These geomaterials are under so called “unsaturated conditions,” and the matric suction of soil plays an important role in determining the shear strength of unsaturated compacted geomaterials (Fredlund & Morgenstern 1977, 1978, Freudlund *et al.* 1978).

The behaviors of the unsaturated shear strength and the volumetric deformation according to the matric suction of compacted geomaterials so far have been an important matter of concern in many studies for soil mechanichs (Bishop 1959, Alonso *et al.* 1990, Kohgo *et al.* 1993, Sun *et al.* 2008, Han & Vanapalli 2016, Zhou *et al.* 2016, Sujatha *et al.* 2018, Lin *et al.* 2018). Although the triaxial compression test would be a useful testing method, this usually requires a long time to desaturate a specimen and needs a complicated testing procedure as well. On the other hand, the constant water content compression (CWCC) test under different suction conditions can be carried out just by adjusting to initial degree of saturation in compacted specimens, therefore, this would be a more effective and simpler testing method to evaluate the unsaturated shear behavior of compacted soils (Chae *et al.* 2010, Gao *et al.* 2019). The CWCC test involves the modified triaxial compression test, which is performed using a triaxial cell type apparatus under low confining pressure condition according to the diverse initial degrees of saturation.

It has been reported that the shallow slope failure that occurs along with the original slope in less than 3.0 m in depth generally (Rahardjo *et al.* 1995, Ng and Shi 1998, Fourie *et al.* 1999, Tiranti *et al.* 2019). The confining pressure for this depth would be less than 50 kPa, and this stress range has been recognized as a very low confining pressure (Tatsuoka *et al.* 1986, Fannin *et al.* 2005). Thus, the stress states in the shallow layers of a natural slope or embankment would be under such a low confining pressure condition, and the CWCC test can be optimized in the study of the mechanical behavior for such unsaturated condition. From a practical standpoint view, it is expected that the CWCC test can also play an important role in understanding the mechanism of the shallow failure problem in natural or engineered earth structures as one of useful testing methods.

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On the other hand, most previous studies for unsaturated soil using the unconfined compression test in estimating the undrained shear strength as the total stress approach have only focused on the range of a high degree of saturation (Ridley and Burland 1993, Shogaki 1995, Mitachi and Kudo 1996, Cunningham *et al.* 2003, Li and Zhang 2015). This is mainly because of the cavitation phenomenon which interrupts the measurement over the negative pore water pressure of about -100 kPa using the ceramic disk under the atmospheric pressure (Baker and Frydman 2009). Several studies to overcome the cavitation phenomenon and measure the suction up to 1500 to 2000 kPa have been performed (Ridley and Burland 1993, Ridley 1995, Guan and Fredlund 1997, Take and Bolton 2003). Despite these experimental studies, a reliable simple method measuring the suction has not yet been fully established. A simpler and more efficient approach is needed.

This study proposes a methodology to evaluate the effect of the suction on the unsaturated mechanical behavior for a silty sand using the CWCC test under low confining pressure. A series of CWCC tests under the initial degrees of saturation from about 20% to 90 % are carried out using a silty sand. The applicability of the suction stress proposed by Karube *at al.* (1996) and Karube and Kawai (2001) is evaluated using two methods; the conventional suction measured method (Chae *at al.* 2010) and the Suction stress-SWRC Method (SSM, in short; Kim *et al.* 2010). The relationships between the peak deviator stress state from the CWCC test and the failure line in the triaxial compression test under the saturated state are examined using the suction stress derived from the two methods.

2. Theoretical background

2.1 Application of suction stress to estimate the shear strength for unsaturated soils

The shear strength for unsaturated soil is affected by the relationship between the moisture content and the matric suction. The relationship of both is known as the soil water retention curve (SWRC, in short). The distribution of soil water existing like the bulk water and the meniscus water is related to the increase of the intergranular adhesive force and the stiffness of the soil skeleton from a microscopic point of view (Karube & Kato 1994). The equation of an effective stress for unsaturated soil at first was proposed by Bishop (1959) based on the Terzaghi's classical expression for saturated soil as follows

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \tag{1}$$

where σ = the total stress; u_a = the pore air pressure; u_w = the pore water pressure; and χ = the effective stress parameter (0~1) which has a value of 1 for saturated state and a value of 0 for completely dry state.

The effective stress parameter, χ is related to the degree of saturation in unsaturated soils. It is well known that the unsaturated shear strength varies according to the degree of saturation, and is expressed based on the failure criterion of the unsaturated soils as Eq. (2). The increase of the shear strength due to the suction (u_a-u_w) is also defined as an increase of apparent cohesion (Δc) as Eq. (3). Many researchers have studied on the apparent cohesion with the parameter, χ according to the degree of saturation for evaluating the shear strength for unsaturated soils (Gens 1996, Vanapalli *et al.* 1996, Khalili and Khabbaz 1998, Xu and Sun 2002, Sheng *et al.* 2008, Oh and Vanapalli 2018).

$$\tau = c' + (\sigma - u_a)\tan\phi' + \chi(u_a - u_w)(\tan\phi') \tag{2}$$

$$\tau = c' + (\sigma - u_a)\tan\phi' + \Delta c \tag{3}$$

where τ= the shear stress; c'= the effective cohesion; ϕ'= the effective angle of internal friction

On the other hand, in order to examine the increase of the shear strength due to the suction, Karube *at al.* (1996) and Karube and Kawai (2001) proposed the suction stress based on the suction and the moisture content, that is, the effective degree of saturation. They reported that the unsaturated shear strength shows a unique relationship with the saturated shear strength by applying the suction stress as the equivalent confining pressure. This means that the unsaturated shear strength could be estimated by applying the suction stress based on the failure line for saturated soil as shown Fig. 1. Here, the suction stress is given by the following equation.

$$p_s = \frac{S_r - S_{r0}}{100 - S_{r0}} \cdot s \tag{4}$$

where S_r is the degree of saturation, and S_{r0} is the residual degree of saturation, and s is the matric suction.

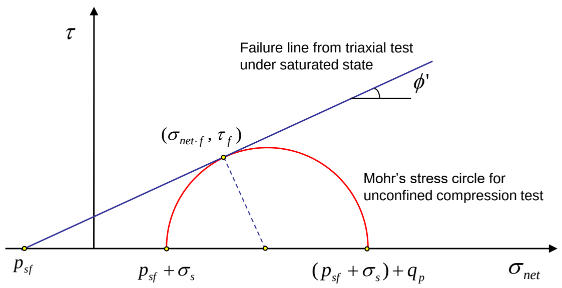

Fig. 1 The geometric relation by the application of the suction stress between the failure line from the triaxial test under the saturated state and the Mohr's stress circle of the unconfined compression test in (σ_{net}, τ) plane (Modified from Chae *et al.* 2010)

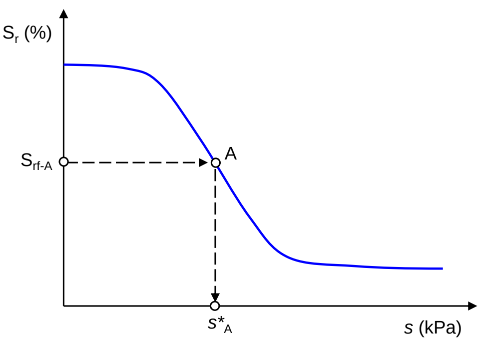

Fig. 2 Notion of the SSM to determine the suction value based on the soil-water retention curve at failure

There are several studies for the application of the suction stress to the shear strength of unsaturated soil. Chae *et al.* (2010) carried out a series of the unconfined compression tests for a compacted silty clay material, and showed that the maximum compressive strengths agree with the failure line of the saturated state in the triaxial compression test by applying the suction stress as the equivalent confining pressure. The following relation was derived by the test results.

$$q_u = \frac{4\sin\phi'}{1-\sin\phi'} \times p_s \tag{5}$$

where q_u = the unconfined compressive strength.

2.2 Application of suction stress-SWRC method (SSM)

The suction stress-SWRC method (SSM) proposed by Kim *et al.* (2010) is a method to derive the suction stress by applying the matric suction obtained on the basis of the soil-water retention curve. Fig. 2 shows the process to determine the suction value for the degree of saturation at failure based on the SWRC on the potential shear plane. When the suction value derived by the SSM is expressed as 's^*', the equation of the suction stress in Eq. (4) is represented as follows

$$p_s = \frac{S_r - S_{r0}}{100 - S_{r0}} \cdot s^* \tag{6}$$

They carried out a series of direct shear tests under a constant overburden pressure condition using a compacted weathered granite specimen for saturated and unsaturated states. They reported that the suction stresses obtained from the SSM were applied to each of the test results, and the relationship of shear strengths between saturated and unsaturated states could then be explained by applying the suction stress. In particular, they also showed that the suction stress by the SSM could be applied to the results in the unsaturated triaxial compression test obtained by Karube *at al*. (1996) and Karube and Kawai (2001).

On the other hand, Kim *et al.* (2013) also examined the application of suction stress on the results of the direct shear test under constant volume condition for unsaturated soil. It was reported that the stress paths for unsaturated soil agreed well with the maximum volumetric compression point line of saturated soil under constant pressure condition by applying the suction stress.

3. Testing program

3.1 Characteristics of soil sample and preparation of specimens

The soil sample used in this study is a natural silty sand obtained from the Kyongsang province in Korea. This sample has the specific gravity of 2.53, the passing percentage of sieve # 200 (75 μm) of 25.8%, and the plasticity index of about 5 %. The maximum dry density and the optimum water content are 14.7 kN/m^3 and 24.8%,

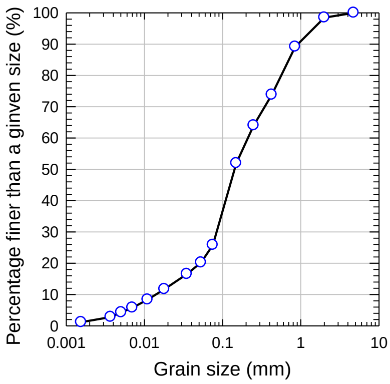

Fig. 3 Grain-size distribution curve of silty sands

Table 1 Physical properties of silty sands used

Physical properties	Value
Soil particle density, ρ_s (kN/m^3)	25.3
Passing percents of Sieve # 200 (%)	30.7
Liquid limit (%)	37.7
Plastic limit (%)	32.6
Optimum water content (%)	24.8
Maximum dry density, ρ_{max} (kN/m^3)	14.7
Unified Soil Classification System, USCS	SM
Cohesion (kN/m^2) from CU-TC	0
Angle of internal friction (°) from CU-TC	35.5

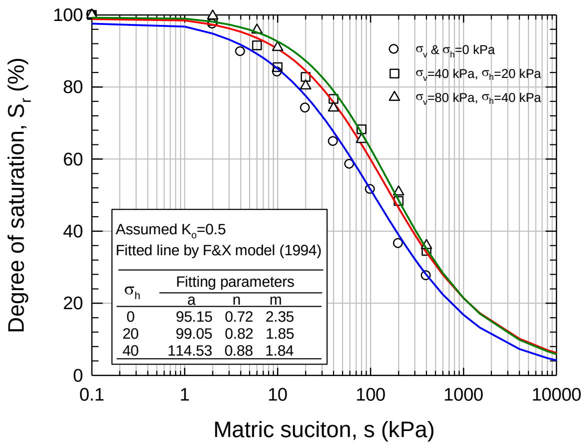

Fig. 4 Soil water characteristic curves according to each confining pressure condition for silty sands

respectively. The grain size distribution curve is shown in Fig. 3. In addition, the cohesion of 0 kPa and angle of internal friction of 35.5° were obtained from the consolidated-undrained triaxial compression test under the saturated condition. The physical properties of silty sands are summarized in Table 1.

In order to establish the relationship between soil water and matric suction, the soil-water retention test was carried out under the overburden pressures of 0, 40 and 80 kPa using oedometer type apparatus (i.e., corresponding to isotropic confining pressure, p_0 of 0, 26.7, and 53.3 kPa, when the coefficient of earth pressure at rest is assumed to 0.5). The specimen size used was 63.5 mm in diameter and

Table 2 The conditions at initial and failure for each test series

p_0 (kPa)	No.	Initial condition		
		w_i (%)	S_{ri} (%)	s_i (kPa)
0	1	4.9	17.5	93.1
	2	6.6	24.6	87.6
	3	9.3	33.2	80.8
	4	11.4	40.6	79.3
	5	13.1	47.3	77.3
	6	14.9	53.4	74.4
	7	17.2	60.8	71.0
	8	18.7	66.5	68.5
	9	20.1	71.1	58.9
	10	22.8	81.4	32.9
	11	25.0	89.2	19.1
	12	25.2	90.0	20.1
26.7	13	5.7	20.4	95.2
	14	8.8	30.8	103.2
	15	11.5	40.8	96.0
	16	14.2	50.2	103.9
	17	17.5	61.2	91.8
	18	20.0	71.2	72.3
	19	22.6	81.2	42.2
53.3	20	5.3	20.5	87.4
	21	8.8	30.4	92.4
	22	10.8	39.9	91.3
	23	13.9	49.6	95.5
	24	15.4	60.9	93.5
	25	20.3	73.2	76.1
	26	22.8	79.5	49.8

*p_0: initial confining pressure, w_i: initial water content, Sr_i: initial degree of saturation, s_i & s_f: initial measured suction, and suction measured at failure, $p_{sf\text{-con}}$ & $p_{sf\text{-}ssm}$: suction stresses by a conventional suction-measured method and the SSM at failure

32.0 mm in height, and the specimen was prepared by the static compaction method under the maximum dry density of 14.7 kN/m^3. The results of SWRC test for the drying path using the suction plate method are shown in Fig. 4. In this figure, the fitting curves obtained by Eq. (7) (Fredlund and Xing 1994) are shown as the solid lines.

$$\theta = C(\psi)\left\{\frac{\theta_s}{\ln[e+(\psi/a)^n]}\right\}^m \tag{7}$$

where ψ = the total soil suction; 'e' = the natural number (2.71828); and $C(\psi)$ = the correction function that forces the soil-water retention curve through a suction of 1000000 kPa and zero water content, and is given as follows

$$C(\psi) = \left[1 - \frac{\ln(1+\psi/\psi_r)}{\ln(1+10^6/\psi_r)}\right] \tag{8}$$

where ψ_r = the suction value corresponding to residual water content; 'a' = a soil parameter that = related to the air entry value of the soil (kPa); 'n' = a soil parameter that controls the slope at the inflection point in the soil-water retention curve; 'm' = a soil parameter that is related to the residual water content of the soil.

Fitting parameters for each SWRC are also shown in Fig. 4. From the results of the SWRC test, the air-entry values according to each condition are within the range of around 7 to 15 kPa.

On the other hand, the specimens in the CWCC tests are composed in three layers by the static compaction under various initial water contents, and the dry densities of the maximum dry density of 14.7 kN/m^3 were applied to each specimen. The size of specimen is 50 mm in diameter and 100 mm in height. Prepared specimens were sealed up and kept at a constant temperature in the humidity chamber for one day. The condition of specimens manufactured by the static compaction method is summarized in Table 2.

3.2 Constant water content compression tests under unsaturated state

A series of the constant water content compression (CWCC) tests under an unsaturated state were carried out using the modified constant water content compression apparatus as shown Fig. 5. A ceramic disk with an air entry value of 500 kPa was installed in the base pedestal to measure the pore water pressure from the specimen, while a porous metal plate was set in the loading cap. A pore water pressure transducer was connected to the water line of the pedestal, and the operation for this connection was conducted under a water tank filled with the de-aired water in order to exclude any air and to measure the matric suction correctly.

The specimen then was installed, and sealed with a membrane and O-rings. The pore air pressure of the specimen was released into the atmosphere by means of a drain line of the loading cap during setting. The inside cell was fully filled with the de-aired water to measure the volume change under the undrained unsaturated state. The volume changes of the specimen are measured through the use of the differential pressure transducer with taking into account of the variation of the water level of the double burette and the amount of cell water drainage for the piston penetration into the cell during shearing. In the case of unconfined pressure condition, the double burette was released into the atmosphere In the case of the confining pressure condition, the same air pressure for each confining pressure is applied to the double burette to measure the volume change of specimen. The suction value was

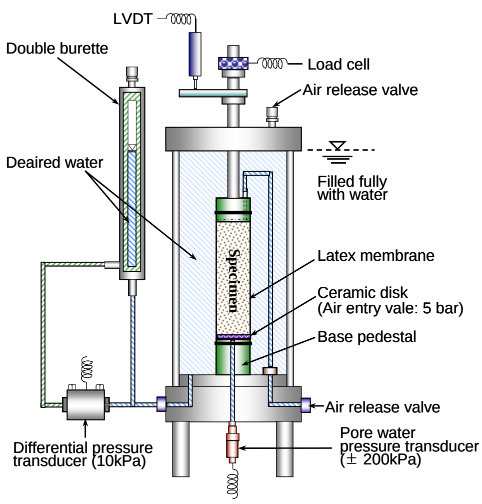

Fig. 5 Schematic diagram of the constant water content compression (CWCC) apparatus

calculated by the difference between the atmospheric pressure and the measured pore water pressure.

Initial negative pore water pressure ($-u_w$), that is, the matric suction (u_a-u_w), was measured under a constant temperature of 25°C as soon as the specimens were placed on the base pedestal. After measuring the initial suction, the sample was loaded isotropically under each confining condition (i.e., isotropic confining pressure, p_0 of 0, 26.7, and 53.3 kPa). Subsequently, the shearing rate of 0.1%/min in was applied. According to the study of Nishimura (2006), it was reported that the nearly constant shear strengths in the unconfined compression test of a compacted silty clay were obtained under the shear rates from 0.05% to 1% per minute. Thus, it was considered that the shearing rate of 0.1%/min would not affect the pore-water pressure distribution inside the soil specimen. The pore-water pressure, the axial strain, and the volume change were automatically measured during shearing. The volume change of the specimen during applying confining pressure is ignored when calculating the volume of specimen during the shear process.

4. Results of the CWCC test

A series of CWCC tests under three low confining pressure conditions (p_0= 0 kPa, 26.7 kPa, and 53.3 kPa) were carried out according to the initial moisture state. Among these results, the typical stress-stain relationships in the CWCC test on the results under unconfined pressure condition are representatively shown in Fig. 6. It is found that the peak deviator stress varies due to the effect of suction according to the initial degree of saturation. As shown, when the initial degree of saturation, S_{ri} is 33.2%, the maximum shear stiffness and the peak deviator stress were observed. Here, the initial degree of saturation represents that after the compaction of specimen. The specific saturation level like the initial degree of saturation of 33.2% affects the peak sehar strength, because the effect of the binding process of the soil skeletal structure due to the static compaction in the preparation of the specimen, and the efftec of the suction stress as a confining pressure due to the soil water condition according to the degree of saturation are occurred.

Therefore, it could be understood that the peak shear strength in the experimental results under the unconfined condition was exhibited at a specific initial degree of saturation of 33.2%. For this reason, it is found that the peak shear strengths was exhibited at specific initial degrese of saturation of about 40% and 50% under the confining pressures of 20 kPa and 40 kPa, respectively as shown in Fig. 7. As the initial degree of saturation decreases, each specimen gradually shows a strain-hardening failure behavior until the initial degree of saturation of 33.2%. It is observed that the deviator stress in the residual state are almost merged into the range between 50 kPa and 80 kPa regardless of the initial degree of saturation.

On the other hand, as the initial degree of saturation reaches to the saturation state, the magnitude of a dilatancy of the specimen decreases. This indicates that the effect of suction decreases with the increment of the initial degree of

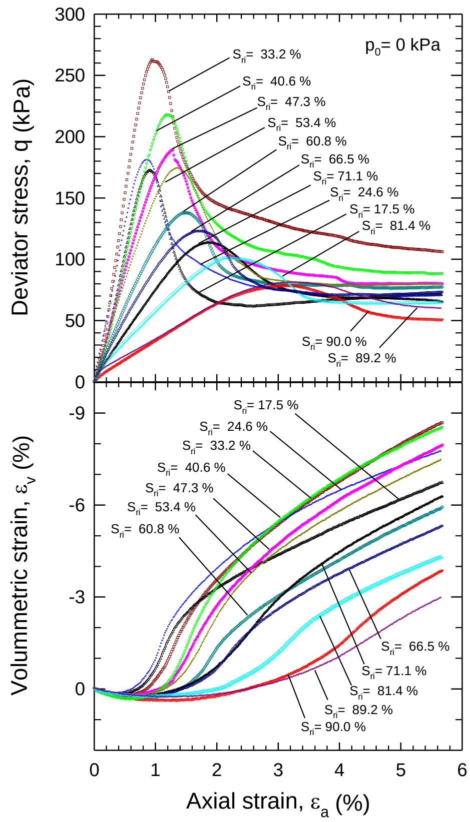

Fig. 6 Typical stress-stain relationships under unconfined condition (p_0= 0 kPa)

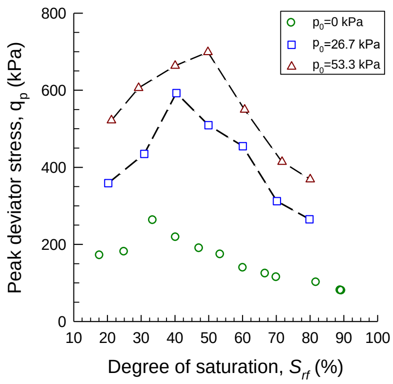

Fig. 7 Variation of the peak strength according to the degree of saturation at failure

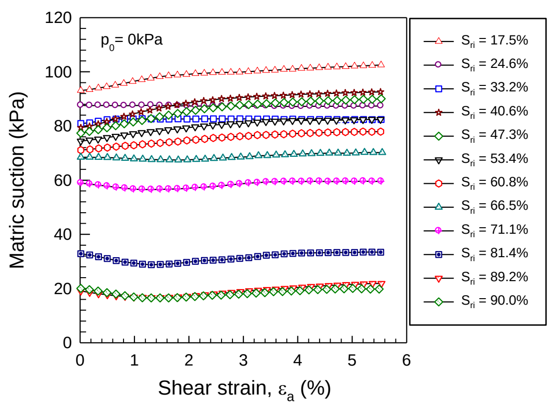

Fig. 8 The results of the matric suction measured under unconfined condition during shearing

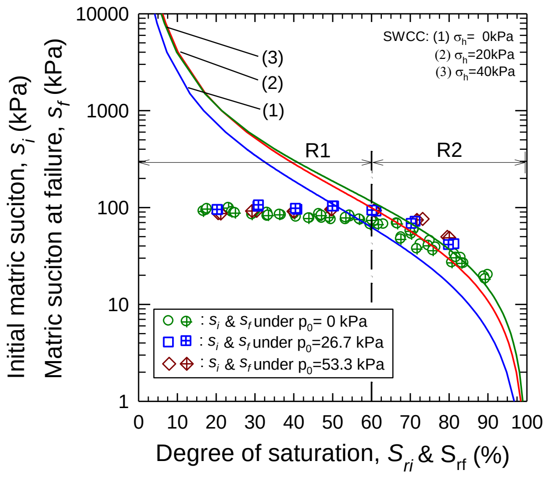

Fig. 9 Variation of suction values measured according to the degree of saturation at the initial and failure states

saturation. Even though the initial degree of saturation decreases, it is important that the peak deviator stress values and the dilative behavior do not increase continually. By the effect of the suction stress as a confining pressure, the maximum peak deviator stress increases. The suction stress is affected by both the suction value and the state of soil water (the degree of saturation etc.) as shown in Eq. (4). This relationship emerges the icreasing and decreasing tendency of the suction stress for the degree of saturation as shown later, which influence on the peak deviator stress observed. Kim *et al.* (2016) analyzed the unconfined compression test for the compacted silty soil, and reported that the specimens moving toward the critical state with expansion. The test results in Fig. 6 show the similar expansive behavior with them.

Fig. 7 shows the relationship of the peak deviator stress and the degree of saturation at failure. The peak deviator stress increases with the confining pressure. As the degree of saturation of the specimen decreases to less than about 30 to 50%, the peak deviator stress decrease because the influence of the dilation behavior becomes smaller. Fig. 8 shows the typical results of the matric suction measured under the unconfined condition according to the initial degree of saturation. It is found that as the initial degree of saturation decreases, the magnitude of initial suction increases. The variation of suction values is hardly observed during shearing.

On the other hand, the suction values at the initial and failure states according to the initial degree of saturation are shown in Fig. 9. It is observed that the suction values measured under the unconfined condition are slightly lower than those under the confining pressure conditions of 20 kPa and 40 kPa. Furthermore, these results were compared with the results of soil water characteristic curves obtained for each confining pressure condition. It is difficult to judge whether these relationships correspond to each other. This is because the measured suction values increase according to the decrease of the initial degree of saturation, and then these values merge to about 100 kPa at the lower part of the initial degree of saturation of 60 % for all conditions. These tendencies do not agree with the dynamic trends in the stress-strain relationships as previously shown, where the behaviors of the deviator stress and the dilatancy according to the initial degree of saturation changed significantly. From these tendencies, it is expected that in the case of testing conditions less than the initial degree of saturation of 60%, the cavitation phenomenon occurred naturally inside the pore water measuring system in the apparatus. The interpretation of these results will be discussed in the latter part of this paper.

5. Discussion for application of the suction stress

The shallow slope failure has been occurring mainly as a result of the decrement of suction value that is caused by the increment of disappearance of the meniscus water due to an infiltration of rainfall. The importance to evaluate the variation of the unsaturated shear strength according to the suction value has been recognized. In order to verify the relationship of the shear strengths between saturated and unsaturated soils, the concept of the suction stress proposed by Karube *et al.* (1996) was adapted in this study. The application of the suction stress was evaluated based on two methods; the conventional suction measured method (Chae *at al.* 2010) and the SSM (Suction stress-SWRC Method; Kim *et al.* (2010)). Using the suction stress estimated by the two methods, the relationship between the peak shear strength from the CWCC test and the failure line from the triaxial compression test under the saturated state was examined.

5.1 Outline of the calculation of the suction stress (p_s)

When the suction stress was calculated by Eq. (6), the input of residual degree of saturation of silty sands is needed. It is generally difficult to decide the residual degree of saturation of soil for silty and clayey soils because the high air pressure over thousands kPa is needed in the pressure plate method. Furthermore, the more measuring time, additional process and equipment also are required, and the residual state in some case is not clearly recognized. Thus, this study paid attention to the wilting point used in the field of agricultural engineering. In general, according to a study in the field of agricultural engineering, the wilting point is defined as the suction value of 1500 kPa (about 4.2 in pF value) expressing the limitation of the magnitude of the field capacity based on the available plant water capacity in the natural soil (Meyer and Gee 1999). The amount of evapotranspiration is equal to the difference between field capacity and the wilting point. Furthermore, based on the studies by Gardner (1960) and Hillel (1971), it is found that the formation of meniscus water is difficult in the condition in which the suction value is greater than the wilting point, that is, 1500 kPa. It is expected that the effect of the suction stress due to the suction for silty sands would mostly disappear around the wilting point. The suction value of 1500 kPa on silty sands could be defined as the residual degree of saturation in an engineering perspective. On the other hand, many researchers have pointed out the similarity between the wilting point and the residual state (e.g., Kirkham, 2014). Van genuchten (1980) defined the residual water content as the water content at a soil suction of 1500 kPa, which corresponds to the wilting point. Vanapalli *et al.* (1998) also treated the water content at the wilting point as the residual water content. From these standpoints, the degree of saturation at suction value of 1500 kPa in this study was defined as the residual degree of saturation.

The equation (6) related to the suction stress derived by the SSM can be represented as follows

$$p_s = \frac{S_r - S_{rW.P}}{100 - S_{rW.P}} \times s^* \tag{9}$$

where $S_{rW.P}$ = the degree of saturation at the wilting point of 1500 kPa.

The degrees of saturation ($S_{rW.P}$) such as 13.24 % (p_0= 0 kPa), 17.26% (p_0= 26.7 kPa), and 17.07% (p_0= 53.3 kPa) atthe wilting point according to each confining pressure condition could be obtained from the results of the SWRC test.

5.2 Application of the suction stress with conventional suction-measured method

Fig. 10 shows the results of the suction stress derived by the conventional measured method to the peak deviator stress state in the (σ_{net}, τ_f) plane. From the geometric relationship between the failure criteria and the Mohr's stress circle at failure in Fig. 1, the interpretation method proposed by Chae *et al.* (2010), that is, the concept of equivalent confining stress by the suction stress in the unconfined compression test, was adapted. The sum of the net vertical stress and the suction stress, ($\sigma_{net\text{-}f} + p_s$) was plotted with the term of the shear strength, τ_f in the (σ_{net}, τ) plane. The results below the A-A line agrees with the failure line for the saturated state in the triaxial compression test regardless of the confining pressure condition, whereas the test results above the A-A line do not agree with the failure line. The A-A line represents a boundary line between the ranges of R1 and R2, and the boundary degree of saturation of A-A line is 60% in Fig. 9. These discrepancies among the shear strength, the suction stress and the degree of saturation can be explained as follows.

This trend is generally caused by the influence of the cavitation phenomenon of water inside the pore water measuring system under the ceramic disk. The cavitation phenomenon prevents the development of high tension in the soil water (Bishop 1959). According to the study by Guan and Fredlund (1997) and Ridley and Burland (1999), the failure to remove the air completely from the measuring device causes the cavitation phenomenon, and then the reduction consequently of the maximum measured water tension in the chamber to approximately 100 kPa. In practice, because the cavitation phenomenon occurred while measuring the matric suction, the pore water pressure greater than about 100 kPa in the common measurement system, such as with the use of the capacity tensiometer, could not be measured (Sweeny 1982). Thus, measuring the high matric suction in the CWCC test has a limitation unless some method is used to prevent the cavitation phenomenon such as the application of a back pressure.

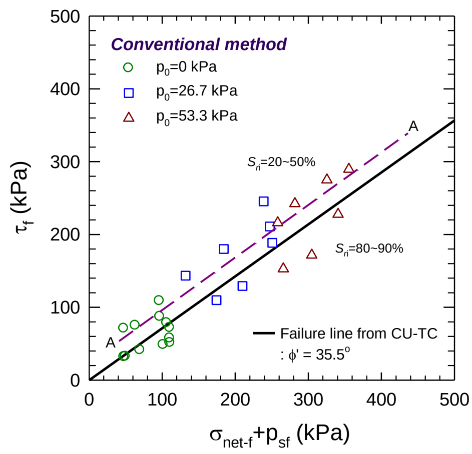

Fig. 10 Application of the suction stress derived by the conventional suction-measured method to the peak shear strengths in (σ_{net}, τ_f) plane

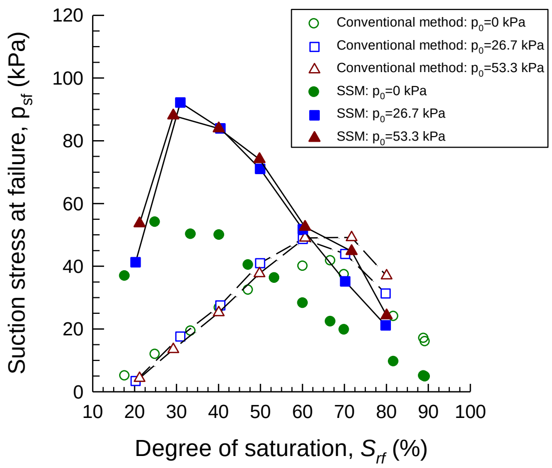

Fig. 11 Variation of the suction stress according to the degree of saturation at failure

The conventional suction-measured method which uses the measured suction to derive the suction stress in this study can be applied within the range of R2 in Fig. 9. It is possible, in only the range of R2, to evaluate the relationship of the peak shear strength between saturated and unsaturated soils by applying the suction stress as an equivalent confining stress in the CWCC test.

5.3 Application of the suction stress derived by the SSM

The important point in the SSM is to determine the suction value on the potential shear plane. As explained above, the suction values corresponding to the degree of saturation during shearing can be obtained based on the SWRC. That is, because the criterion is the degree of saturation, the suction values on the potential shear plane can correspond to the volume change during shearing. Thus, the suction stress obtained from the SSM was also applied to each peak deviator stress state, and the applicability of the SSM between saturated and unsaturated states was examined in the (σ_{net}, τ) plane.

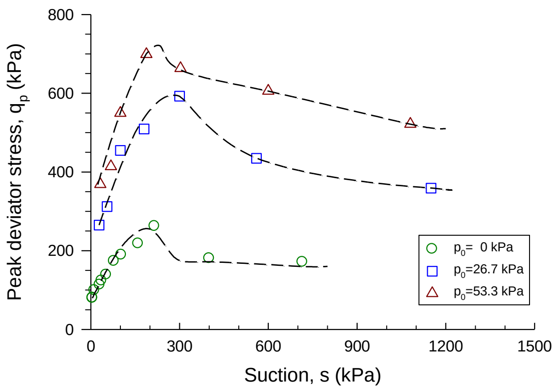

Fig. 12 Relationships between the peak deviator stress and the suction derived by the SSM at failure

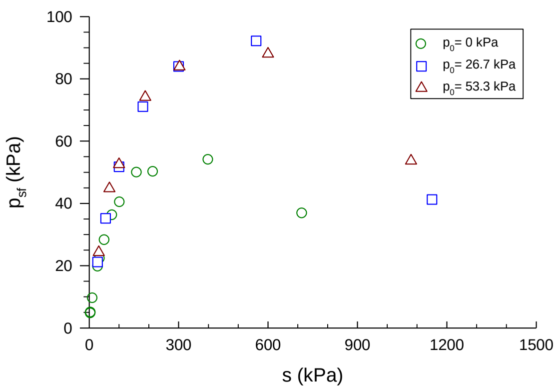

Fig. 13 Relationships between the suction stress and the suction derived by the SSM at failure

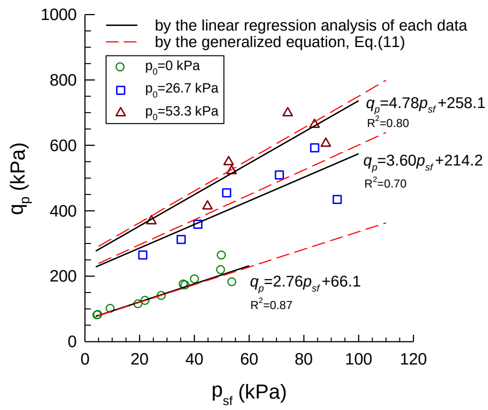

Fig. 14 Relationships between the peak deviator stress and the suction stress derived by the SSM at failure, and the estimated results by the generalized equation

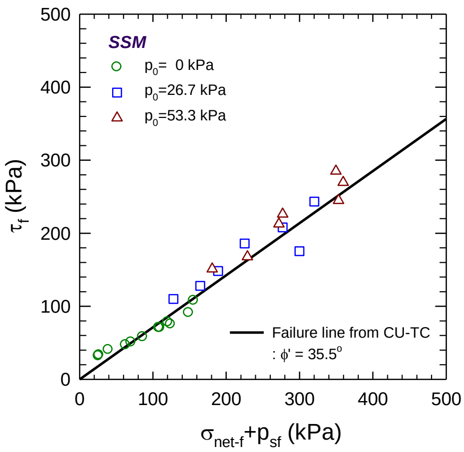

Fig. 15 Application results of the suction stress derived by the SSM to the peak shear strengths in ($\sigma_{net\text{-}f}$+p_s, τ_f) plane

The suction stresses derived by the SSM with the degree of saturation at failure were shown in Fig. 11 with the suction stress derived by conventional suction-measured method. In the range of 60 to 80% in degree of saturation, both methods show a similar tendency. However, the suction stress by the SSM shows peak values around 20 to 30 % of degree of saturation in the lower range than 60% of degree of saturation. On the other hand, in the results of conventional suction-measured method, the suction stress decreases linearly likewise. The cavitation phenomenon occurring in range R1 in Fig. 8 affects this reduction. It should be noted that the similarity in higher range of degree than 60% supports that the SSM has the same efficiency with the conventional suction-measured method to obtain the suction stress value.

Fig. 12 shows the relationships between the peak deviator stress and the suction derived by the SSM at failure. As shown, when the suction values are between 200 kPa and 300 kPa, the peak deviator stresses according to each confining pressure condition manifest, and these values then decrease and converge on certain magnitudes with the increment of the suction. This shows a typical behavior in the variation of the shear strengths according to suction, and compared to the results of Donald (1957) modified by Vanapalli *et al.* (2009), it is found that both results show a similar tendency. Furthermore, unlike the results obtained by applying the conventional suction-measured method, this result indicates that the SSM method can trace the suction values within the range of R1 lower than the degree of saturation of 60% (cf. Fig. 9). In addition to this result, the relationships between the suction stress and the suction derived by the SSM at failure are shown in Fig. 13. The magnitude of the suction stress also varies similarly to the previous trend between the suction and the peak deviator stress with the increment of the suction. Because the degree of saturation ($S_{rW.P}$) at the wilting point of 1500 kPa in this study was defined as the term of the residual degree of saturation, the magnitude of the suction stress is theoretically zero at the suction of 1500 kPa.

Fig. 14 shows the relationships between the peak deviator stress and the suction stress derived by the SSM at failure. It can be observed that there is a definite patternbetween the peak deviator stress and the suction stress according to the confining pressure condition. The peak deviator stress can be estimated using the value of the suction stress from the following relation equations through the linear regression analysis for each data

$$q_p = 2.76 p_{sf} + 66.1 \quad (\text{under } p_0 = 0 \text{ kPa}) \tag{10a}$$

$$q_p = 3.60 p_{sf} + 214.2 \quad (\text{under } p_0 = 27.7 \text{ kPa}) \tag{10b}$$

$$q_p = 4.78 p_{sf} + 258.0 \quad (\text{under } p_0 = 53.3 \text{ kPa}) \tag{10c}$$

where q_p = the peak deviator stress; p_{sf} = the suction stress at failure.

These relation equations can be expressed as a generalized equation according to the confining pressure condition as follows. Provided that this equation is modified through additional data under other confining pressure conditions, the peak deviator stress according to the suction stress and the confining pressure condition could be estimated more exactly.

$$q_p = (0.04 p_0 + 2.7) \times p_{sf} + (-0.07 p_0^2 + 7.5 p_0 + 66.1) \tag{11}$$

On the other hand, the application results of the suction stress derived by the SSM in (σ_{net}, τ) plane as well as the previous conventional suction-measured method are shown in Fig. 15. From the trend of the SSM previously explained, it is found that the stress states at failure shown as stress point, ($\sigma_{net\text{-}f}$, τ_f) in Fig. 1 agree well with the failure line in the triaxial compression test regardless of the confining pressure condition in the ($\sigma_{net\text{-}f}+p_s$, τ_f) plane. This result implies that the generalized equation of Eq. (11) could be applicable to estimate the shear strength for the silty sand. In addition, compared to the results of the conventional suction-measured method, this indicates that the applicability of the SSM for the silty sand is more suitable in the CWCC test because the SSM is not restricted by the cavitation phenomenon. Therefore, it is expected that the application of the SSM would reduce the time required, and the projected cost with the pore water measuring device in the CWCC test.

6. Conclusions

The mechanical behaviors of the unsaturated shear strength and the volume deformation according to the initial degree of saturation using reconstituted and compacted specimens of silty sands used as a construction material in this study were examined with the results obtained by the CWCC test under the low confining pressure conditions. The specimens of initial degrees of saturation from about 20% to 90% were prepared, and the suction value was measured by the pore water pressure transducer installed below the ceramic disk. The obtained results then were compared and discussed by applying the suction stress (p_s) derived by two methods; the conventional suction-measured method and the SSM. The following conclusions could be drawn.

(1) As the degree of saturation at failure, S_{rf}, decreases, the suction decreases and a dilatancy of the specimen was increased. In the range of the initial degree of saturation of around 30 to 50%, the peak deviator stresses were observed under each confining pressure condition.

(2) In the case of the conventional suction-measured method, the suction stress increased with the decrease of the degree of saturation from the saturation condition and then started to decrease due to the cavitation phenomenon when the degree of saturation was within the range of R1 in Fig. 9 for all the test conditions. This tendency did not agree with the dynamic trends in the stress-strain relationships of the shear strength and the dilatancy according to the degree of saturation. Thus, it was limited that the conventional suction-measured method in only the range of R2 could be adapted to evaluate the relationship of the peak shear strength between saturated and unsaturated soils by applying the suction stress (p_s) in the CWCC test.

(3) In the case of the SSM, when the suction values were between 200 kPa and 300 kPa, the peak deviator stresses according to each confining pressure condition were manifested and these values then decreased and converged on certain magnitudes with the increment of the suction. This result was identical to the past typical behaviors, and implies that the SSM method can also trace the suction values within the ranges of R1 and R2. Furthermore, the variation of the suction stress similarly to the previous trend could be observed between the suction and the peak deviator stress with the increment of the suction. In addition, it was found that the peak deviator stress according to the confining pressure conditions can be estimated using the generalized equation proposed from the relationships between the peak deviator stress and the suction stress in this study.

(4) When the suction stress based on the SSM was applied to the peak deviator stresses in the (σ_{net}, τ) plane, it was found that the peak deviator stresses agree well with the failure line in the triaxial compression test regardless of the confining pressure condition in the ($\sigma_{net}+p_s$, τ) plane. Compared to the results of the conventional suction-measured method, this indicated that the applicability of the SSM for the silty sand in the CWCC test is more suitable because the SSM is not restricted by the cavitation phenomenon. Therefore, it could be said that the application of the SSM would reduce the testing time, and the projected cost with the additional equipment in the CWCC test.

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