The behavior of anisotropically consolidated unsaturated soil

Le comportement d'un sol non-saturé anisotropiquement consolidé

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ABSTRACT: Suction influences on the mechanical behavior of unsaturated soil. However, suction cannot be regarded as a part of effective stress. The interpretation of suction effect is of much difference in the formulation of constitutive modeling. The authors have confirmed that we can predict the shear strength of unsaturated soil by adding the suction-induced stress to the net normal stress. In this study, anisotropical consolidation tests are performed under the condition of various net normal stress ratios. As a result, the relationship between the stress ratio and the incremental strain ratio is obtained. And the coefficient of earth pressure at rest is estimated by interpolation. The effects of suction on strains are revealed clearly.

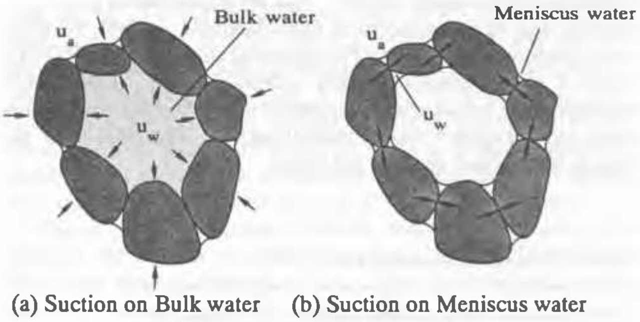
RÉSUMÉ: Il est confirmé que la succion influence le comportement de sol non-saturé. Cependant, on ne peut pas considerer la succion comme une partie de contrainte effective. Par consequent, quelques modèles constitutifs sont proposés dans lesquels la manière d'estimer les effets de la succion sont différents. Des auteurs ont confirmé qu'on peut prédire la résistance au cisaillement de sol nonsaturé avec l'application de la contrainte de succion. Dans cette étude, dans le but de reveler les effets de la succion sur la déformation de sol non-saturé, nous comparons the coefficient de la poussée des terres au repos pour le sol insaturé avec celui de sol saturé. Le coefficient de la possée des terres au repos est calculé anisotropicalement à patir des tests de consolidation sous quelques rapports de résistance. Comme résultat, ilaétait confirmé que nous devons prendre en considération le rapport de résistance qui continent les les effects de succion.

1 INTRODUCTION

The existing constitutive model for saturated soil cannot account the behavior of unsaturated soil. Since there is the boundary of water and air in unsaturated soil, the pressure difference occurs between pore-air and pore-water. This pressure difference is called suction, and it is shown as the following equation.

$$s = u_a - u_w \tag{1}$$

in which s is suction, u_a is pore-air pressure and u_w is pore-water pressure. It is generally determined as negative pore-water pressure when pore-air continues for atmosphere. On the theory of saturated soil, the suction, which greatly affects the behavior of unsaturated soil, is regarded as negative pore-water pressure and induces the effective stress. The suction determines deformability of soil, increases shear strength and allows designation in more safety side than saturated soil. There is no problem as far as we predict shear strength of unsaturated soil under constant suction. However, the suction value changes with the fluctuation of groundwater level and rainfall. And, the compression called as 'collapse' can occur when the suction decreases. The effective stress is defined as a stress component which influences on not only shear strength but also deformation. If we regard suction as a part of effective stress, the collapse, which indicates the compression due to decrease of effective stress, cannot be explained in the framework of the effective stress theory. The suction not merely compresses soil skeleton like the effective stress in saturated soil but also increases stiffness of the soil without hardening by compression. At present, some constitutive models considering these effects have been proposed (Karube (1987), Alonso et al. (1987) and Kohgo et al. (1993)) and the finite element analysis applying these models have been conducted (Alonso et al. (1988), Kohgo (1995) and Iizuka et al. (2000)). However, the determination of parameters for the analysis is difficult. The coefficient of earth pressure at rest is the one of them. In this study, anisotropical consolidation tests on unsaturated soil are conducted. From their results, the coefficient of earth pressure at rest in unsaturated soil was calculated and the applicability of existing constitutive model was examined.



(a) Suction on Bulk water (b) Suction on Meniscus water

Figure 1. The effects of suction.

2 EXISTING CONSTITUTIVE MODELS FOR UNSATURATED SOIL

Suction greatly affects the mechanical behavior of unsaturated soil. Increase of suction causes compression of soil mass and brings gain of shear strength. In this process, the effects of suction identify to that of effective stress. On the contrary, decrease of suction can possibly cause both of expansion and compression called as 'collapse'. Accordingly, we cannot regard suction as effective stress. Some researchers proposed constitutive models, which were able to express 'collapse' (Karube (1987), Alonso et al. (1987) and Kohgo et al. (1993)). There is each to one's way to handle the effect of suction.

Karube showed that form of pore-water in soil is divided into 'bulk water' and 'meniscus water' (Figure 1) and that each effect of suction on pore-water is different. Bulk water occupies pore of soil. Suction acting on it compresses soil skeleton and increase stiffness. Meniscus water clings to contact of soil particles. Suction acting on it increases stiffness without compressing soil skeleton. Both effects are isotropic and expressed as 'bulk stress p_b' and 'meniscus stress p_m' respectively. Ka-

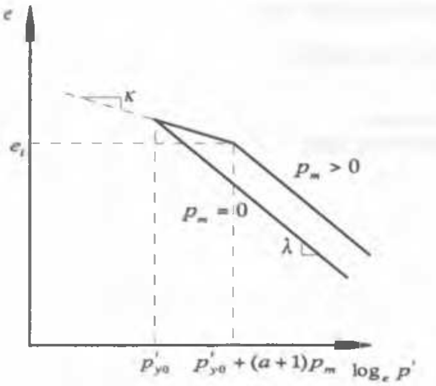


Figure 2. Isotropic compression of unsaturated soil.

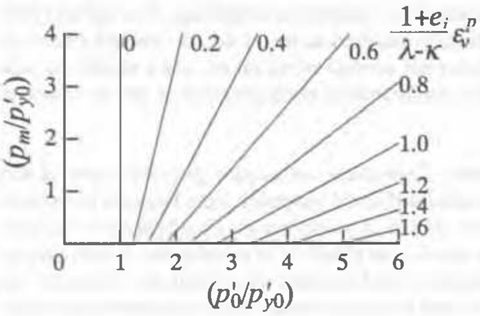


Figure 3. The group of yield curves on isotropic stress plane.

rube et al. (1998) proposed the following equation to express the stiffness of soil mass of unsaturated soil under isotropic stress state.

$$\frac{\partial e}{\partial p'} = \frac{\lambda}{p' + p_m} \tag{2}$$

in which e is void ratio, p' is skeleton stress and defined as $p' = p + p_b$, and p is mean net stress defined as $p = p_T - u_a$. p_T is the mean total stress. λ is the compression index. To express 'collapse', the effect of meniscus stress is shown as the following equations. Equation (5) is the initial yield function.

$$p' = p'_{y0} + ap_m \tag{5}$$

$$\varepsilon_v{}^p = \frac{\lambda - \kappa}{1 + e_i} \log_e \frac{p' + p_m}{p'_{y0} + (a+1)p_m} \tag{6}$$

in which p'_{y0} is p' at $p_m = 0$, a is the inclination of initial yield function on p' - p_m plane, κ is the expansion index, ε_v^p is plastic volumetric strain and e_i is void ratio at yield point. Figure 2 shows Equation (2) at constant p_m. Figure 3 shows the group of yield curves normalized by p'_{y0} at $a = 0$.

Moreover, Karube et al. (1998) expressed the energy equation for unsaturated soil under triaxial stress condition as Equation (7) and proposed yield function shown by Equation (8) under the assumption that associated flow rule is applicable.

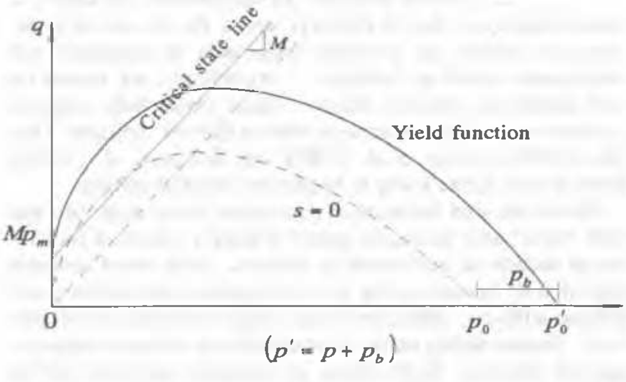


Figure 4. Yield functions under triaxial compression.

$$q = M(p' + p_m) - p'(d\varepsilon_v{}^p / d\varepsilon_s) \tag{7}$$

$$\frac{q}{M} = -p' \log_e \frac{p'}{p'_0} + p_m\left(1 - \frac{p'}{p'_0}\right) \tag{8}$$

in which M is stress ratio as $q/(p' + p_m)$ at critical state, ε_s is shear strain and p'_0 is p' at $q = 0$. Figure 4 shows yield function on $(p + p_b) - q$ plane. Expansion of yield function (hardening) is expressed on this plane. Above equations include 'bulk stress' and 'meniscus stress'.

Karube (1997) introduced 'driest curve' and attempted to express ratio of bulk water and meniscus water. Driest curve is defined as the water retention curve having no bulk water. We can estimate bulk stress and meniscus stress in terms of degree of saturation on driest curve, S_{rd}, as the following equation.

$$p_b = \frac{S_{rb}}{100 - S_{r0}} \times s = \frac{S_r - S_{rd}}{100 - S_{rd}} \times s \tag{9}$$

$$p_m = \frac{S_{rm}}{100 - S_{r0}} \times s = \frac{(100 - S_r)(S_{rd} - S_{r0})}{(100 - S_{r0})(100 - S_{rd})} \times s \tag{10}$$

in which S_{rb} is degree of saturation of bulk water, S_{rm} is degree of saturation of meniscus water and S_{r0} is residual degree of saturation. Accordingly, the suction stress, p_s, can be shown as the following equation.

$$p_s = p_b + p_m = \frac{S_r - S_{r0}}{100 - S_{r0}} s \tag{11}$$

However, there is still a question how to specify the driest curve in lower suction region.

3 EXPERIMENTAL METHOD

3.1 *Preparation of the soil specimen*

The silty clay, whose material properties are summarized in Table 1, is used for tests.

The clay, humidified to double value of liquid limit water content, was preconsolidated in oedometer (100mm in diameter) to make saturated specimen. The block sample preconsolidated by vertical stress, $\sigma_v = 156.8$(kPa), was trimmed to the specimen, 35mm in diameter and 80mm in height. The specimen was set in the triaxial apparatus for unsaturated soil (Figure 5).

3.2 *Experimental procedure*

Triaxial apparatus is improved to enable to control three stresses, axial pressure, cell pressure and pore-air pressure, independently. Pore-air pressure under perfectly drained condition is equal to suction. We must carefully measure the volume change of soil specimen because drainage is not equal to volume change on unsaturated soil. In this study, two lateral displacement meters are used for directly measuring the volume change together with axial displacement meter. Tests are conducted in two steps, suction loading and anisotropic consolidation. At first, the saturated specimen is desaturated by applying suction of s=294(kPa). Table 2 shows conditions after suction loading. Desaturated specimens are anisotropically consolidated following stress paths indicated in Figure 6 under constant suction. The value of p in Figure 6 is defined as mean net stress.

Table 1. Material properties of clay.

G_s	w_p	w_l	I_p
2.7	20.3	33.5	13.2

Table 2. Initial condition of specimen after suction loading.

Specimen	*w* (%)	*e*	*Sr* (%)
A	18.48	0.712	70.30
B	22.38	0.686	82.62
C	20.70	0.639	86.39
D	20.60	0.668	82.39

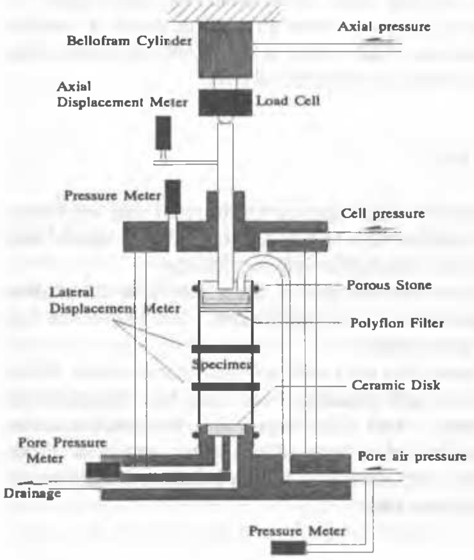


Figure 5. Triaxial apparatus for unsaturated soil.

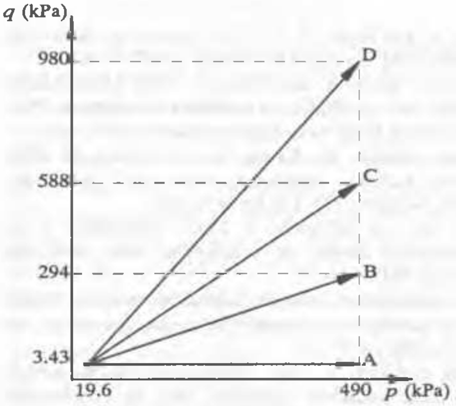


Figure 6. Stress paths.

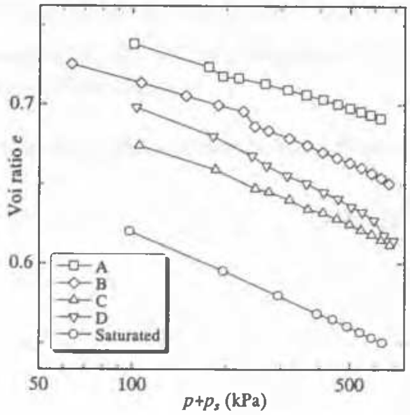


Figure 7. $(p + p_s)$-Void ration under anisotropic consolidation.

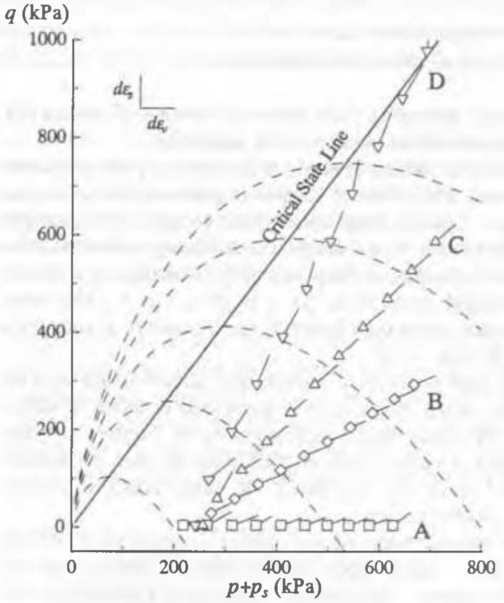


Figure 8. Vectors of strain increment on $(p + p_s)$-q plane.

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 *Anisotropic consolidation*

Figure 7 shows relationship between $p + p_s$ and void ratio through test from suction loading to anisotropic consolidation. In the figure, result of isotropic consolidation on saturated soil is also shown. It is found that larger stress ratio, q/p, is applied, more compression occurs. The Cam-clay model says that, in anisotropic consolidation on saturated soil, compression index, which is expressed on $e - \log_e p$ plane, is constant, when q/p is constant. In this study, suction is treated as isotropic stress. On unsaturated soil, stress component, which occurs dilatancy is expressed as $q/(p + p_s)$, stress ratio including effects of suction. As a results, specimen with large q/p is more compressed.

Figure 8 shows vectors of strain increment on $(p + p_s)$-q plane in the process of anisotropic consolidation. Solid line in this figure shows critical state line. Since the specimen used in this study showed expansive characteristics even in the normally consolidated state, this critical state line is determined from the stress state of the most compressive point in which the effect of dilatancy on shear strength has been removed. Dashed lines are theoretical yield function calculated from Equation (8) at $p_m = 0$. We found that vectors of strain increment intend to be normal to theoretical yield loci. Karube (1987) assumed associ-

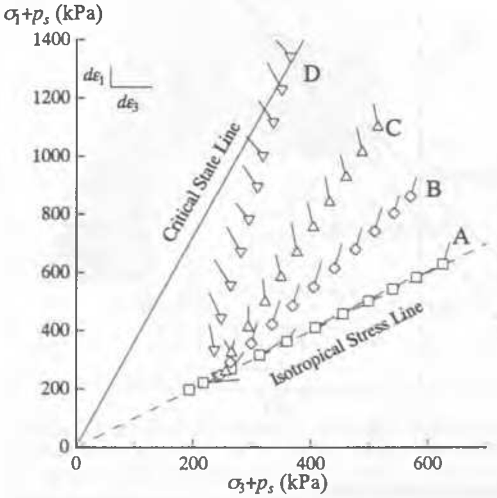


Figure 9. Vectors of strain increment on principal stress plane.

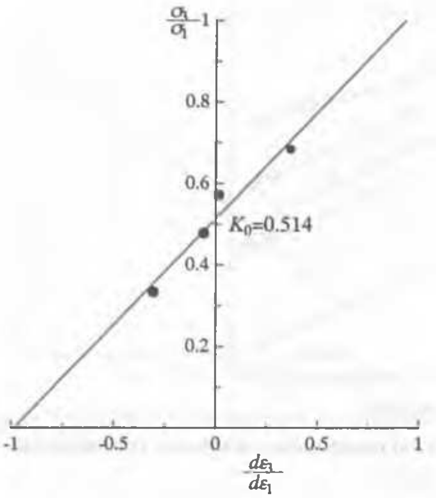


Figure 10. Principal stress ratio-principal strain ratio(saturated).

ated flow rule to determine yield function shown as Equation (8). We can confirm that this assumption is applicable.

Figure 9 shows vectors of strain increment on principal stress plane. We must add effect of suction to principal stress as suction stress, p_s. Lateral strain corresponds to minimum principal strain. We found that lateral displacement changes from positive (compression) to negative (expansion) in accordance with decrease in principal stress ratio, $(\sigma_3 + p_s)/(\sigma_1 + p_s)$. The stress ratio corresponds to the coefficient of earth pressure at rest when lateral strain is zero.

Figure 10 shows results of anisotropic consolidation tests on saturated soil. Here, stress ratio is expressed in terms of effective stress. We found liner relationship in the Figure. We can regard intersect at vertical axis as coefficient of earth pressure at rest. From Figure 10, coefficient of earth pressure at rest, $K_0 = 0.514$, is determined.

Figure 11 shows results of anisotropic consolidation tests on unsaturated soil. Here, open points indicate stress ratio expressed as net stress. The coefficient of earth pressure at rest, $K_0 = 0.422$, expressed with net stress in unsaturated soil is smaller than that in saturated soil. This result dose not account for effects of suction. The coefficient of earth pressure at rest of unsaturated soil should be expressed considering stress component including effects of suction. Since earth pressure at rest can be interpreted to be a sort of resistance against deformation of soil, we should use the sum of net stress and bulk stress, which can cause deformation of unsaturated soil. However, it is difficult to quantitatively specify the value of bulk stress p_b. Closed points in Figure 11 are results from calculation with sum of net stress and suction stress. Consequently, The coefficient of earth pressure at rest, $K_0 = 0.523$, determined with application of suction stress is slightly lager than that on saturated soil. Liner correlation with application of bulk stress can be expressed between that of net stress and that of sum of net stress and suction stress. Since specimens in this study have relatively high degree of saturation, ratio of meniscus stress to suction stress is smaller. Therefore, in this case, bulk stress is applicable for earth pressure and skeleton stress for unsaturated soil.

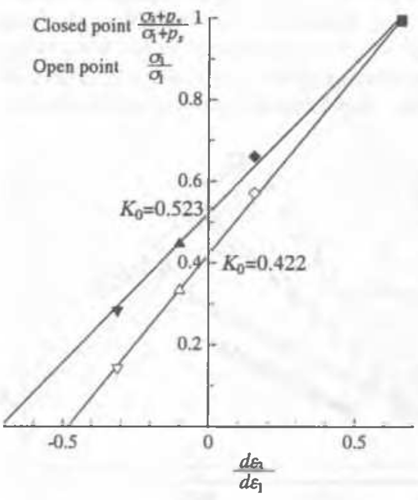


Figure 11. Principal stress ratio-principal strain ratio(unsaturated).

5 CONCLUSIONS

Anisotropical consolidation tests on unsaturated soil were conducted, and the applicability of existing constitutive model was examined and came to the following conclusions.

(1) The existing constitutive model are defined on assumption that associated flow rule is applicable. We found that this assumption is adequate.

(2) It was confirmed that we could not use suction stress, which affect shear strength of unsaturated soil, but bulk stress as effective stress. And it is found that the earth pressure should be expressed as sum of net stress and bulk stress. Consequently, earth pressure of unsaturated soil corresponds to that of saturated soil.

REFERENCES

Alonso, E. E., Gens, A. and Hight, D. W. 1987, Special problem soils. General Report, *Proc. 9th Europian RC-SMFE* : 1087-1146.

Alonso, E. E., Batle, F., Gens, A. and Lolet, A. 1988, Consolidation analysis of partially soils-application to earthdam construction, *Proc. Int. Conf. On Numerical Methods in Geomechanics* : 1303-1308.

Iizuka, A., Honda, M., Nishida, H., Kawai, K. And Karube, D. 2000, Soil/water coupled analysis considering unsaturated pore water distribution, *JSCE*, No.659/ : 165-178 (in Japanese).

Kohgo, Y., Nakano, M. and Miyazaki, T. 1993, Verification of the generalized elastoplastic model for unsaturated soils, *Soils and Foundations*, Vol.33, No.4 : 64-75.

Kohgo, Y. 1995, A consolidation analysis method for unsaturated soils coupled with an elastoplastic model, *Proc. 1st Int. Conf. On Unsaturated Soils* : 1085-1093.

Kawai, K. Karube, D. and Kato, S. 2000, Triaxial compression tests on unsaturated soils under undrained condition, *Proc. An International Conf. On Geotechnical & Geological Engineering, Melbourne* : SNES1010.

Karube, D. 1987, Basic stress-strain relations of unsaturated soil, *Proc. 8th Asian RC-SMFE* : 49-52.

Karube, D. 1997, Stress analysis of unsaturated soil based on the 'driest curve', *Proc. 14th ICSMFE* : 333-336.

Karube, D., Kato, S., Honda, M. and Kawai, K. 1998, A constitutive model for unsaturated soil evaluating effects of soil moisture distribution. *Proc. 2nd IC on Unsaturated Soils*, Vol.1 : 485-490