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AN IDEAL UNSATURATED SOIL AND THE BISHOP'S SOIL
UN SOL NON-SATURE IDEAL ET LE SOL DE BISHOP

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SYNOPSIS Effect of suction on mechanical properties of unsaturated soil is examined theoretically and experimentally. Firstly suction stress is divided in meniscus stress and bulk stress components by considering the unique roles of meniscus water and bulk water in soil skeleton. Then coefficient "R" expressing the ratio of bulk stress to suction stress is introduced and yield surface is defined with parameter "R". For the case R=0, that is called as "an ideal unsaturated soil", increase of suction causes no strain hardening but collapse and for the case R=1, that is called as "the Bishop's soil", the opposite phenomenon happens. To prove this theory, triaxial test on two kinds of kaolin clay specimens were done. Comparing the test results with the theory, it was confirmed that the value of coefficient R is smaller for compacted specimens and bigger for consolidated specimens.

INTRODUCTION

Failure stress of unsaturated soil can be properly explained with Bishop's effective stress equation. However Jennings and Burland(1962) pointed out that this equation had limitations to describing the volume change and drainage of unsaturated soils. They discussed on the point of view that each soil particle in an unsaturated soil mass had meniscus water around their contact points. In this paper we will call these soils as "ideal unsaturated soil", in which all of the free water is contained in meniscus water, in short word, with no bulk water (Fig.1a). But in the state that Bishop's equation has meaning, it is assumed that suction stress is fully converted to externally loaded normal stress, and then the pore state model is thought in which there are few meniscus water around the particle contact points and almost all of the free water is bulk water (Fig.1b). In the former case, suction force caused by menisci acts normally to the particle contact points, and there happens no slippage at contact points, in other word, suction force cannot cause strain hardening. But in the latter case, suction force caused by bulk water has isotropically compression effect on soil skeleton as the negative pore water pressure does in saturated soil and it causes plastic deformation and strain hardening of the soil mass. In this paper, mechanical characteristics of unsaturated soil are discussed introducing these two components of suction stress.

DETAILS OF SUCTION STRESS

We can make a soil sample, in which almost all of the free water is contained in menisci, by wetting process as shown in Fig.2 from point C, state of having lost free water by high suction, to point B. During this wetting process suction value and induced "suction stress" are decided only by the quantity of water and soil particles, therefore they become the function of water content. On the other hand, the soil sample can be made in which almost all free pore water is the bulk water, by the first low suction portion of drying process from point A in saturated state to C. In this case suction stress is decided by degree of saturation and value of suction. Soils in natural state will have both meniscus and bulk water. So suction stress may be

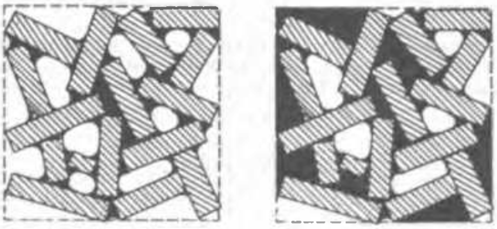

(a) (b)

Fig.1 (a) Ideal unsaturated soil
(b) Bisop's soil

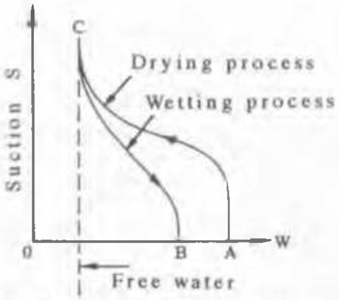


Fig.2 Moisture characteristic curve

given by

$$p_s = p_m + p_b \tag{1}$$

where p_s : compressive stress yielded by suction ("suction stress" ; which is once defined by authors as "f(S)" (Karube and Kato (1989))

p_m : compressive stress yielded by meniscus water ("meniscus stress")

p_b : compressive stress yielded by bulk water ("bulk stress").

It should be pointed out in concern with Eq.(1) that more the ratio of bulk water quantity becomes, less the numbers of contacts points surrounded by meniscus, so meniscus stress decreases. Here if we introduce a coefficient of R that means the ratio of bulk stress p_b to suction stress p_s, then the following equations are deduced

$$p_m = (1 - R)\, p_s \tag{2a}$$

$$p_b = R\, p_s \tag{2b}$$

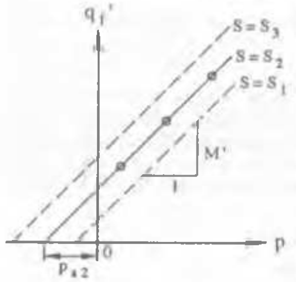


Fig.3 Family of corrected failure lines

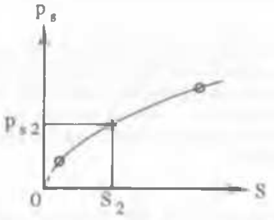
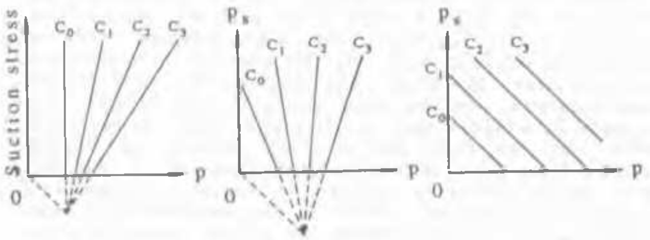


Fig.4 Suction and suction stress



(a) R=0 (b) 0<R<1 (c) R=1

Fig.5 Yield loci related to R

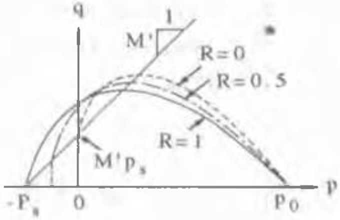


Fig.6 Yield locus related to R (section of constant p_s)

The value of coefficient R becomes R=0 in "an ideal unsaturated soil", and in turn R=1 in "the Bishop's soil". We expect that behavior of unsaturated soil shall be affected not only by suction value but also coefficient R.

EVALUATION OF SUCTION STRESS

To evaluate the suction stress possessed by unsaturated soil sample, we must do some triaxial test and the results should be analyzed under next two assumptions. They are, coefficient R is constant during the test, and failure stress state is governed by the following equation

$$q_f' = M' (p + p_s) \tag{3}$$

where q_f'; deviator stress at failure with surface energy correction

M'; coefficient of shear resistance

$p = p_T - u_a$, where p_T is total mean stress and u_a is pore air pressure.

If we conduct the triaxial test at several levels of suction, and plot the corrected failure stress as shown in Fig.3, we can know the suction stress p_s at each suction level. Plotting p_s versus suction S, we can get relation curve as shown in Fig.4.

EQUATION OF ISOTROPIC CONSOLIDATION

For saturated soils, differential form of normally consolidation curve is

$$\frac{dp}{-de} = \frac{2.3}{C_c}\, p \tag{4}$$

where e: void ratio of clay, p: consolidation pressure, C_c: compression index.

Eq.(4) means that skeleton stiffness of saturated soil, (-dp/de), is proportional to consolidation pressure. For unsaturated soils, skeleton stiffness is given by $d(p+p_b)/(-de)$, and is thought to be yielded by stress $(p+p_s)$. Therefore the differential equation becomes

$$\frac{d(p + Rp_s)}{-de} = \frac{2.3}{C_c}(p + p_s) \tag{5}.$$

When consolidation pressure p is increased at a constant suction and it is assumed coefficient R keeps a constant value, Eq.(5) can be integrated as follows:

$$e = e_1 - C_c \log_{10}\frac{p + p_s}{p_1 + p_{s1}} \tag{6}$$

in which, when $p = p_1$, it becomes $e = e_1$, $s = s_1$, $p_s = p_{s1}$.

YIELD SURFACE

Yield Loci of Isotropic Compression

If unsaturated soil is assumed to be elasto-plastic material, plastic volumetric strain yields when isotopic consolidation stress exceeds the yield stress. And differential equation for that phenomenon is

$$\frac{dv^P}{d(p+Rp_s)} = m_v - m_v' = \frac{\lambda - \kappa}{1+e_i}\,\frac{1}{p+p_s} \qquad (7)$$

where m_v' : elastic volume compressibility.

And if this equation is integrated as R and p_s are constant, we can get the following equation

$$v^P = \frac{\lambda - \kappa}{1+e_1}\ln(p+p_s) + G(p_s) \qquad (8)$$

where $G(p_s)$: function of p_s

If the soil mass is formed under the stress condition of (p, p_b), initial yield function C_0 will become

$$p + R\,p_s = C_0 \qquad (9)$$

Because plastic volumetric strain v^P is zero on Eq.(9), Eq.(8) becomes:

$$v^P = \frac{\lambda - \kappa}{1+e_1}\ln\frac{p+p_s}{C_0+(1-R)p_s} \qquad (10)$$

Rewriting Eq.(10), the equation of constant plastic strain line is got as,

$$p = C_0\exp(C_i) + [(1-R)\exp(C_i)-1]\,p_s \qquad (11)$$

where, $C_i = \dfrac{1+e_1}{\lambda - \kappa}(v^P)_i$ = constant.

The intersection coordinate of Eq.(9) and Eq.(11) becomes $(p, p_s) = [C_0/(1-R), -C_0/(1-R)]$.
Fig.5 (a),(b),(c) shows equal plastic strain lines, in other words, subsequent yield loci for R=0 (ideal unsaturated soil), 0<R<1 (real soil), and R=1 (Bishop's soil) respectively.

Yield Surface of Triaxial Compression Test

Energy equation of original Cam Clay model for unsaturated soil is given by

$$(p + R\,p_s)\,dv^P + q\,d\varepsilon = M'(p+p_s)\,d\varepsilon \qquad (12)$$

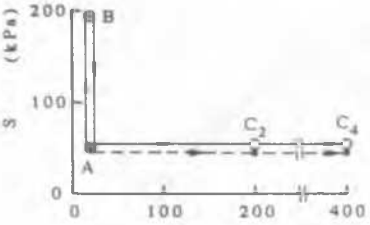


Fig.7 Isotopic stress psths

Table-1

Specimen (Symbol)	Stress Path	Initial Sr
QA2(▲) QA4(▼) QB2(●) QB4(■)	AC_2 AC_4 $ABAC_2$ $ABAC_4$	96% about
UA2(△) UA4(▽) UB2(○) UB4(□)	AC_2 AC_4 $ABAC_2$ $ABAC_4$	55% ~ about

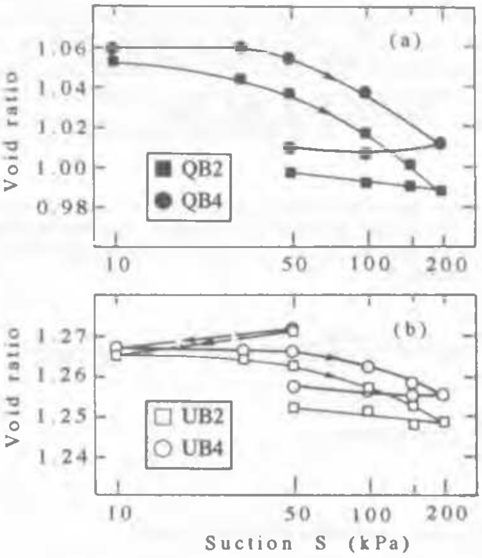


Fig.8 Void ratio vs Suction

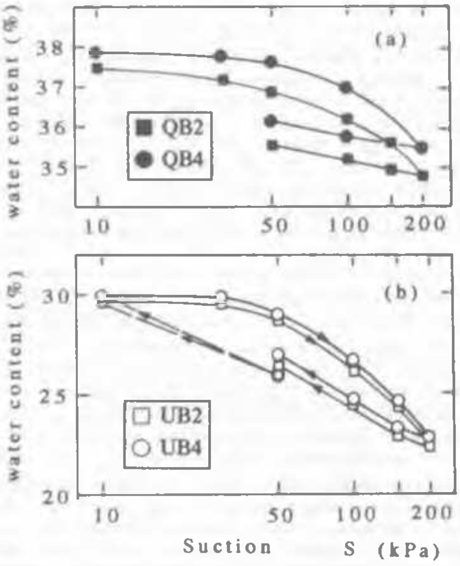


Fig.9 Water content vs Suction

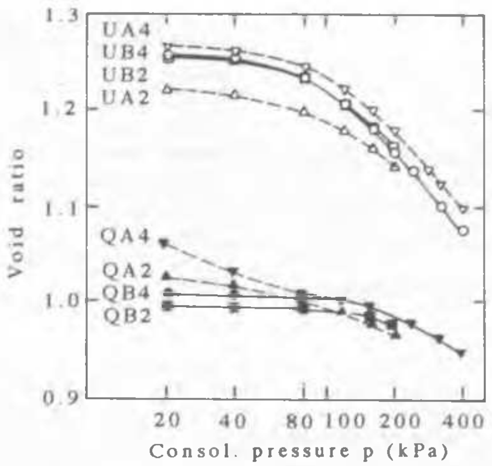


Fig. 10 Void ratio versus consolidation pressure

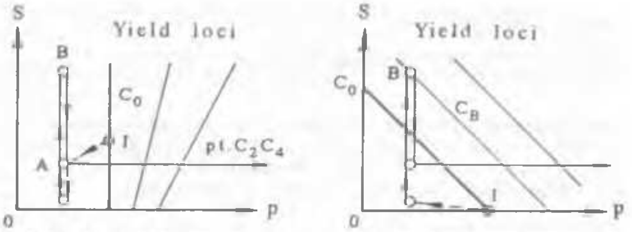
We can get the following equation of yield surface applying the same method as Karube and Kato(1989). Fig.6 shows the section of yield locus which depends on coefficient R.

$$q=-(p+R\,p_s)\log\left(\frac{p+R\,p_s}{p_0+R\,p_s}\right)+(1-R)p_s\left(1-\frac{p+R\,p_s}{p_0+R\,p_s}\right) \qquad (13)$$

where p_0 is p at q=0.

RESULTS OF CONSOLIDATION TEST

Series of triaxial test were conducted on quasi-saturated and unsaturated specimens. The former (Q-specimens, Sr=96%) were prepared by consolidating slurried kaolin clay and the latter (U-specimens, Sr=55%) were prepared by compacting moist kaolin powder. Specimens traced the stress paths from point A to point C_2 or C_4 in Fig.7. The tested specimens were listed in Table 1. Fig.8 shows the void ratio change during suction hysteresis process. Q-specimens show bigger compression but in the path of B to A, U-specimens in Fig.8b show bigger expansion. Fig.9 shows the water content change in the same process. U-specimens in Fig.9b show a considerable change and behave more elastically. Adding the stress path of full line in Fig.7 to Figs.5 a and c, Figs.11a and c are got respectively. Initial yield loci in Figs.11a and c were formed by compaction for U-specimens and consolidation for Q-specimen. If the initial yield locus is located as shown in Fig.11a, stress path A—B—A is in the elastic region, therefore specimens yield elastic strain only. On the other hand, if yield locus is located as shown in Fig.11c, stress path A to B goes out of initial yield locus and specimens yield elasto-plastic strain. However unloading path of B to A goes inside of subsequent yield locus C_B, so specimens yield elastic strain only. It is thought that pattern of yield loci for U-specimen is the same as shown in Fig.11a, because the strain behavior of this specimens is seemed to elastic one. On the other hand, strain behavior of Q-specimens is nearly the same as shown in Fig.11c.



(a) U- specimens (c) Q- specimens

Fig. 11 Influence of pre-suction

Fig.10 shows the void ratio change during subsequent consolidation process from A to C_2 or C_4. All the U-specimens show the same shape of consolidation curve regardless of suction hysteresis, which can be predicted from Fig.11a. As to the Q-specimens, QB2 and QB4 which experienced suction hysteresis show the flat consolidation curve in the first part, which can be understood from Fig.11c. From these examinations it is thought that U-specimens belong to the category of "an ideal unsaturated soil" and Q-specimens belong to the category of "the Bishop's soil" respectively. Alonso at al. (for instance 1990) proposed "coupling" effect to explain the phenomena that "loading-collapse" yield locus is moved by increasing suction. But the experiments mentioned above show that coupling does not always occur even when suction increases to the virgine value. The theory introducing coefficient R can explain uniquely the behavior of various unsaturated soil.

CONCLUSIONS

Suction stress yielded by suction consists of stress components by meniscus water and by bulk water. In this paper it is pointed out that complicated volume change and drainage behaviour of unsaturated soils is affected by these two suction components. Effective stress proposed by Bishop(1960) is strictly applied to the soil in which all of the free pore water is bulk water. Family of yield loci of the Bishop's soil cannot cause collapse phenomena. But family of yield loci of the soil in which all of the free water is meniscus water shows that strain hardening does not occur and reduction of suction can cause collapse. In real soils, there exist both meniscus and bulk water. To describe their behavior, we introduced coefficient R. Yield loci for 0<R<1 was calculated on the assumption that R is constant even if suction or applied stress are changed.

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