Air-coupled effects on triaxial behavior of silty specimens under a constant confining pressure and various exhausted conditions

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ABSTRACT

Many studies in unsaturated soil mechanics have focused attention on suction difference. It is also necessary to take into account the flow and high compressibility of the pore air. During rainfall, earthquakes, or other conditions under which air cannot be sufficiently exhausted, changes occur in the pore air pressure, causing changes in the pore air volume. There is an increasing need for methods of testing and analysis capable of dealing with cases where the pore air pressure varies from atmospheric pressure. Based on the background, numerical simulation of unsaturated silty triaxial tests under undrained and unexhausted conditions and under undrained at various controlled air pressure levels was carried out using a soil-water-air coupled analysis code taking the triaxial test as an initial value/boundary value problem. The processes of back pressure increase, suction variation, consolidation, and shear were simulated beginning from a “single initial condition” as in the case of the experiments. As a result, in the simulations of the undrained and unexhausted shear tests, it was shown that since the mechanical behavior is significantly affected by the compressibility of air, it is possible, by simply taking into consideration air coupling, to describe the differences in the mechanical behavior corresponding to the differences in the degree of saturation. Through the simulations of the undrained shear tests with air pressure control, it was found to be possible to reproduce soil mechanical behaviors that change from hardening to softening corresponding to the level of volumetric constraint. Softening behavior can be portrayed on the basis of the loss of structure described by the SYS Cam-clay model. In addition, behaviors that could not be explained without the effects of factors other than air coupling such as suction were also shown.

Keywords: unsaturated soil, triaxial test, three phase coupled analysis

1. INTRODUCTION

Studies on the mechanics of unsaturated soil have been carried out up to the present according to the frameworks proposed by Alonso et al. (1990) and Kohgo et al. (1993) and have been centered on development and refinement of constitutive equations that consider the effect of matric suction (hereafter referred to as suction). In the case of unsaturated soils, however, it is also necessary to take account of the compressibility and flow of the pore air. During rainfall, earthquakes, or other conditions under which air cannot be sufficiently exhausted or drawn in, changes occur not only in the pore water pressure but also in the pore air pressure. This produces changes in the volume of the pore air itself. This issue has been studied by Kodaka et al. (2006) and Oka et al. (2010), who have described the results of triaxial tests on unsaturated soil under undrained and unexhausted conditions in addition to drained and exhausted conditions. Studies employing numerical analysis have been carried out by Khoei and Mohammadnejad (2011) and by Unno et al. (2013) regarding the governing equations. They compared the results of analysis obtained using a method of coupling the mass conservation law of pore air against those obtained using a second method that assumed the pore air to be at atmospheric pressure always and concluded that it is necessary to take account of the effects of air as in the former method. The above indicates that there is an increasing need for methods of testing and analysis capable of dealing with cases where the pore air pressure varies from atmospheric pressure to complement existing methods of testing and analysis in which the pore air pressure is considered to remain constant.

Based on the above background, numerical computations of triaxial tests were carried out here using a method of analysis for 3-phase systems with air and water being coupled to the soil skeleton. From the standpoint of treating the triaxial test as an initial value/boundary value problem in which the initial conditions and boundary conditions have been clearly defined, the soil-water-air coupled finite deformation analysis code (Noda & Yoshikawa, 2014) developed by the authors has been used in this study to simulate the triaxial tests performed by Kodaka et al. (2006) and
Oka et al. (2010) on unsaturated silt. The authors wish to emphasize the fact that this paper simulates, beginning from a “single initial condition,” the processes of back pressure rise, suction variation, consolidation, and shear, as was in the case of the triaxial tests. The elasto-plastic constitutive equation of soil skeleton mounted on the analysis code (Noda & Yoshikawa, 2014) used here is the SYS Cam-clay model (Asaoka et al., 2002). Since this study focused its attention on the coupling of air, calculations were performed without modifying the constitutive equations to deal with the effects of suction, etc. However, it is demonstrated that simply by employing air coupling it is possible to describe quite well the distinctive features of the mechanical behavior of unsaturated silt under various conditions of exhaust and drainage. Of course, behavior that cannot be described unless the effects of suction are taken into account are also explained expressly in order to point out issues that need to be solved to improve the precision of the analysis code in the future.

2 OUTLINE OF REFERENCE TESTS USING DL CLAY AND CONDITIONS OF ANALYSIS

The reference tests (Kodaka et al., 2006; Oka et al., 2010) are described briefly below. The soil used for the tests was DL clay (specific gravity 2.65), and the specimens were prepared as follows:

i) DL clay, with its water content adjusted to 20%, was used to prepare unsaturated test specimens by static compaction in cylindrical molds. The specimens were 50 mm in diameter and 100 mm in height, with a void ratio of 1.14 and degree of saturation of 46–47%. The suction at the specimen preparation stage was about 20 kPa.

ii) The specimens were placed in the triaxial test apparatus, and the cell pressure was raised to 20 kPa under undrained conditions. The cell pressure and air pressure were then raised simultaneously by 250 kPa.

iii) The water pressure alone was then changed in order to attain the prescribed level of suction, after which the cell pressure alone was increased to 450 kPa, and consolidation was carried out for about 1 day.

iv) Shear tests were performed using the above specimens under (A) drained and exhausted conditions, (B) undrained and unexhausted conditions, and (C) undrained conditions at various controlled levels of air pressure. Since this paper focuses attention on air coupling, only the results of tests (B) and (C), in which the air pressure was varied during shearing and a volume change of the air itself occurred, are described. The results of test (A) are omitted due to a lack of space.

The material constants and initial conditions related to the SYS Cam-clay model (Asaoka et al., 2002) constitutive equation of the soil skeleton are shown in Table 1. For simplicity, anisotropy is not considered in this paper. Since the constitutive equation for saturated soil was used, the material constants and initial conditions that best simulated the results of constant volume, undrained shear tests under controlled air pressures (Section 4), in which the volume constraint conditions were similar to those of the tests on saturated soil, were adopted. Table 2 shows the material constants and initial conditions related to the soil-water characteristics and to the water and air permeabilities. The van Genuchten’s equation (van Genuchten, 1980) was used as the soil-water characteristic equation, and the Mualem’s equation (Mualem, 1976) was used as the coefficients of water and air permeability model. Figure 2 depicts the soil-water characteristic curve plotted using the parameters shown in Table 2. The test results (Kodaka et al., 2006; Oka et al., 2010) that are plotted within the figure are the average values of the degree of saturation at various suction levels. The parameters of the soil-water characteristic were set so that the curve matched the test results as far as possible. The initial values shown in Tables 1 and 2 are those obtained when a cell pressure of 20 kPa was applied after preparing the test specimens. These initial values were used in all simulations, even in cases where the amount of suction or the exhaust/drainage conditions during shear differed. Figure 3 depicts the finite element mesh used for the analysis and the boundary conditions. For simplicity, a 1/4 section of the test specimen was used, assuming up-down symmetry and axial symmetry of the cylindrical specimen and the loading conditions. At the sides of the specimens, the boundary conditions relating to water and air were assumed to be undrained and unexhausted, while the conditions of the upper end were varied according to each stage.

Table 1. Material constants and initial conditions related to the constitutive equation of the soil skeleton.

| Material parameters | Value |
|---------------------|-------|
| Specific volume at $q = 0$ and $p' = 98.1 \text{kPa on NCL}$ | N |
| Critical state constant | M |
| Compression index | $\lambda$ |
| Swelling index | $\kappa$ |
| Poisson’s ratio | $\nu$ |

| Evolution rule parameters | Value |
|---------------------------|-------|
| Degradation index of overconsolidation | $m$ |
| Degradation index of structure | $a$ |
| Degradation index of structure | $c$ |
| Evolution index of rotational hardening | $b$ |
| Limit of rotational hardening | $m_o$ |

| Initial conditions | Value |
|-------------------|-------|
| Degree of structure | $1 / R^*$ |
| Overconsolidation ratio | $1 / R_o$ |
| Void ratio | $e_0$ |
| Stress ratio | $\sigma_0$ |
| Degree of anisotropy | $\phi_0$ |
Fig. 1. Simulated results of undrained constant volume shear tests under air pressure control (determination of the material constants and initial conditions related to the constitutive equation of the soil skeleton).

Table 2. Material constants and initial conditions related to the soil-water characteristics.

| Soil water characteristics                  | Value  |
|--------------------------------------------|--------|
| Maximum degree of saturation %            | 70.0   |
| Minimum degree of saturation %            | 5.00   |
| van Genuchten parameter kPa⁻¹ α            | 0.07   |
| van Genuchten parameter n’                 | 1.6    |
| van Genuchten parameter m’                 | 0.375  |
| Saturated coefficient of water permeability m/sec k’w | 2.0 × 10⁻² |
| Dry coefficient of air permeability m/sec k’a | 1.1 × 10⁻² |
| Initial suction kPa p’i                      | 20.0   |
| Initial degree of saturation % s’i          | 49.7   |

| Physical properties                       | Value  |
|-------------------------------------------|--------|
| Soil particle density g/cm³ ρ               | 2.65   |
| Bulk modulus of water kPa K                | 2.19 × 10⁶ |
| Specific gas constant of air m²/sec/K μ     | 287.04 |
| Absolute temperature K Θ                   | 293.15 |

During shear, the specimens were compressed from the upper end at a constant rate of axial displacement, the axial strain rate being kept constant at 0.5%/min as in the case of the experiments. The results of the calculations are presented here as the apparent behavior of the specimen when it viewed as a single element. The stress values shown refer to the mean skeleton stress, which is derived from the definition of the average soil skeleton stress (Jommi, 2000).

Only the experimental and calculated results at the stage of shearing are described in the sections below. The results at the stages of cell pressure rise, suction variation, and isotropic consolidation are omitted due to space restrictions.

Fig. 2. Soil-water characteristic curve

Fig. 3. Finite element mesh and boundary conditions

Fig. 4. Experimental results (Kodaka et al., 2006; Oka et al., 2010) (left) and calculated results (right) of undrained and unexhausted shear tests.

The experimental results (Kodaka et al., 2006; Oka et al., 2010) and calculated results of triaxial compression tests performed under undrained and unexhausted conditions with constant confining pressure using specimens isotropically consolidated after suction variation are shown in Fig. 4. The deviator stress-axial strain relationship in Fig. 4(a) shows that the strength increases with increasing suction p’i. This is because the skeleton stress paths move to the right for higher values of p’i, as seen in Fig. 4(b). When p’i is large, the degree of saturation is low, and the amount of air is large. The skeleton stress path moves to the right because the presence of air permits volumetric compression of the specimen due to air being much more compressible than water. The volumetric strain-axial strain relationships illustrated in Fig. 4(c) indicate that the experimentally determined volumetric strains are nearly the same for all levels of initial suction, whereas the calculated volumetric strains become large when the suction is large. In addition, although the experimentally obtained deviator stress-axial strain relationship (Fig. 4(a)) shows that the
initial stiffness is larger at higher levels of suction, such behavior was not reproduced in the calculated results. This appears to be due to the effect of suction, which needs to be reflected in the constitutive equations, etc. It was confirmed that this effect of suction appears even under undrained and unexhausted conditions.

4 UNDRAINED SHEAR TESTS WITH AIR PRESSURE CONTROL

Fig. 5. Experimental results (Kodaka et al., 2006) (left) and calculated results (right) of undrained shear tests with air pressure control.

The experimental results of triaxial compression tests under constant confining pressure and undrained conditions on specimens isotropically consolidated after suction application (the suction before shearing being 50 kPa) while the air pressure was being controlled at various levels are illustrated in Fig. 5 together with the calculated results. The method of air pressure control was as mentioned in Fig. 5(d), which depicts the pore air pressure-axial strain relationships. Three rates of controlled air pressure increase, i.e. "rapid," "medium," and "gradual" were employed. Tests were also carried out for the case of the specimen volume being maintained constant during shear by suitably controlling the air pressure (this case is denoted as "constant volume" in the above figure). The results obtained in tests under drained and exhausted conditions (denoted as "drained" in the figure) and under undrained and unexhausted conditions (denoted as "undrained") are also shown within the figure.

Looking at the deviator stress-axial strain relationships in Fig. 5(a), the experimental results as well as the calculated results show that there is a softening trend in the order of stronger volume constraint (i.e., in the order "drained," "undrained," "gradual," "medium," "rapid," and "constant volume"). It is seen from Fig. 5(b), which depicts the soil skeleton stress paths, that in the experimental results, softening takes place below the straight line indicated by M=1.23 and that this phenomenon was simulated extremely well by the calculations. Since structure (level of bulkiness) is part of the concept of soil skeleton structure in the SYS Cam-clay model (Asaoka et al., 2002), it is possible to express the softening due to loss of structure, which is accompanied by plastic compression in the stress field below the critical state line. The volumetric stress-axial strain relationships depicted in Fig. 5(c) show that the features of the experimental results were captured well by the calculations. However, attention needs to be paid to the fact that, as has been stated by Oka et al. (2010), experimental values of volumetric strain are reliable for axial strains up to 10% only.

5 CONCLUSIONS AND FUTURE PROSPECTS

Numerical simulation of triaxial tests (Kodaka et al., 2006; Oka et al., 2010) on unsaturated silt specimens under various drainage/exhaust conditions and constant confining pressure were carried out by utilizing the soil-water-air coupled finite deformation analysis code (Noda & Yoshikawa, 2014) incorporating the SYS Cam-clay model (Asaoka et al., 2002) mounted on the constitutive equation of the soil skeleton and making use of the average soil skeleton stress (Jommi, 2000) in the stress equations. Beginning with a "single initial state," the same sequence of processes as those of the tests, i.e., all stages from cell pressure increase and suction variation up to isotropic consolidation and shearing, were calculated. The results showed that it is possible describe many of the mechanical features of unsaturated silt. Simulation of the undrained and unexhausted shear tests indicated that since the mechanical behavior is significantly affected by the compressibility of air, it is possible to describe the differences in the mechanical behavior corresponding...
to the differences in the degree of saturation by simply taking account of the air. In the case of undrained shear tests with air pressure control, simply varying diversely the boundary conditions of the air as in the triaxial tests allowed the calculations to simulate very well the softening behavior that is dependent on the level of volumetric constraint and that can be expressed by the loss of structure (which is a part of the concept of soil skeleton structure expressed by the SYS Cam-clay model (Asaoka et al., 2002)). However, it was also evident that even under undrained and unexhausted conditions, accurate simulation of the stiffness at the initial stages of shear and volumetric strain would also require the constitutive equations, etc., to take account of the effect of suction, as has been suggested in past studies.

Figure 6 is a contour diagram of the specific volume change distributions in the case of the constant volume tests. Although they are test specimens, their internal states appear to be complicated. The constitutive equations used in this study do not take the effects of suction into consideration. When developing analysis codes mounted with more detailed models through studies about constitutive equations that take suction into account or through research about soil-water characteristics with consideration for the effects of hysteresis and the void ratio, it would be necessary to always treat triaxial tests on unsaturated soils as initial value/boundary value problems with clearly defined initial conditions and boundary conditions.

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