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Effect of stress state on the unsaturated shear strength of a weathered granite

In-Mo Lee, Sang-Gyu Sung, and Gye-Chun Cho

Abstract: The effect of stress state on the unsaturated shear strength of a Korean residual soil was studied using modified triaxial tests. Experimental results show that the soil-water characteristic curve and shear strength of this soil are significantly affected by the change of net normal stresses. This effect should be taken into consideration in the model to precisely describe the shear strength envelope of unsaturated soils. Thus, a new model for estimation of unsaturated shear strength is proposed using the soil-water characteristic curve and the saturated shear strength parameters.

Key words: prediction model, soil-water characteristic curve, matric suction, triaxial test, unsaturated shear strength.

Résumé : On a étudié au moyen d'essais triaxiaux modifiés l'effet de l'état des contraintes sur la résistance au cisaillement d'un sol résiduel Coréen non saturé. Les résultats expérimentaux montrent que la courbe caractéristique sol-eau et la résistance au cisaillement de ce sol sont remarquablement affectées par le changement des contraintes normales nettes. Cet effet devrait être pris en considération dans le modèle pour décrire précisément l'enveloppe de résistance au cisaillement des sols non saturés. Ainsi, on propose un nouveau modèle pour l'estimation de la résistance au cisaillement non saturée au moyen de la courbe caractéristique sol-eau et des paramètres de la résistance au cisaillement saturée.

Mots clés : modèle de prédiction, courbe caractéristique sol-eau, succion matricielle, essai triaxial, résistance au cisaillement non saturé.

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Introduction

Most subsurface soils are typically in an unsaturated state. In unsaturated soils, suction pressure in the pore water contributes to an increase in the shear strength of the soils. For this reason, several investigators were interested in understanding the principles of unsaturated soil mechanics since the pioneering work in the 1950s and 1960s (e.g., Aitchison and Donald 1956; Donald 1956; Aitchison 1960; Bishop 1959, 1961; Bishop and Blight 1963).

It seems impractical to estimate the behavior of unsaturated soils directly from numerous and tedious laboratory tests, the characteristics of which are highly variable under several conditions such as the state of stress, inherent fabric, and the saturation–desaturation process. Therefore, there have been numerous intensive studies to effectively obtain the unsaturated shear strength using more simplified methods (e.g., Fredlund and Rahardjo 1993; Vanapalli et al. 1996; Khalili and Khabbaz 1998; Rassam and Williams 1999). Nonetheless, the effect of stress state on the unsaturated shear strength has been poorly understood.

This study centres on understanding the effect of net normal stresses on the behavior of unsaturated soils. The general features of unsaturated soils are discussed first, and then the soil-water characteristic curve (SWCC) tests and modified triaxial tests are carried out by varying net normal stresses. Lastly, a new model for estimation of the unsaturated shear strength is proposed considering the effect of net normal stress.

Soil-water characteristic curve

The relationship between matric suction and the degree of saturation (or water content) is very well defined by the SWCC (or soil-water retention curve). This curve captures mainly the pore-size distribution of a soil, which is relevant to a continuous water phase. Thus, the SWCC has been most frequently used to investigate the behavior of unsaturated soils, including strength and permeability.

The SWCC can be empirically expressed. Among others, Fredlund and Xing (1994) suggest an equation based on the pore-size distribution curve of the soil matrix as follows:

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$$[1] \qquad \theta = C(\psi)\frac{\theta_s}{\left\{\ln\left[e + \left(\frac{\psi}{a}\right)^n\right]\right\}^m}$$

where θ is the volumetric water content; θ_s is the volumetric water content at saturation; a, n, and m are fitting parameters; ψ is the matric suction; and $C(\psi)$ is a correction factor that can be determined by the following equation:

$$[2] \qquad C(\psi) = 1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{1\,000\,000}{\psi_r}\right)} \qquad 0 \le \psi \le 10^6 \text{ kPa}$$

where ψ_r is a virtual matric suction corresponding to the residual water content. Equation [1] has often been used because of its practical applicability (Leong and Rahardjo 1997; Sillers and Fredlund 2001).

Unsaturated shear strength

There are two general approaches for evaluating the shear strength of unsaturated soils (τ_f): the effective stress state variable method (Bishop 1959, 1961), and the independent stress state variable method (Fredlund and Morgenstern 1977). The effective stress state variable method considers the increase of matric suction and the reduced area occupied by the water in the pores (which can be obtained from the equilibrium analysis). This can be expressed as follows:

$$[3] \qquad \tau_f = c' + [(\sigma_n - u_a) + \chi(u_a - u_w)]\tan\phi'$$

where c' is the apparent cohesion at saturation, σ_n is the normal stress, u_a is the air pressure, u_w is the pore-water pressure, ϕ' is the internal friction angle at saturation, and χ is the parameter to be determined experimentally. To a first approximation, the parameter χ varies with the degree of saturation, from $\chi = 1$ for saturated soils to $\chi = 0$ for dry soils (Aitchison and Donald 1956; Aitchison 1960; Blight 1967). However, χ also depends on wetting history, loading path, soil type, internal structure of the soil, and specimen size near percolation (i.e., the boundary effect). Thus, Bishop's equation has difficulties in predicting the value of χ, and it can fail to explain phenomena such as the collapse of some soils upon wetting (i.e., massive volume change takes place as the matric suction decreases; for details, see Alonso et al. 1990 and Bernier et al. 1997).

The limitations in eq. [3] can be discussed from different perspectives. On the one hand, eq. [3] involves a soil parameter χ as in a constitutive equation rather than being a description of the state of stress. On the other hand, it mixes global and local conditions. In Terzaghi's effective stress equation for saturated media, both pore pressure and total stress are boundary actions; however, the pore-water pressure in unsaturated soils causes a local action at the particle level (this is more readily seen in a discontinuous water phase, but it is the case in a continuous water phase as well; Cho and Santamarina 2001). Nonetheless, the effective stress state variable method is recently receiving attention because of its convenience (Fleureau et al. 1995; Öberg and Sallfors 1995; Bolzon et al. 1996; Khalili and Khabbaz 1998).

Today's macroscale interpretation of the engineering behavior of unsaturated soils is based on two independent state variables, namely, matric suction $(u_a - u_w)$ and net normal stress $(\sigma_n - u_a)$, to avoid such limitations (Bishop and Blight 1963; Fredlund et al. 1978). Thus, the shear strength of unsaturated soils can be expressed as follows:

$$[4] \qquad \tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$$

where ϕ' is the effective angle of internal friction, and ϕ^b is the angle indicating the rate of increase in shear resistance due to the increase of matric suction.

Vanapalli et al. (1996) proposed a more practical model that expresses the shear strength of unsaturated soils with the SWCC and the saturated strength parameters without obtaining ϕ^b values from laboratory tests. This model, as a modified form of the independent stress state variable method, presumes the matric suction as another form of effective stress and supersedes the ϕ^b of eq. [4] with the term for the degree of saturation. The shear strength in unsaturated soils can be rewritten as follows:

$$[5] \qquad \tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)(\Theta^\kappa)\tan\phi'$$

where Θ is the normalized volumetric water content ($= \theta/\theta_s$), θ is the volumetric water content at unsaturation, θ_s is the volumetric water content at saturation, and κ is a fitting parameter.

In theory, the net normal stress, $(\sigma_n - u_a)$, and matric suction, $(u_a - u_w)$, are independent of each other, but some experimental data show that the net normal stress may affect matric suction and shear strength (e.g., Escario and Saez 1986; Vanapalli et al. 1999; Rassam and Williams 1999; Ng and Pang 2000). That is, the increase in net normal stress will cause the pore size of an unsaturated soil to decrease relatively. Therefore, the soil offers more resistance, increasing the capacity of the soil system to retain water. Ultimately, the contact area of soil particles and water will be increased, and thus the shear strength of the soil matrix will also increase. This is verified in the following sections.

Experimental study

To investigate the effect of net normal stresses on the shear strength of unsaturated soils, SWCC tests and revised triaxial tests were carried out on a weathered granite. Details of the tested soils, test equipment, and experimental procedures are discussed in the next section.

Soil tested

The weathered granite used for the laboratory experimental tests is one of the most common residual soils in Korea. The grain-size distribution of the soil is shown in Fig. 1, and its properties are summarized in Table 1. The soil has the characteristics of a silty sand. The soil was initially oven-dried at 95 °C for 48 h and then sieved to remove soil particles greater than 2 mm (No. 10 sieve). The dried soil was mixed with distilled water to a water content of 10%, and the soil mixture was then passed through the No. 10 sieve to prevent conglomeration. The soil mixture was placed in a humidity-controlled desiccator and stored for at least 24 h to

Fig. 1. Grain-size distribution of the weathered granite.

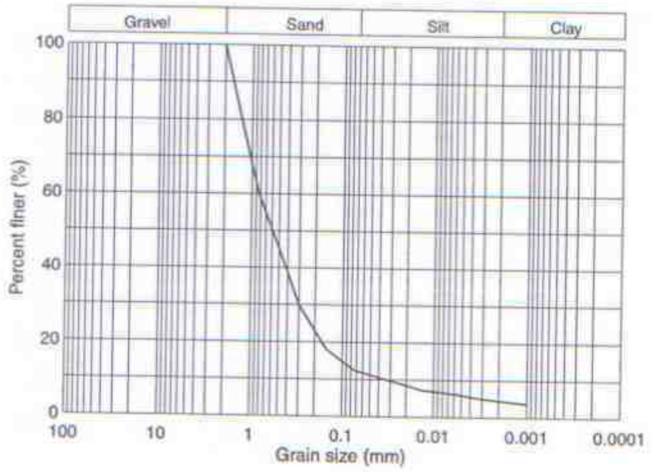


Table 1. Properties of the weathered granite soil used in the laboratory tests.

$\gamma_{d(\max)}$ (kN/m^3)	18.64
OMC (%)	10
F200 (%)	12.4
Plasticity	NP
G_s	2.65
USCS	SM

Note: G_s, specific gravity; F200, percentage passing the No. 200 sieve; NP, non-plastic; OMC, optimum moisture content; USCS, Unified Soil Classification System; $\gamma_{d(\max)}$, maximum dry unit weight.

ensure uniform water distribution. All specimens were reconstituted at a relative compaction of 90% (porosity n = 0.358). Specimen sizes with respect to test types are summarized in Table 2.

Testing equipment

A pressure-plate extractor (Soilmoisture Equipment Corp., Santa Barbara, Calif.) and tempe cell (University of Saskatchewan, Saskatoon, Sask.) were used to obtain the SWCC. The confining pressure controlled extractor (CPCE) is a modified pressure-plate extractor that can obtain the SWCC at any isotropic confining pressure for the matric suction range of 0–500 kPa (Fig. 2). The pedestal of the CPCE has the same diameter as the specimen size as described in Table 2. A disk with a high air-entry value of 550 kPa was used, and a transducer was connected to the cell pressure controller line to monitor the overall volume change of the specimen.

A typical triaxial compression test apparatus was modified for unsaturated soils based on the method suggested by Fredlund and Rahardjo (1993). It was also used to obtain the SWCC under isotropic confining pressure conditions.

Experimental procedures

Four kinds of laboratory tests were performed to obtain the SWCC and the unsaturated shear strength. The tempe cell tests and the pressure-plate tests were carried out to obtain the SWCC following the procedures of the American Society for Testing and Materials (ASTM) test methods D2325-68 and D3152, respectively. Consolidated–drained triaxial compression tests were performed to obtain the unsaturated shear strength. The strain rate of 0.0001%/s was used as suggested by Fredlund and Rahardjo (1993).

Compared with the CPCE test developed in this study, the conventional pressure-plate extractor or the tempe cell has less error in evaluating the change of water content in a specimen because the weight of the specimen is directly measured during testing. In the CPCE test, however, the overall volume change of the specimen and the water content are indirectly estimated through a transducer that measures the volume of water expelled from the specimen. Thus, there are several factors that can affect the accuracy of the test, such as leakage, diffusion, volume change of fluid with pressure and temperature, and air bubbles within the cell or the line. Extreme care was taken to avoid such problems. Leakage was controlled by sealing and using double O-rings, and air diffusion was controlled by the diffused air volume indicator (DAVI). Deaerated distilled water was used, and the temperature of the laboratory was maintained at a constant 20 °C. Fluid cleaner, which has a low surface tension, was mixed with water and contained in the internal burette of the DAVI, enhancing the upward movement of diffused air bubbles. An identical dummy specimen made of acrylic material was tested using the same procedure and conditions as those in actual tests to identify the effect of pressure and temperature on the change of water volume, irrespective of the change of specimen volume and water content. Lastly, the results from testing of dummy specimen were used for calibrating the apparatus.

Results and analysis

Effect of net confining stress on the SWCC

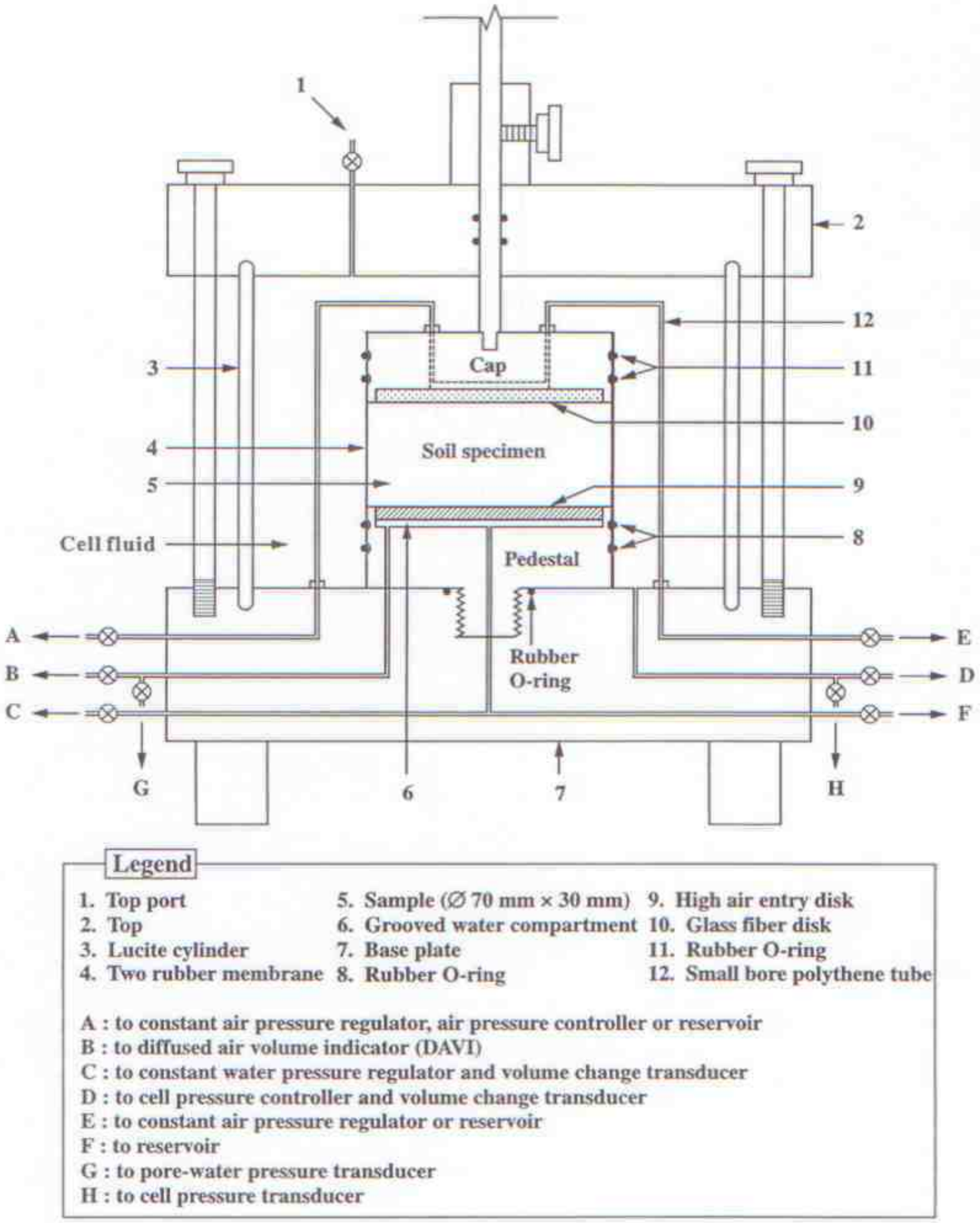
Figure 3 shows the change of the SWCC with different net normal stresses. As the net confining stress increases at a given matric suction, the water content and degree of saturation increase and the slope of the curve beyond the air-entry value becomes relatively less steep. As the macropore becomes smaller with the increase in confining stresses, the amount of water retained in the soil matrix increases. The SWCC is sensitive to the variation of confining stress in the range of low matric suctions where the macropore is dominant but not in the range of high matric suctions. The four curves in Fig. 3 are almost identical when the matric suction is greater than 1500 kPa. Sandy soils used in this study will not be greatly influenced by stress history in the range of high matric suctions because water becomes disconnected moving to the contacts of soil particles approaching the pendular stage.

In microscale, macropores are connected to one another and are easily compressed, but most micropores are trapped and the pore air or pore water cannot escape easily, so the volume cannot change easily. Thus, macropores (i.e., relatively large pores in the system) are readily affected by the change of confining stress, whereas micropores are not (Gens and Alonso 1992; Delage and Graham 1995). When a

Table 2. Specimen sizes with respect to test types.

Specimen size	Test for SWCC Pressure-plate extractor test	Tempe cell test	CPCE test	Triaxial compression test
Diameter (mm)	50.2	63.8	70	50
Height (mm)	10.0	25.5	30	100

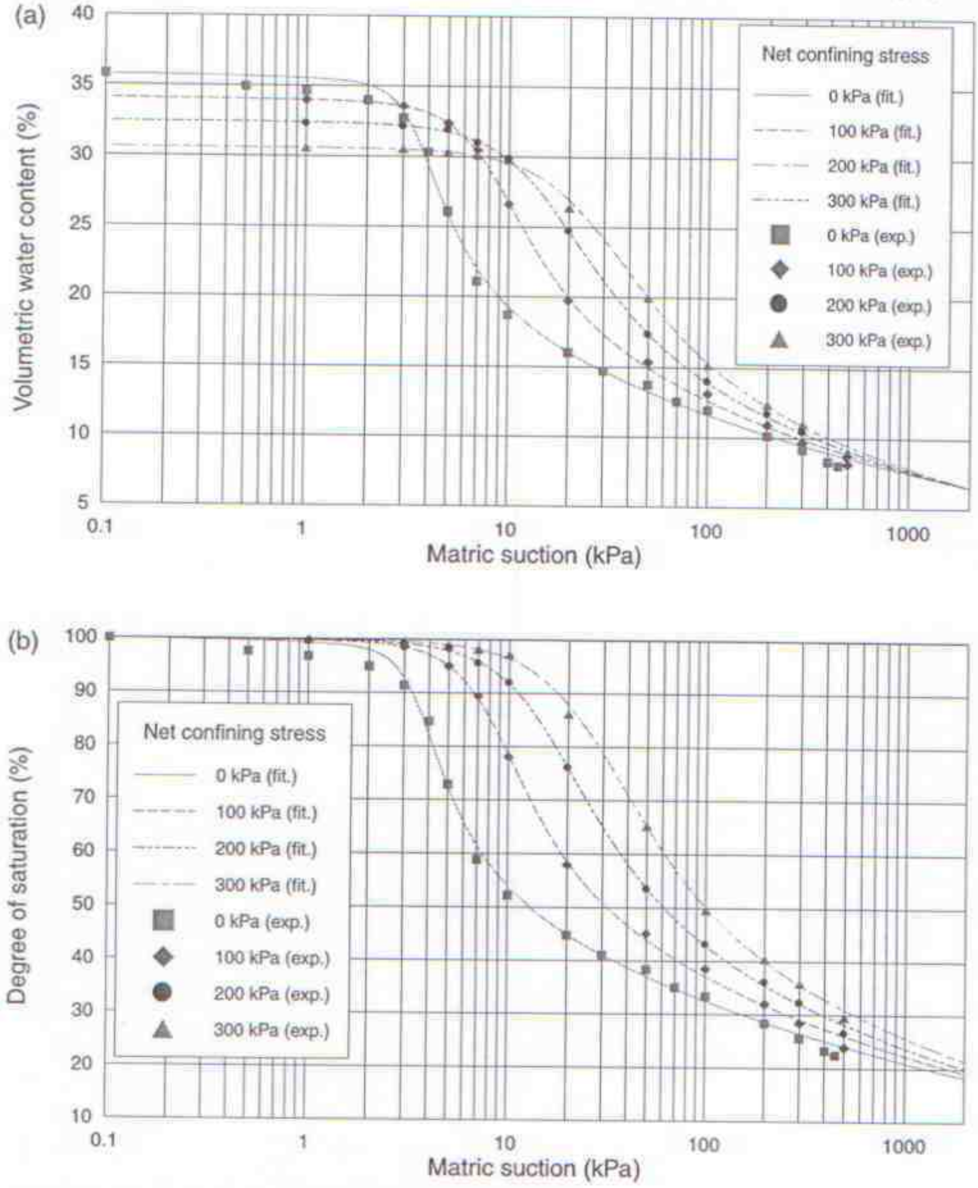
Fig. 2. Schematic drawing of the CPCE test setup.



soil is compacted at a low initial water content, as in this study, this phenomenon will be more dominant because the proportion of micropores will be relatively low, whereas the proportion of macropores will be high.

Figure 4 shows the relationship between net normal stress and air-entry value from this study and data gathered from the literature. It is apparent that the relationship is linear (also shown by Rassam and Williams 1999) and the slope is dependent on soil types and initial states. Furthermore, the curve-fitting parameters (i.e., a, n, and m) for eqs. [1] and

Fig. 3. Soil-water characteristic curves: volumetric water content (*a*) and degree of saturation (*b*) versus matric suction with variation of the net confining stress. The symbols represent experimental (exp.) values and the lines are the SWCCs (fit.).



[2] were determined using a commercial program (Soil-Vision Systems Ltd., Saskatoon, Sask.). Table 3 summarizes these parameters at different net confining stresses, and shows that there is a linear trend between them. Thus, the SWCC even at other normal stresses can be reliably estimated without performing additional sophisticated and time-consuming CPCE tests.

Effect of net confining stress on shear strength

Figure 5 shows one of the typical results of triaxial compression tests performed on unsaturated soil specimens at a matric suction of 300 kPa and with different net confining stresses. The deviator stress – deviator strain curve does not exhibit post-peak behavior, even at large strains. It shows stress-hardening behavior until the strain level is around 15%, and then it approaches a constant state.

The Mohr–Coulomb failure envelopes are shown in Fig. 6 with different matric suctions. For a given matric suction, the shear strength increases as the net confining stress increases. The friction angle increases slightly with an increase in matric suction. The tendency of ϕ' variance with respect to matric suction can be expressed in the form of an exponential function (Fig. 7). It is seen that the increment is greater in the lower matric suction range than in the higher suction range where the water content decreases. This can be explained by the fact that the effective contact area between the soil and water decreases as the water content decreases. It is clear that when the net normal stress increases, the degree of saturation (the effective wetted contact area) also increases, and thus the increment of shear strength induced by the matric suction becomes more significant.

The variation of shear strength with net normal stress at different matric suctions is shown in Fig. 8 based on data from experimental tests. The results show that the shear strength increases with an increase in matric suction. Meanwhile, the lines in Fig. 8 are predicted from eq. [5] but are

Fig. 4. Relationship between air-entry value and net normal stress (after Rassam and Williams 1999).

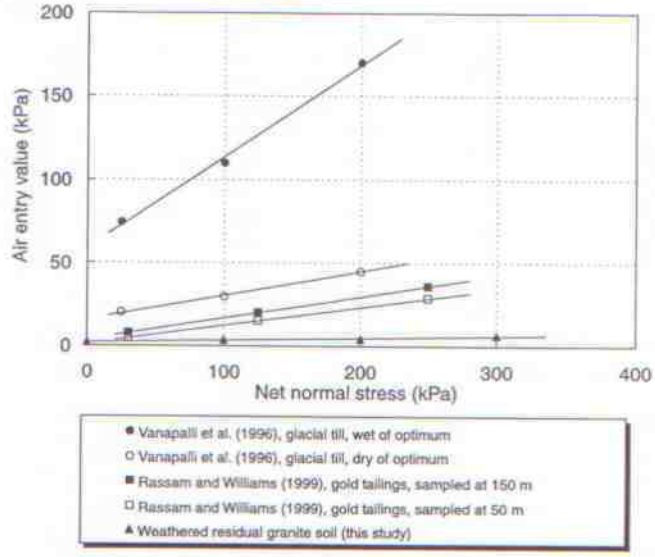


Table 3. Fitting parameters adopted for estimation of soil-water characteristic curves.

Net confining stress (kPa)	a (kPa)	n	m	ψ_r (kPa)
0	3.2935	5.5878	0.3087	12.9
100	7.1951	3.3159	0.3967	40.2
200	13.2882	2.4237	0.4797	92.7
300	22.4849	2.2241	0.5165	161.3

Fig. 5. The stress–strain curve obtained from triaxial compression tests at a constant matric suction of 300 kPa. σ_3, minor principal stress.

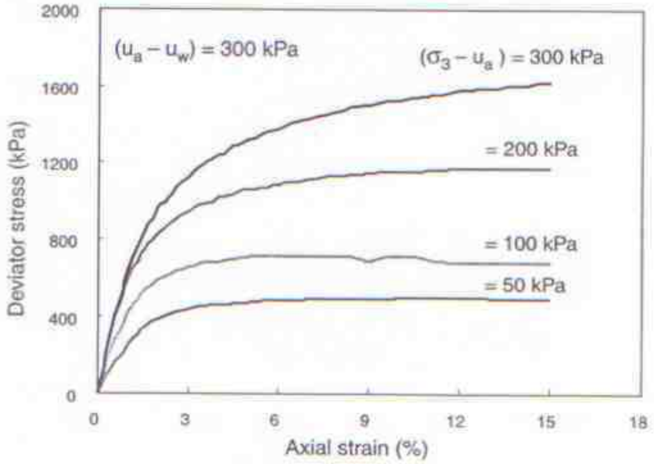


Fig. 6. Failure envelopes at different matric suctions.

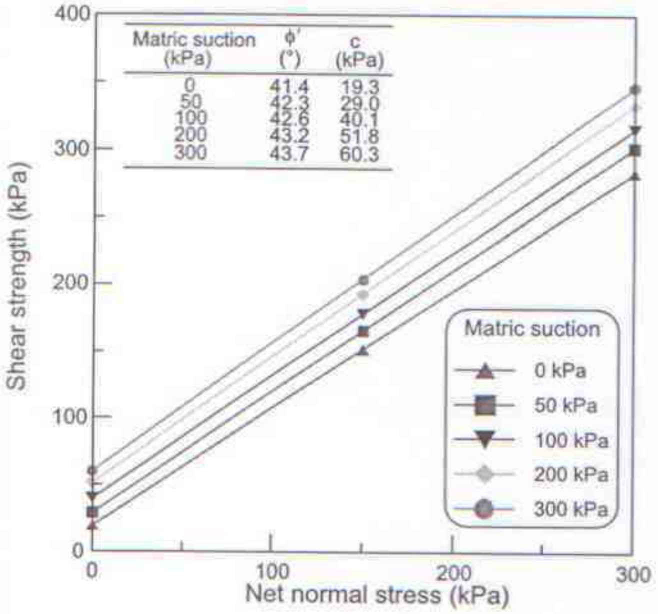
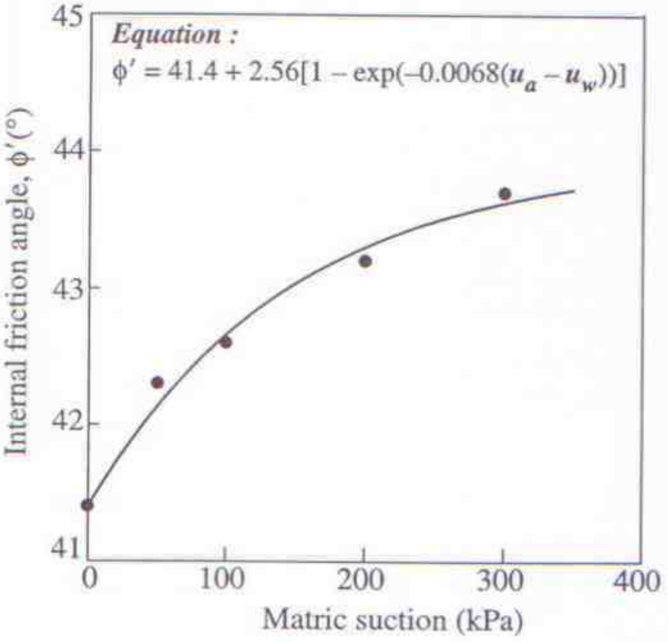


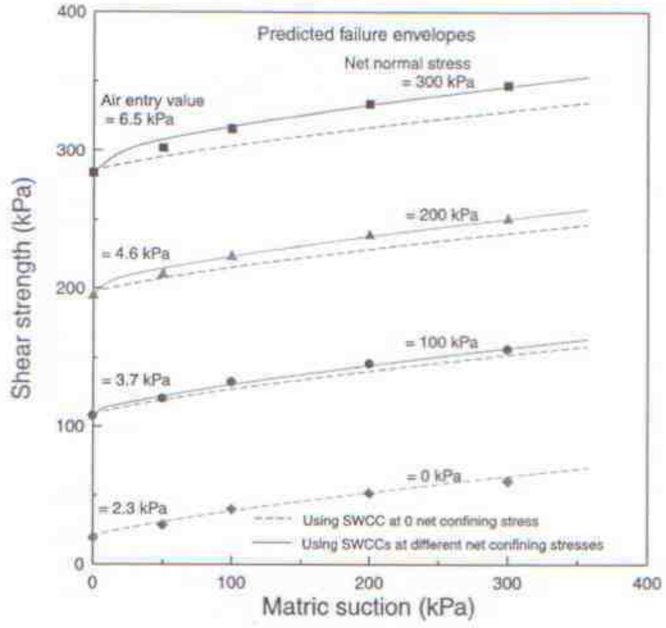
Fig. 7. Relationship between internal friction angle and matric suction.



based on two different approaches. One approach uses one SWCC performed at zero net normal stress to predict shear strengths at different net normal stresses. This approach is commonly used because of its simplicity. Also, in low-plasticity soils, net normal stress has limited influence (if ϕ' is not influenced significantly) on the shear strength and suction pressure (Vanapalli et al. 1996). The broken lines in Fig. 8 represent the predictions using this approach. There is a distinct discrepancy between the experimental and predicted data. The other approach, which is suggested by this study, uses all SWCCs performed at different net normal stresses so that the effect of net normal stress on matric suction can be considered in predicting shear strengths. The solid lines in Fig. 8 represent the latter approach, showing a better prediction compared with that using one SWCC.

In consequence, to reliably predict unsaturated shear strength, all SWCCs must be obtained at different net normal stresses. It is a cumbersome and expensive task to run multiple tests, however, and thus eq. [5] is modified in the following section by considering the effect of the net normal stress on matric suction.

Fig. 8. Relationship between shear strength and matric suction curve at different net normal stresses.



Modified model for unsaturated shear strength

The shear strength of unsaturated soils can be reliably estimated without having to obtain a number of SWCCs at different net normal stresses. In this study, eq. [5] is modified to have an additional term so that the model can consider the effect of net normal stress change on the matric suction by using only the SWCC obtained at zero net normal stress. As the degree of saturation changes linearly with the change of net confining stresses in the range of matric suctions as shown in Fig. 8, it might be enough to add a linear term in eq. [5].

Since all the matric suction contributes to the effective stress in the range of matric suctions below the air-entry value, it can be assumed that ϕ^b is equal to ϕ' in the range of matric suctions below the air-entry value (Fredlund and Rahardjo 1993; Rassam and Williams 1999). Thus, the relationship between the air-entry value (AEV) and the net normal stress is taken to be linear (Fig. 9) (Rassam and Williams 1999) as follows:

$$[6] \quad \mathrm{AEV} = \mathrm{AEV_I} + \mathrm{AEV_S}(\sigma_n - u_a)$$

where $\mathrm{AEV_I}$ is the intercept of the line, $\mathrm{AEV_S}$ is the angle of the line, and these parameters are obtained through regression analysis using results of SWCC tests. Lastly, the modified model for unsaturated shear strength can be written as follows:

$$[7a] \quad \tau = c' + [(\sigma_n - u_a) + (u_a - u_w)]\tan\phi' \qquad \text{if } (u_a - u_w) \le \mathrm{AEV}$$

$$[7b] \quad \tau = c' + [(\sigma_n - u_a) + \mathrm{AEV}]\tan\phi' + [(u_a - u_w) - \mathrm{AEV}]\Theta^{\kappa}[1 + \lambda(\sigma_n - u_a)]\tan\phi' \qquad \text{if } (u_a - u_w) > \mathrm{AEV}$$

Fig. 9. Comparison between shear strengths obtained from experimental test results (symbols) and those predicted from the modified model (lines).

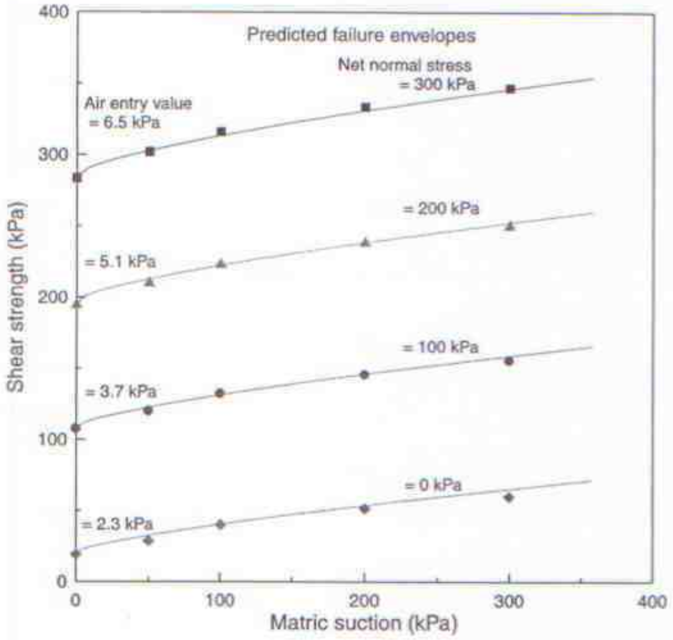


Table 4. Fitting parameters of the modified strength model on the weathered granite.

$\mathrm{AEV_I}$ (kPa)	2.3
$\mathrm{AEV_S}$	0.014
κ	1.34
λ	0.001

where λ is the fitting parameter, and κ is obtained through regression analysis using strength test results at zero net normal stress. The proposed equation is valid only in the low matric suction range, as shown in Fig. 3, where the degree of saturation changes with the net normal stress.

The fitting parameters obtained from regression analysis of strength test results on the weathered granite residual soil are summarized in Table 4. Shear strengths predicted from eq. [7*b*] are plotted in Fig. 9 with data from experimental test results. The prediction matches well with the test results. Thus, the suggested model can be used to effectively predict the shear strength of the given soil under various conditions without performing additional unsaturated triaxial tests.

Conclusions

To investigate the effect of net normal stresses on the shear strength of unsaturated soils, soil-water characteristic curve (SWCC) tests and revised triaxial tests were carried out on weathered granite soil, the dominant soil type in Korea, by varying net normal stresses. The main conclusions from this study are as follows:

(1) As the net confining stress increases, the air-entry value also increases linearly, the degree of saturation at the same matric suction increases, and the slope of the curve beyond the air-entry value becomes flattened.

Thus, the capacity of the soil system to hold the water at the same matric suction increases due to condensed soil structure by the increased net normal stress.

(2) Experimental results show that the SWCC and shear strength of unsaturated soils are significantly affected by the change of net normal stress.

(3) The comparison of the experimental data on unsaturated shear strength tests with the shear strength envelope predicted from the commonly used model suggests that the effect of net normal stress on the shear strength should be taken into consideration in the model to precisely describe the shear strength envelope of unsaturated soils.

(4) A modified model for estimation of unsaturated shear strength is proposed to consider the effect of net normal stress on the unsaturated shear strength. The suggested model can be used to effectively predict the shear strength of the given soil under various conditions without performing additional unsaturated triaxial tests.

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References

Aitchison, G.D. 1960. Relationships of moisture stress and effective stress functions in unsaturated Soils. *In* Proceedings of the Conference on Pore Pressure and Suction in Soils. Butterworths, London, UK. pp. 47–52.

Aitchison, G.D., and Donald, I.B. 1956. Effective stresses in unsaturated soils. *In* Proceedings of the 2nd Australia – New Zealand Conference on Soil Mechanics and Foundation Engineering, Christchurch, New Zealand. Technical Publications Ltd., Wellington, New Zealand. pp. 192–199.

Alonso, E.E., Gens, A., and Josa, A. 1990. A constitutive model for partially saturated soils. Géotechnique, **40**(3): 405–430.

Bernier, F., Volckaert, G., Alonso, E., and Villar, M. 1997. Suction-controlled experiments on Boom clay. Engineering Geology, **47**: 325–338.

Bishop, A.W. 1959. The principle of effective stress. Lecture delivered in Oslo, Norway, in 1955. Teknisk Ukeblad I Samarbeide Med Teknikk, **106**(39): 859–863.

Bishop, A.W. 1961. The measurement of pore pressure in the triaxial test. *In* Proceedings of the Conference on Pore Pressure and Suction in Soils. Butterworths, London, UK. pp. 38–46.

Bishop, A.W., and Blight, G.E. 1963. Some aspects of effective stress in saturated and partly saturated soils. Géotechnique, **13**(3): 177–196.

Blight, G.E. 1967. Effective stress evaluation for unsaturated soils. Journal of the Soil Mechanics and Foundations Division, ASCE, **93**(2): 125–148.

Bolzon, G., Schrefler, A., and Zienkiewicz, O.C. 1996. Elastoplastic soil constitutive laws generalized to partially saturated state. Géotechnique, **48**(2): 279–289.

Cho, G.C., and Santamarina, J.C. 2001. Unsaturated particulate materials — particle-level studies. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, **127**(1): 84–96.

Delage, P., and Graham, J. 1995. Understanding the behavior of unsaturated soils requires reliable conceptual models. *In* Proceedings of the 1st International Conference on Unsaturated Soils (UNSAT'95), Paris, 6–8 September 1995. *Edited by* E.E. Alonso and D. Delage. A.A. Balkema, Rotterdam, The Netherlands. Vol. 3, pp. 1223–1256.

Donald, I.B. 1956. Shear strength measurements in unsaturated non-cohesive soils with negative pore pressures. *In* Proceedings of the 2nd Australia – New Zealand Conference on Soil Mechanics and Foundation Engineering, Christchurch, New Zealand. Technical Publications Ltd., Wellington, New Zealand. pp. 200–204.

Escario, V., and Saez, J. 1986. The shear strength of partly saturated soils. Géotechnique, **36**(3): 453–456.

Fleureau, J.M., Kheirbek-Saoud, S., and Taibi, S. 1995. Experimental aspects and modelling the behaviour of soils with a negative pressure. *In* Proceedings of the 1st International Conference on Unsaturated Soils (UNSAT'95), Paris, 6–8 September 1995. *Edited by* E.E. Alonso and D. Delage. A.A. Balkema, Rotterdam, The Netherlands. Vol. 1, pp. 57–62.

Fredlund, D.G., and Morgenstern, N.R. 1977. Stress state variables for unsaturated soils. Journal of the Geotechnical Engineering Division, ASCE, **103**(GT5): 447–466.

Fredlund, D.G., and Rahardjo, H. 1993. Soil mechanics for unsaturated soils. John Wiley and Sons, Inc., New York.

Fredlund, D.G., and Xing, A. 1994. Equations for the soil-water characteristic curve. Canadian Geotechnical Journal, **31**: 521–532.

Fredlund, D.G., Morgenstern, N.R., and Widger, R.A. 1978. The shear strength of unsaturated soils. Canadian Geotechnical Journal, **15**(3): 313–321.

Gens, A., and Alonso, E.E. 1992. A framework for the behaviour of unsaturated expansive clays. Canadian Geotechnical Journal, **29**: 1013–1032.

Khalili, N., and Khabbaz, M.H. 1998. A unique relationship for χ for the determination of the shear strength of unsaturated soils. Géotechnique, **48**(5): 681–687.

Leong, E.C., and Rahardjo, H. 1997. Review of soil-water characteristic curve equation. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, **123**: 1106–1117.

Ng, C.W.W., and Pang, Y.W. 2000. Influence of stress state on soil-water characteristics and slope stability. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, **126**(2): 157–166.

Öberg, A.-L., and Sallfors, G. 1995. A rational approach to the determination of the shear strength parameters of unsaturated soils. *In* Proceedings of the 1st International Conference on Unsaturated Soils (UNSAT'95), Paris, 6–8 September 1995. *Edited by* E.E. Alonso and D. Delage. A.A. Balkema, Rotterdam, The Netherlands. Vol. 1, pp. 151–158.

Rassam, D.W., and Williams, D.J. 1999. A relationship describing the shear strength of unsaturated soils. Canadian Geotechnical Journal, **36**: 363–368.

Sillers, W.S., and Fredlund, D.G. 2001. Statistical assessment of soil-water characteristic curve models for geotechnical engineering. Canadian Geotechnical Journal, **38**: 1297–1313.

Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E., and Clifton A.W. 1996. Model for the prediction of shear strength with respect to soil suction. Canadian Geotechnical Journal, **33**: 379–392.

Vanapalli, S.K., Fredlund, D.G., and Pufahl, D.E. 1999. The influence of soil structure and stress history on the soil-water characteristic of a compacted till. Géotechnique, **49**(2): 143–159.