Soils and Foundations 2015;55(6):1372–1387

HOSTED BY

ELSEVIER

CrossMark

The Japanese Geotechnical Society

Soils and Foundations

www.sciencedirect.com
journal homepage: www.elsevier.com/locate/sandf

SOILS AND FOUNDATIONS

Effects of air coupling on triaxial shearing behavior of unsaturated silty specimens under constant confining pressure and various drained and exhausted conditions

Takahiro Yoshikawa[a], Toshihiro Noda[b,*], Takeshi Kodaka[c]

[a]Department of Civil Engineering, Nagoya University, Nagoya, Japan
[b]Disaster Mitigation Research Center, Nagoya University, Nagoya, Japan
[c]Department of Civil Engineering, Meijo University, Nagoya, Japan

Received 19 June 2014; received in revised form 23 June 2015; accepted 25 July 2015
Available online 28 November 2015

Abstract

A simulation of triaxial shear tests on unsaturated silty specimens was performed under constant confining pressure and various drained and exhausted conditions starting from a single initial condition and passing through processes of suction variation and isotropic consolidation considering the triaxial test as an initial and boundary value problem. The simulation made use of a soil–water–air coupled finite deformation analysis code incorporating the SYS Cam-clay model as the constitutive equation of the soil skeleton and applying the average soil skeleton stress in the stress equation. The results showed that the coupling effect of the highly compressible air has a significant effect on the mechanical behavior. In addition, the results also explained other behaviors that would have been outside the capability of an analysis model that did not take account of factors other than air coupling such as suction. The authors wish to place special emphasis on the following findings:

(1) For simulation purposes, even using a soil water characteristic curve determined uniquely by the relationship between the degree of saturation and suction, it is still possible to calculate the increase in the degree of saturation for the drained and exhausted shear tests (under constant suction).

(2) A comparison of the experimental and calculated initial stiffnesses, volumetric strains, etc. showed that suction has an inhibiting effect on plastic deformation not only in drained and exhausted, but also in undrained and unexhausted conditions.

(3) For tests in which the volumetric restraint conditions of specimens were varied by controlling the air pressure under undrained conditions, results suggested that an introduction of gas leading to a rise in gas pressure within a highly structured ground may produce a risk of the ground displaying strain softening behavior. In the simulation, it was shown that this softening behavior can be represented in terms of structure decay as described by the SYS Cam-clay model.

Keywords: Soil–water–air coupled analysis; Unsaturated soil; Triaxial test; Initial-boundary-value problem; Finite deformation theory; Constitutive equation; SYS Cam-clay model (**IGC**: D06/E13)

1. Introduction

The difference between an unsaturated and a saturated soil depends on the presence or absence of air. Presence of air in a soil will create surface tension on the pore water, allowing the pore water pressure to remain at values lower than the pore air

*Corresponding author. Tel.: +81 52 789 3833.
E-mail addresses: yoshikawa.takahiro@b.mbox.nagoya-u.ac.jp (T. Yoshikawa), noda@nagoya-u.jp (T. Noda), kodaka@meijo-u.ac.jp (T. Kodaka).

Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2015.10.004
0038-0806/

pressure. This pressure difference is termed matric suction (from here on, "suction"). Since the amount of suction has an effect on the mechanical behavior of unsaturated soils, many studies have focused on suction difference. The Barcelona Basic Model (BBM) developed by Alonso et al. (1990) based on the Modified Cam-clay model (Schofield and Wroth, 1968; Roscoe and Burland, 1968) marked the first attempt to develop a constitutive equation permitting a unified description of the compression and shear behaviors of unsaturated soils. By introducing suction into the yield function, the BBM made it possible to represent such typical mechanical behaviors of unsaturated soils as collapse compression after an absorption of water and the increases produced by suction in pre-consolidation stress, strength and stiffness. Kohgo et al. (1993) not only treated suction as a function of the yield surface but also proposed an effective stress equation that made particular reference to differences in the water retention conditions of soils. In place of suction, there are other constitutive equations include the (effective) saturation degree in the yield function (for example, Tamagnini, 2004; Ohno et al., 2007; Zhang and Ikariya, 2011). However, most of the studies undertaken to date for the development and refinement of constitutive equations have been carried out in the frameworks proposed by Alonso et al. (1990) and/or Kohgo et al. (1993).

In the case of soils that contain air, there is also a need to take account of its flow and high compressibility. In heavy rainfall, earthquakes, or other conditions under which air cannot be sufficiently expelled or adsorbed, changes of pressure occur not only in the pore water but also in the pore air, causing variations in the volume of the air itself, and hence also in that of the soil pores. The considerable effect that a change in volume can have on the mechanical behavior of a soil is more than evident from the differences in behavior found with saturated soils under drained and undrained shear conditions, and for this reason it is important to give due attention to the air properties of permeability and high compressibility. Kodaka et al. (2006) have demonstrated the importance of this with their results from triaxial tests on unsaturated silty specimens under undrained and unexhausted conditions as well as drained and exhausted ones. Additional details relevant to these tests have been described in the work of Oka et al. (2010). As for research based on numerical analysis, Khoei and Mohammadnejad (2011) in their analyses of results for seismic responses in dams, compared the reliability of governing equations using pore air pressure estimates (1) obtained from the equation of the law of conservation of mass applied to the pore air and (2), without use of the equation, based on a simple assumption that the pore air is always at atmospheric pressure. Their study showed that the method (1) is necessary for a reliable prediction of the behavior of unsaturated soils. Unno et al. (2013) used a simulation of undrained and unexhausted cyclic triaxial tests to investigate how the results of analyses are affected by the use of the same two methods, (1) and (2), and also a third method, (3), in which it is assumed that the pore air pressure is equal to the pore water pressure. They concluded that the method (2), the assumption that the pore air pressure remains constant at atmospheric pressure, is unable to replicate the experimental results because it overestimates the compressibility of the air. As can be seen, 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 as distinct from the methods used up to now that have regarded pore air pressure as remaining constant.

With the above background in mind, this paper reports a numerical simulation of triaxial tests performed in a 3-phase system in which analyses of the soil skeleton are coupled not only with the states of the pore water but also, as in assumption (1) above, with those of the pore air. In order to investigate the effect of the air at the test specimen level, albeit from a more elemental standpoint, the triaxial test is treated as an initial and boundary value problem in which the initial and boundary conditions are clearly specified. On the basis of this, a series of drained/exhausted and undrained/unexhausted triaxial compression tests on unsaturated silty specimens (Kodaka et al., 2006; Oka et al., 2010) is simulated. In addition, details are also provided of triaxial tests in which the air pressure was controlled at various levels under an undrained condition (Kodaka et al., 2006) and simulation results for these controlled-pressure tests are presented.

Two of the points made above should be emphasized. The first is that the triaxial test is treated as the solution for an initial and boundary value problem by a soil–water–air coupled analysis differently from several studies in which a model test was treated (for example, Xiong et al., 2014; Matsumaru and Uzuoka, 2014). The second is that the processes of back pressure increase, suction variation, consolidation, and shear were all simulated beginning from a "single initial condition" as would be the case in a real experiment. The analysis code used was the soil–water–air coupled finite deformation analysis code (Noda and Yoshikawa, 2015) developed by the authors and the constitutive equation of the soil skeleton mounted on it is the SYS Cam-clay model (Asaoka et al., 2002). Since the main focus here is on the air coupled effects, no account is taken in the calculations to the alterations occurring in the constitutive equation due to suction or in the soil water characteristic curve due to factors such as hysteresis or void ratio variation. It is shown, however, that this reference to the air coupling alone is sufficient to allow a good description of the distinctive features of the mechanical behavior of the unsaturated silt under the various drained and exhausted conditions. Of course, it is frankly conceded that there are also behaviors that cannot be described without recourse to the effects of suction. But this merely highlights one future issue that needs to be resolved in order to improve further on the precision of the analysis code.

2. Outline of the method of analysis (Noda and Yoshikawa, 2015)

The analysis code is based on a $\boldsymbol{u}$–p^{w}–p^{a} formulation. For the spatial discretization of the equation of motion, the finite element method is employed, while for the soil skeleton–water–air coupled equations, extensions of the physical models