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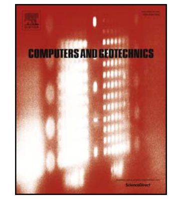

Research Paper

Including degree of capillary saturation into constitutive modelling of unsaturated soils

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ABSTRACT

The degree of saturation (S) of soil can be separated into two components: the degree of capillary saturation (S') that is based on the capillary water and the degree of adsorptive saturation (S'') that is based on the adsorbed water. This paper discusses the role of the degree of capillary saturation (S') in modelling the coupled hydro-mechanical behaviour of unsaturated soils and proposes a new constitutive model for unsaturated soils by using the degree of capillary saturation (S') and the effective inter-particle stress (σ_{ij}'). An enhanced hydraulic model is introduced to describe the hydraulic hysteresis and hydro-mechanical interaction in terms of the degree of capillary saturation (S'). In the proposed constitutive model, the shear strength, yield stress and deformation behaviour of unsaturated soils are governed directly by the above two constitutive variables, namely σ_{ij}' and S'. To be in line with the existing finite element frameworks for unsaturated soils, the proposed model is eventually generalised to constitutive functions consisting of only primary variables such as the net stress (σ_{ij}), suction (s) and degree of saturation (S). The typical performance of the model for simulating the characteristic trends of unsaturated soil behaviour is discussed in several different scenarios. The model is then validated against a variety of experimental data in the literature, and the results show that a reasonable agreement can be obtained using this new constitutive model.

1. Introduction

A number of publications on unsaturated soils concern what constitutive variables are suitable for modelling unsaturated soil behaviour including both shear strength and deformation [21,48,33]. The first constitutive variable used for unsaturated soil modelling is the Bishop effective stress [6], which was extended from Terzaghi's effective stress for saturated soils. The formulation of Bishop's effective stress (σ_{ij}') can be written as follows

$$\sigma_{ij}' = \sigma_{ij} + \chi s\delta_{ij} = \overline{\sigma}_{ij} - u_{\mathrm{a}} + \chi(u_{\mathrm{a}} - u_{\mathrm{w}})\delta_{ij} \tag{1}$$

where σ_{ij} is the net stress with $\sigma_{ij} = \overline{\sigma}_{ij} - u_{\mathrm{a}}$, $\overline{\sigma}_{ij}$ is the total stress, u_{a} is the pore air pressure, χ is the effective stress parameter, s is the suction ($s = u_{\mathrm{a}} - u_{\mathrm{w}}$), u_{w} is the pore water pressure and δ_{ij} is the Kronecker delta. Bishop's effective stress (σ_{ij}') is also known as the average skeleton stress [27]. Eq. (1) is widely accepted in unsaturated soil mechanics but parameter χ, initially set to be the degree of saturation (S), is still controversial. Jennings and Burland [26] pointed out the single use of Bishop's effective stress is unable to capture the deformation behaviour of unsaturated soils (the loading collapse behaviour particularly). Khalili et al. [30] reviewed the application of effective stress principle to unsaturated soils and refuted the argument of Jennings and Burland [26] against Bishop's effective stress. However, the recent comparative study by Sheng et al. [53] indicated that the employment of Bishop's effective stress if $\chi = S$ leads to a large overestimation of shear strength of unsaturated clayey soils, in particular, when the suction is relatively high. In addition, Khalili and Zargarbashi [31] also addressed that the degree of saturation may not be a suitable candidate as the effective stress parameter for quantifying the contribution of suction to the effective stress of the solid skeleton including the hysteresis effects due to wetting and drying.

Fredlund et al. [13] suggested the unsaturated behaviour can be modelled by two independent constitutive variables $\{\sigma_{ij}, s\}$, i.e. net stress and suction. Based on the above argument, the first comprehensive elastoplastic model capable of describing loading collapse behaviour of unsaturated soils was proposed by Alonso et al. [1], which is well known as the Barcelona Basic Model (BBM). In the BBM, the slope of normally consolidated line (NCL) is assumed to be a function of suction and the yield surface is also presented in the space of net stress and suction. Detailed discussion on the BBM can be found in Wheeler et al. [59]. Inspired by the BBM, numerous models [61,9,22,49], were

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proposed by adopting $\{\sigma_{ij}, s\}$ as constitutive variables to interpret the observed mechanical behaviour of unsaturated soils.

By acknowledging that the effect of hydraulic components on unsaturated soil behaviour cannot be ignored, Bishop's effective stress was revisited [27,7,29,30] and the role of degree of saturation was highlighted again with introducing the water retention curve (WRC) into unsaturated soil modelling. In consequence, many constitutive models were proposed by using Bishop's effective stress and suction $\{\sigma'_{ij}, s\}$ as constitutive variables [7,37,50,44,54,55]. Aside from its role in Bishop's effective stress, suction is also used as a state variable to define either the slope or the initial point of the NCL for unsaturated soils in the above models. Like $\{\sigma'_{ij}, s\}$, some other similar alternatives include $\{\sigma'_{ij}, s^*\}$ and $\{\sigma'_{ij}, \xi\}$, where s^* is the revised suction [24,60] and ξ is a function combining suction and degree of saturation [19,25].

It is recently argued that $\{\sigma'_{ij}, S\}$ is a better option than $\{\sigma'_{ij}, s\}$ in describing the non-linear compression behaviour, non-linear loading collapse behaviour and fully hydro-mechanical interaction [56,65,72,73,16,5]. By this new approach, the degree of saturation (S) (or the effective degree of saturation, S_e) rather than the suction is employed to define the hydro-mechanical state of an unsaturated soil, as an additional variable to Bishop's effective stress.

Apart from the selection of a suitable pair of constitutive variables, the other common issue in unsaturated soil modelling is the determination of effective stress parameter χ, if Bishop's effective stress is involved. The most classical option for χ is the degree of saturation (S) [6,7,60,56,18], but recently using the effective degree of saturation (S_e) as the effective stress parameter is getting more and more popular [15,2,39,72,17,70]. The effective degree of saturation (S_e) takes a constant residual degree of saturation out of the degree of saturation (S), based on the argument that the residual degree of saturation does not affect the constitutive behaviour of unsaturated soils. The pore water is divided into two categories: the water in macropores and that in micropores. The effective degree of saturation represents the degree of saturation related to the macropore water, and the residual degree of saturation stands for the degree of saturation related to the micropore water. The macropore water is assumed to be affected by the applied suction and mechanical load, but micropore water is treated as a constant [2]. In such a circumstance, the effective degree of saturation (S_e) can directly be calculated from the degree of saturation (S) since the residual degree of saturation is a constant (i.e., namely the residual degree of saturation is treated as a parameter other than a variable). However, the concept of residual degree of saturation is questionable, for example, it conflicts with the evidence that the degree of saturation should be zero when soil is oven dried because the oven-dry state is used as the benchmark for zero water content [11,14]. More importantly, dividing the pore water factitiously into the macropore water and the micropore water overlooks the two different mechanisms to retain the water in the soil.

The research on surface forces indicates, for a given suction (or chemical potential), water is retained in soil pores due to two different processes (i.e., capillary and adsorptive processes) and consequently contributes differently to the shear strength and deformation behaviour of the soil [34,68]. Therefore, compared with macropore/micropore water, the pore water retained in soil pores can more reasonably be divided into different categories according to its retaining mechanisms, namely the capillary water and the adsorbed water [11,57,38]. The volume of the adsorbed water in the soil is not a constant but governed by the chemical potential following the adsorptive mechanism. Although both directly contribute to the degree of saturation, only the capillary water contributes to the mechanical responses of unsaturated soils (such as strength and deformation). Because the capillary water exists among soil particles and the pressure of capillary water affects the contact stress among soil particles. Therefore, the stress carried by the capillary water is classified as an inter-particle stress. Compared with the capillary water, the contribution from the adsorbed water to the shear strength and deformation of a soil is very limited [4,39,17,34,68]. In principle, this is because adsorbed water wraps the surface of each soil particle. The pressure of the adsorbed water should be more likely treated as the internal pressure inside of a particle-surface water system and thus almost does not affect the contact stress among the systems. Thus, the stress carried by the adsorbed water is reasonably treated as an intra-particle stress.

The objective of this study is to establish a constitutive model for unsaturated soils by acknowledging that (i) pore water consists of capillary water and adsorbed water, and (ii) they contribute very differently to the constitutive behaviour of unsaturated soils. In this study, the degree of capillary saturation (S') is selected as the basic constitutive variable to highlight that only the capillary water affects the strength and deformation of unsaturated soils. Specifically, on one aspect, the degree of capillary saturation is used for the effective stress parameter, i.e., $\chi = S'$, and the effective stress when $\chi = S'$ is referred to as the effective inter-particle stress (σ'_{ij}) to emphasize that the intra-particle stress associated with the adsorbed water pressure has been ruled out. On the other aspect, the slope of the NCLs is also a function of the degree of capillary saturation, i.e., $\lambda = \lambda(S')$ to underline that the mechanical state of an unsaturated soil is related to the capillary water only. It is important to note that, although the constitutive relationship is initially established in the space of $\{\sigma'_{ij}, S'\}$, it can be eventually generalised in the space of three primary variables $\{\sigma_{ij}, s, S\}$ that is in accordance with variables adopted for finite element methods [51,67].

This paper is organised as follows. An enhanced hydraulic model for the variation of the degree of capillary saturation is presented, with highlighting hysteresis and mechanical shift. Through the enhanced hydraulic model, the inherent relationship among degree of saturation (S), degree of capillary saturation (S') and degree of adsorptive saturation (S'') can be found for given stress and suction paths. The calibration method and the effect of each hydraulic parameter on the enhanced hydraulic model are discussed then. The normal compression lines (NCLs) are introduced in the space of specific volume (v), degree of capillary saturation (S') and effective inter-particle stress (σ'_{ij}), and then the loading collapse surface is also derived in the plane of degree of capillary saturation (S') and effective inter-particle stress (σ'_{ij}). The calibration of the additional mechanical parameter is presented and the parametric study on the additional mechanical parameter is also performed in both constant suction (CS) and constant water (CW) scenarios. Then the constitutive relationship is established first in the space of $\{\sigma'_{ij}, S'\}$ and then generalised in the space of $\{\sigma_{ij}, s, S\}$. Experimental results from Cunningham et al. [10] and Li et al. [36] are employed to validate the proposed constitutive model. Several different experimental datasets are involved throughout the paper because no single experimental data dataset available can be used to calibrate and validate all aspects of the comprehensive model developed in this paper.

2. Constitutive equations

2.1. Hydraulic equations

2.1.1. Enhanced hydraulic model considering hysteresis and mechanical shift

Pore space geometry is traditionally simplified as a 'bundle of cylindrical capillaries' (BCC), such as in Mualem [41]. However, the BCC model only considers the cylindrical capillarity and ignore the role of specific surface area and liquid films adsorbed on the surface. Recently, Tuller et al. [57] suggested a new pore geometry model to facilitate the consideration of both adsorption and capillary processes. The new pore geometry model consists of a series of capillary pores (either angular or circular) to represent capillary-dominated processes and a series of slit-shaped spaces to represent adsorption-dominated phenomena. The theoretical water retention curve considering both capillarity and adsorption was firstly proposed by Or and Tuller [42]. However, the equation of the theoretical water retention curve derived by Or and Tuller [42] is very complicated and difficult for practical applications.