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Research Paper

Explicit formulation of at-rest coefficient and its role in calibrating elasto-plastic models for unsaturated soils

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ABSTRACT

Normally, suction-controlled triaxial tests are used to characterize soil behavior in constitutive modeling of unsaturated soils. However, this type of tests requires sophisticated equipment and is time-consuming. This has been one of the major obstacles to the implementation and dissemination of unsaturated soil mechanics beyond the research context.

In contrast to suction-controlled triaxial tests, the suction-controlled oedometer test requires simpler equipment and a shorter testing period. Oedometer tests represent the at-rest earth pressure (K_0) condition, which is an important stress state in any simulation. The major disadvantage of the oedometer test is that its lateral stress is controlled by the condition of zero lateral strain and remains unknown during the testing process. At present, no well-established, simple, and objective methods are available that take advantage of oedometer test results for constitutive modeling purposes.

This paper derives an explicit formulation of the at-rest coefficient for unsaturated soils and develops an optimization approach for simple and objective identification of material parameters in elasto-plastic models for unsaturated soils using the results from suction-controlled oedometer tests. This is achieved by combining a modified state surface approach (MSSA), recently proposed to model the elasto-plastic behavior of unsaturated soils, with the quasi-Newton method to simultaneously calibrate all parameters governing virgin behavior in elasto-plastic models. The Barcelona Basic Model (BBM) is used to demonstrate the application of the proposed explicit formulation and calibration method. Results predicted using obtained parameters are compared with laboratory test results for the same stress paths in order to evaluate the simplicity and objectivity of the proposed method.

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1. Introduction

Unsaturated soils often exhibit irrecoverable (elasto-plastic) behavior when subjected to loading and wetting or drying cycles. Alonso et al. [1] proposed the first elasto-plastic model for unsaturated soils, which later was called the Barcelona Basic Model (BBM) [2]. The BBM successfully explained many features of unsaturated soils and received extensive acceptance. Since the 1990s, many elasto-plastic models have been developed [3–26,64–70]. Review of elasto-plastic models for unsaturated soils can be found in several references [7,10,27–29].

At present, most researchers use the results from suction-controlled triaxial tests to develop and calibrate their models. However, suction-controlled triaxial tests require sophisticated and therefore costly testing equipment to accurately measure the volume change of unsaturated soil specimens during triaxial testing. Often a double-cell system proposed by Bishop and Donald [30] is used, although other methods are also available. Such a system typically costs more than $120,000. Due to the requirement for relatively large specimen heights and low unsaturated permeability, it is time-consuming to perform a suction-controlled triaxial test. A single constant suction triaxial test often takes one to three months, and it is not uncommon to spend two to three years in full characterization of the elasto-plastic behavior of an unsaturated soil (e.g., [31–33]). As a result, implementation of the principles of unsaturated soil mechanics cannot be justified for routine engineering projects. This has been one of the major obstacles to the

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Nomenclature

C_1, C_2, C_3, and C'	constants
e	void ratio
e_0	initial void ratio
e^e	void ratio constitutive surface in the elastic zone
G	shear modulus
l	parameter that relates cohesion and suction
M	slope of theoretical critical state line
k	parameter describing the increase in cohesion with suction
$N(s)$	specific volume for $p = p^c$
p	$\sigma_m - u_a$ = net mean stress
p_{at}	atmospheric pressure
p^c	reference stress
σ_m	total mean stress
p_0	apparent preconsolidation pressure at a certain suction
p_0^*	preconsolidation pressure in saturated conditions
$q = \sigma_1 - \sigma_3$	deviatoric stress
r	parameter controlling the slope of the virgin compression line
s	$u_a - u_w$ = soil suction
s_0	maximum historical suction applied to the soil
u_a	air pressure
u_w	water pressure
v	specific volume
α	parameter that controls the non-associated flow rule
β	parameter that controls the slope of the virgin compression line for $s \neq 0$
$d\varepsilon_q^e$	deviatoric strain increment
ε_v	volumetric strain
$d\varepsilon_v$	volumetric strain increment
ε_v^e	elastic strain
ε_v^p	plastic strain
ε_q	deviatoric strain
ε_v^p	plastic volumetric strain
ε_{vp}^p	plastic volumetric strain generated by a mean net stress increment
ε_{vs}^p	plastic volumetric strain generated by a suction increment
κ	slope of the unloading-reloading line associated with the mean net stress
κ_s	slope of the unloading-reloading line associated with soil suction
$\lambda(s)$	slope of the virgin expansion line associated with the mean net stress
λ_s	slope of the virgin compression line associated with soil suction
$\lambda(s)$	slope of the virgin compression line associated with the mean net stress for $s \neq 0$
$\lambda(0)$	slope of the virgin compression line associated with the mean net stress for $s = 0$
$d\varepsilon_v^e$	elastic volumetric strain
$d\varepsilon_v$	total volumetric strain, $d\varepsilon_v = \frac{dV_v}{V_0} = \frac{de}{1+e_0}$
$d\varepsilon_v^p$	plastic volumetric strain
$d\theta^p$	irrecoverable "plastic" volumetric water content variation
X	a vector containing the model parameters
$F(X)$	objective function, measures the difference between the theoretical and experimental results
m and n	lower and upper limits of X
w_i	weight of each experimental data point
v_i	experimental specific volume at virgin states for a stress status of (p_i, s_i)
$\hat{v}_i$	predicted specific volume at virgin states for a stress status of (p_i, s_i)

application and dissemination of unsaturated soil mechanics beyond the research context.

The oedometer test is classical in soil mechanics to simulate the in-situ at-rest stress state for obtaining parameters for the calculation of consolidation settlements and for assessing the stress history of soils. Compared with suction-controlled triaxial tests, the suction-controlled oedometer test requires much simpler equipment and is much easier to perform [34–37]. Since no lateral deformation occurs, the volume change of the soil specimen can be directly derived from the vertical displacement, which can be easily measured using a linear variable differential transformer (LVDT). Due to the smaller thickness of the specimen (normally around 25 mm), the time needed for completing a test is much less. For single-sided drainage, the oedometer test is expected to be at least nine times more efficient than the suction-controlled triaxial test (which typically has heights of 75 mm or more).

The major disadvantage of the oedometer test is that its lateral stress is controlled by the condition of zero lateral strain and remains unknown during the testing process. At present, there are no well-established, simple, and objective methods for directly using the results from oedometer tests for constitutive modeling purposes. Most researchers only use oedometer test results to validate their models, not to develop constitutive models. Since the oedometer test represents the at-rest earth pressure K_0 (defined as the ratio of horizontal to vertical stress) condition, which is an important stress state in any simulation (e.g., [54]), it is highly desirable to have an approach that takes advantage of oedometer test results at the model development stage.

This paper derives an explicit formulation of the at-rest coefficient for unsaturated soils. Based on the explicit formulation, a method is developed to analyze the results from suction-controlled (constant suction) oedometer tests for constitutive modeling purposes. This is achieved by combining a modified state surface approach (MSSA), recently proposed to model the elasto-plastic behavior of unsaturated soils, with the quasi-Newton method to simultaneously calibrate all parameters governing virgin behavior in elasto-plastic models. The BBM is used as an example to demonstrate the role of the proposed explicit formulation in model calibration, although the proposed method can be used for calibrating other constitutive models as well. Results predicted using obtained parameters are compared with laboratory test results for the same stress paths to evaluate the simplicity and objectivity of the proposed method.

2. Bacerlona basic model: an overview

Although since the 1990s, many elasto-plastic models have been developed for unsaturated soil, Sheng et al. [21] concluded that, from the elasto-plastic theory point of view, all existing elasto-plastic models have a similar framework, and can be considered variants of the BBM. Gens et al. [29] concluded that most existing elasto-plastic models have kept the same core of basic assumptions as the BBM, and sought to improve some of the BBM's limitations. The BBM is one of the most widely used elasto-plastic models for unsaturated soils [38]. This is the reason why in this