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Experimental Studies on Strength and Deformation Characteristics of Unsaturated Clay

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Abstract

In this paper, strength and deformation characteristics of unsaturated clays are examined. First, automated triaxial testing system is constructed. The system can automatically measure the data of testing, and record them in the prescribed form. Then, two series of consolidated-undrained shear tests are performed. One is to examine the fundamental properties about unsaturated clay and the other is to examine them about overconsolidated saturated clay to be compared the properties for unsaturated clay. From the results, it is found that there is some similarity between the deformation characteristics of unsaturated clay and that of overconsolidated saturated clay, such as the pore water pressure behavior during undrained shear. But the compressibility of specimen, the strength characteristic and the other characteristics (such as stress-strain relationship and stress path) of unsaturated clays are proved to be quite different from these characteristics of saturated clay.

Introduction

To design and/or analyze soil structures such as fill dams and irrigation ponds, it is essential to determine the soil parameters by soil tests considering the field conditions. The triaxial test is popular among soil tests to determine the soil parameters, because of the accuracy of obtained parameters and the variousness of considerable field conditions, though the testing apparatus and the procedures are rather complicated than conventional uniaxial compression test and direct shear test. On the other hand, many soils near the ground surface and compacted soils constructing soil structures are unsaturated. So, designing and/or analyzing these soil structures, soil parameters must be determined by using unsaturated triaxial test. But the conventional triaxial test are performed to saturated soils, and there in a few standard to perform the unsaturated soils.

The purpose of this paper is to construct an automated triaxial testing system for unsaturated soils, and to examine the mechanical properties of unsaturated soils. Unsaturated soils consist of three phases, namely, solid (soil particles), liquid (pore water) and gas (pore air). From the mechanical point of view, surface tension effects originated form these boundaries between each phase are the most significant, and make it difficult to understand the mechanical behavior of unsaturated soils. The surface tension between water and air contributes to forming a meniscus and induces a pressure difference (that is, suction) between pore water and pore air. On consideration of the mechanical behavior of unsaturated soils, it is very important to appreciate the suction effects.

In this paper, two series of consolidated-undrained shear tests for clays are performed. One is to examine the fundamental properties about unsaturated clays and the other is to examine about overconsolidated saturated clays. From these tests results, the fundamental properties of unsaturated clays are investigated, comparing them with the strength and deformation characteristics of overconsolidated saturated clays. For, it is known that there is some similarity between the deformation characteristics of unsaturated soils and that of overconsolidated soils, because the suction effects work similar to cohesion[1].

Testing Procedure, Apparatus and Specimen

In this study, unsaturated triaxial tests were preformed according to the specification defined for 'a cooperative test program of uniaxial and triaxial compression tests on unsaturated soils[2]' which was carried out by the Japanese Geotechnical Society. There were several kind of testing series assorted by shearing conditions, ventilated-undrained triaxial shearing tests were performed in this study. The details of testing procedures are referred in above specification.

Fig. 1 shows the unsaturated triaxial apparatus used in this study. This system can automatically measure the stresses, strains and volume changes of specimen during consolidation and statical shearing as above mentioned. The details are shown in previous paper[3].

The feature of this apparatus compared with conventional triaxial ones (for saturated soils) are as follows.

a) Inner cell is used to measure the volume change of specimen. From the difference of the water level between inner cell and outer cell, the volume change of specimen can be calculated.

b) To measure only the amount of pore water movement (coming in and out), ceramic disk (air entry value = 2.0 kgf/cm^2) is used at the bottom of specimen. Because water saturated ceramic disk can prevent from passing through the pore air in the specimen.

c) At the top of specimen, glass fiber filter is used only pore air can pass through.

The testing soil used was kaolin clay and its index properties were G_S= 2.774, PL = 66.3% and PI = 37.5. Specimens were prepared to cut a compacted sample in the column 5cm in diameter and 11cm in height. Compaction was carried out in accordance with 'JSF T 711'[4] (the standard

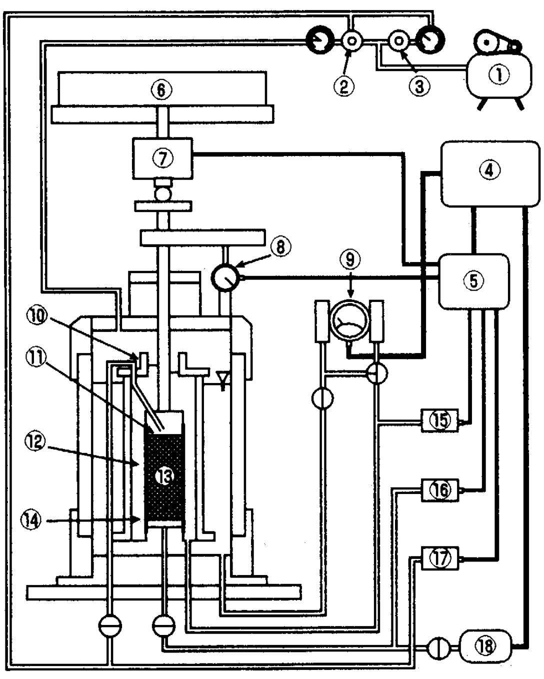

Fig. 1 Overview of unsaturated triaxial system

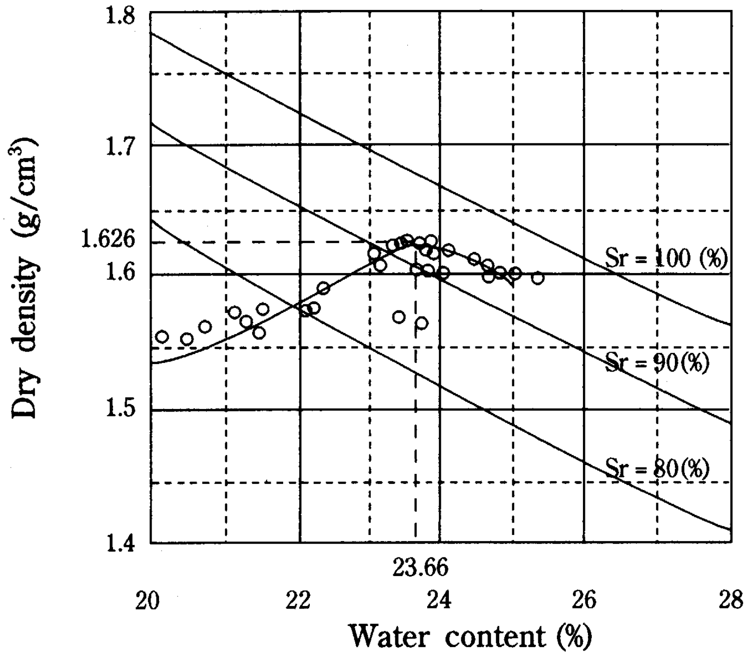

Fig. 2 Compaction curve for kaolin clay

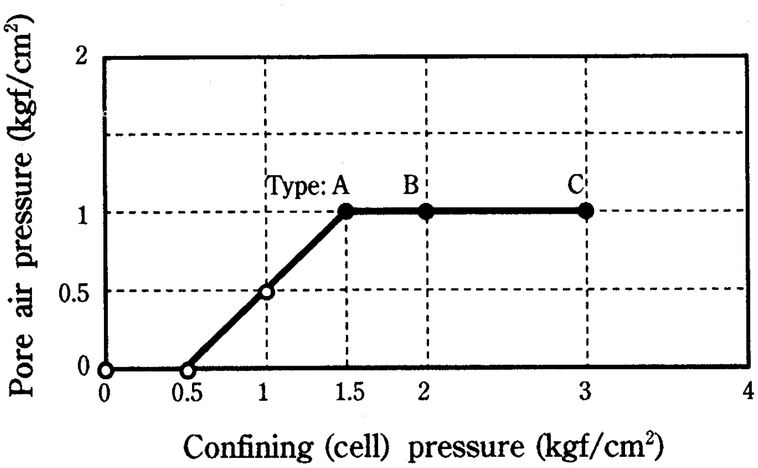

Fig. 3 Stress path for consolidations

of the Japanese Geotechnical Society), the test method for soil compaction using rammer. Fig. 2 shows the dry density v. s. water content relationship obtained, the optimum water content : W_{opt} (which can compact soils most densely) are known about 23.66%. Samples were compacted not less than 95% of the maximum density.

After the specimen is set in triaxial cell and covered with rubber membrane (thickness = 0.2mm), initial confining pressure 0.5 kgf/cm^2 is applied. Then the confining pressure and pore air pressure are increased by 1.0 kgf/cm^2 simultaneously, with the pressure difference keeping constant, consolidation process is started. For the test type : A, statical shear will start after this consolidation. And for test type : B and C, further consolidation is performed only confining pressure is increased by prescribed value, and then start to shear. The stress path for these process is shown in Fig. 3.

On the other hand, triaxial test for saturated clays were carried out according to the standard 'JSF T 523'. Specimens were preconsolidatied 2.0 kgf/cm^2, and then swelled so that the overconsolidated ratio (OCR) were 1.0, 2.0, 4.0, 8.0 respectively, while back pressure was 2.0 kgf/ cm^2. Immediately after the end of consolidation, statical shear is performed. The shear strain rate is 0.06%/min for both unsaturated and saturated clays, and specimen is under ventilated -undrained condition for unsaturated clays and under undrained condition for saturated clays.

Results and Discussions

Stress-strain relationships

Fig. 4 shows the stress-strain (deviator stress v.s. axial strain) relationships of triaxial shearing for unsaturated clays, as well as the one for saturated clays. It can be seen about unsaturated clays that the peak of stress-strain curve are appeared more clearly and that the strength are higher than saturated clays. These properties are caused by the effect of suction.

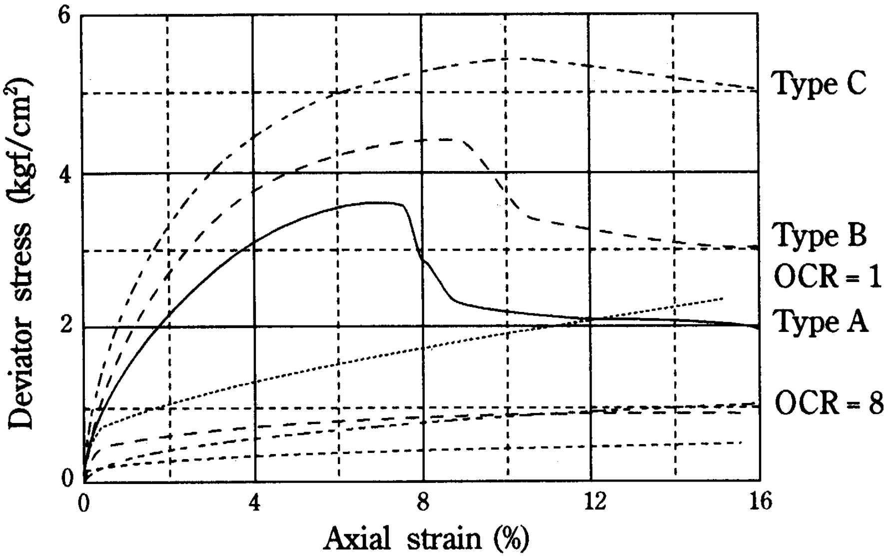

Fig. 4 Deviator stress v.s. axial strain relationships

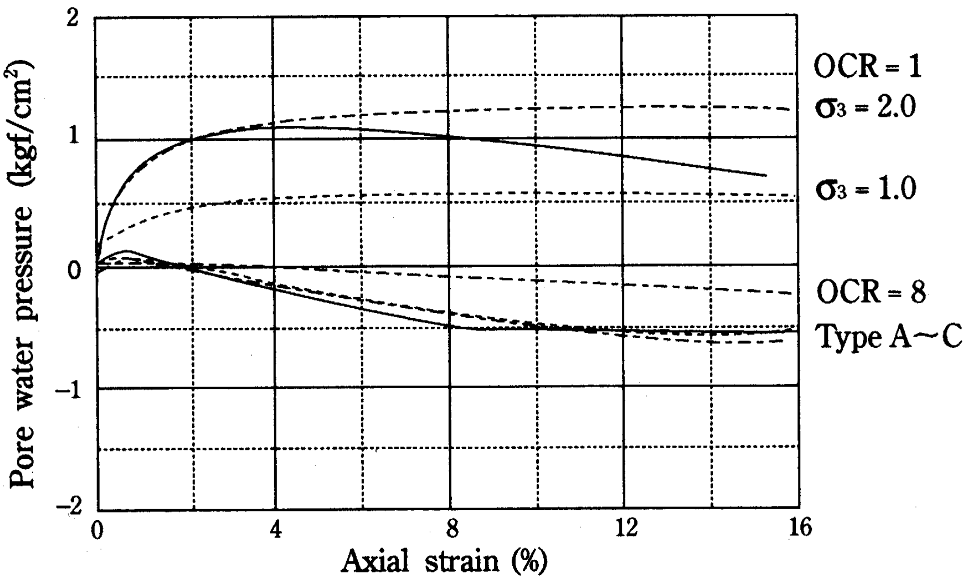

Fig. 5 Pore water pressure v.s. axial strain relationships

And, axial strain at failure and shear strength tend to be larger by increase of confining pressure. It can be considered that the larger confining pressure prevent from the failure at early stage of shearing.

Behavior of pore water pressure and volumetric strain

Fig. 5 shows the pore water pressure v. s. axial strain relationships of triaxial shearing for both unsaturated and saturated clays. It can be seen about unsaturated clay that the pore pressure increase only at the beginning of shear and then decrease to negative value, and converge about -0.6 kgf/cm^2 instead of the difference of confining pressure at test type A, B, C. As to saturated clay, pore pressure in normally consolidated specimens increase with shearing and converge the maximum positive value, while pore pressure in overconsolidated specimens soon decrease. Particularly, pore pressure in heavily overconsolidated specimen (e. g. the case OCR = 8) decrease to negative value, as well as unsaturated one. These properties are considered in detail later, by taking into account for the behavior of volumetric strain.

As for about unsaturated clays, shearing were carried out under ventilated and undrained condition, so volume changes of specimen can be observed (while volume of specimens are kept constant during undrained shear of saturated clays). Fig. 6 shows the volumetric strain v.s. axial strain relationships about unsaturated clays. It can be noted that the volume expansion of specimens are occurred with shearing, though the specimens are compressed. This characteristic of dilation considered to the effect of the specimen preparation method and the suction. That is to say, the specimens are compacted most densely condition (void ratios are 0.69–0.74) and condensed by the suction, the specimens are hardly possible to be more compacted. Considered from microscopic point of view, soil particles in the specimens tend to be away from each other by the dilating behavior, but the suction caused by inter-particle meniscus prevent from departing soil particles each other. For these reason, the pore water pressures are decreasing (see Fig. 5) in proportion to the shearing, and the volumetric strains are also decreasing (e. g. the specimens are expanding). But once the specimens are become failure, inter-effect between the dilation and the suction is also become independent on shear deformation, and the pore water pressure is

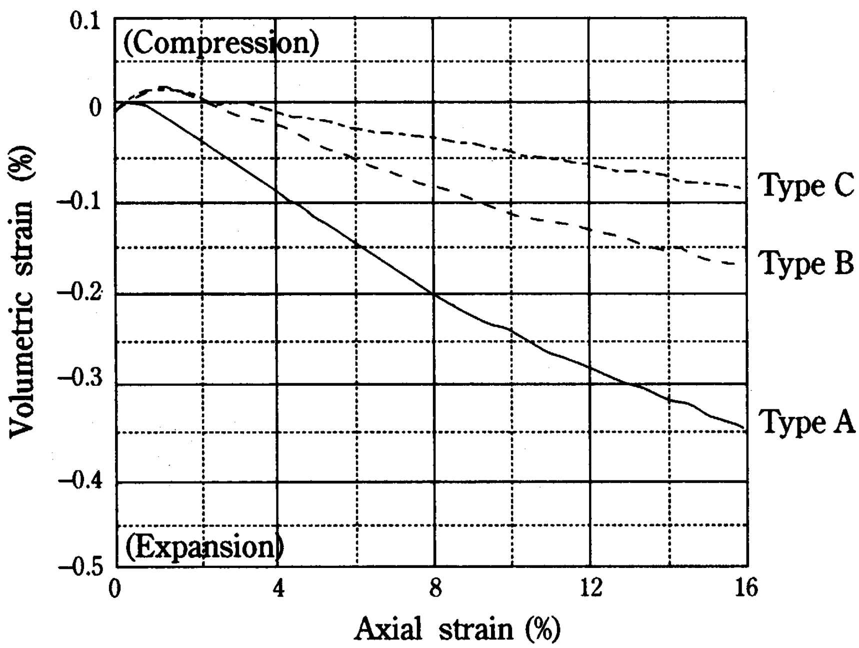

Fig. 6 Volumetric strain v.s. axial strain relationships

converged in about -0.6 kgf/cm^2, in these case. On the contrary, specimens are prepared by consolidating method about saturated clay, soil particles are not so densely (void ratios are about 1.68) than unsaturated clays, and the pore pressures are increasing in proportion to the shearing. But in the cases of overconsolidated saturated clay, specimens are consolidated more densely than normally consolidated clay because of the consolidated yield stresses are much higher. So, the stiffness of specimens become larger with increasing of overconsolidated ratio, and the pore water pressure decrease in proportion to the shearing. From these point of view, it is concluded that the compressibility behavior (considered from pore water pressure and volumetric strain behavior) of unsaturated clays are relatively similar to the behavior of overconsolidated saturated clays.

Effective stress path

Fig. 7 shows the effective stress path in triaxial shearing for unsaturated clays, as well as the one for saturated (both normally consolidated and overconsolidated) clays. The coordinate axes are p' : mean effective stress and q' : deviator stress respectively, and they are represented in expressions below.

$$p' = (\sigma_1 + 2\sigma_3)/3 + (u_a - u_w)$$
$$q' = \sigma_1 - \sigma_3$$

where σ_1 : major principal stress, σ_3 : minor principal stress,
u_a : pore air pressure (in case of saturated clay : $u_a = 0$),
u_w : pore water pressure.

It is shown from this figure that the shapes of stress paths are similar in accordance with the shearing conditions. As for the saturated clays, all stress paths are found to be converged a certain line. This line is called 'failure line' in effective stress plane. But for the unsaturated clays, specimens are found to become failure without reaching at this line. It is considered for the reason that the effect of suction (that is, the term '(u_a-u_w)') is overestimated above equation in defining p', and it is found that the equation couldn't apply to unsaturated clays. To explain

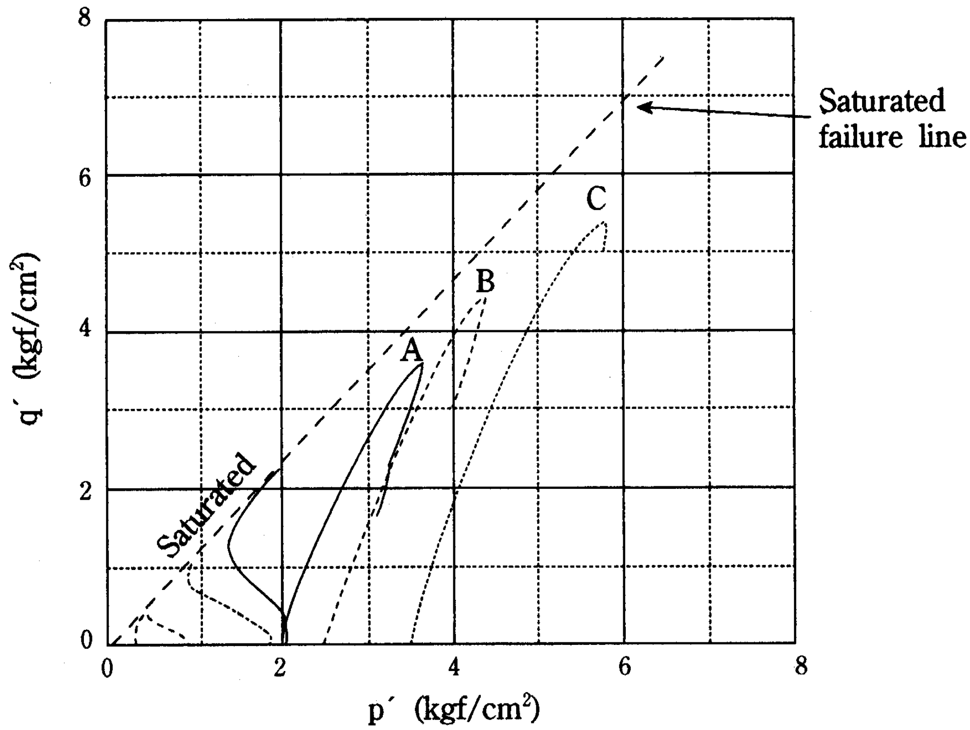

Fig. 7 Effective stress paths

this characteristic of unsaturated soils, Bishop[5] proposed a theory about the effective stress concept of unsaturated soils. In this theory, he derived following equation using new parameter χ.

$$\sigma' = \sigma - u_a + \chi\ (u_a - u_w)$$

where σ' : mean effective stress, σ : mean total stress

In this equation, parameter χ represent the degree of saturation effect, determined by the physical condition of unsaturated soil. The value of χ exist between 0 to 1, and $\chi = 1$ in fully saturated soils, $\chi = 0$ in dry (without water) soils. It is said that this equation can represent the behavior of unsaturated soils correspondingly to the theory of saturated soils, though some kind of soil can not be applicable. In this study, χ is about 0.76 to 0.80 under the condition that Sr (degree of saturation) is about 92-93%. Consequently, Bishop's effective stress theory can apply for this compacted kaolin clay. In other words, the strength and deformation characteristics of this clay are found to be predictable.

Conclusions

Two series of consolidated-undrained shear tests were performed using unsaturated and saturated clays to investigate the deformation and strength characteristics of unsaturated clays. As the result, the following conclusions were obtained.

a) The strength of unsaturated clays are larger and more brittle than saturated clays, because the suction works for similar effect of confining pressure in unsaturated clays.

b) Before the specimen is failure, the suction effect found to increase proportionally with shearing to confine the combination of soil particles. But after the specimen is failure, interaction relationship between pore water and soil particles are also broken, and the suction effect is found to be kept constant.

c) Bishop's effective stress theory can apply for this compacted kaolin clay, and the χ value is about 0.76 to 0.80. This result is considered to suggest that the strength and deformation characteristics of unsaturated clays can be predicted.

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