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Research Paper

A water retention model accounting for the hysteresis induced by hydraulic and mechanical wetting-drying cycles

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ABSTRACT

A comprehensive description of the water retention behaviour of unsaturated soils requires accounting for the hysteresis caused by hydraulic and mechanical wetting-drying cycles. A hysteretic water retention model is proposed by introducing the liquid-solid contact angle to account for the dependency of the response on non-monotonic changes in suction and void ratio. The proposed model reproduces main drying and wetting surfaces and also nonlinear scanning curves during hydraulic or mechanical loading. Experimental tests and numerical simulations were carried out to study the water retention behaviour of a clayey silt. The model simulations captured the experimental results well.

1. Introduction

The behaviour of unsaturated soils and its modelling are more complicated than those of saturated soils, not only because of the complex role of suction but also due to the fact that the relationship between suction and water content depends on several factors. Among them are the structure and porosity of the soil, which descend from its history, and the direction of the hydraulic path – i.e. wetting or drying. An accurate description of water retention is needed for modelling both two-phase flow and mechanical behaviour, and advanced constitutive models explicitly require information related to water content or degree of saturation (e.g. [21,41,40,33,6,52]).

In the present paper, some existing water retention models are briefly discussed before introducing the concept of contact angle hysteresis which describes changes in the contractile skin (the air-water interface formed between soil particles) during wetting-drying and compression-swelling processes. The concept is implemented to develop a water retention model (WRM) which accounts for the hysteresis induced by changes in soil suction (hydraulic wetting-drying) and changes in soil volume (compression-swelling or mechanical wetting-drying).

Experimental tests were carried out to study the water retention behaviour of a clayey silt during hydraulic and mechanical wetting-drying cycles, and the proposed model was employed to predict the experimental data. The experimental results showed a hysteretic behaviour which was well predicted by the model.

1.1. Soil water retention

The relationship between the amount of water stored within pores of unsaturated soils and suction (s) is known as the water retention curve. Different variables are used to describe the quantity of stored water: e.g. gravimetric water content (w), volumetric water content (Θ), degree of saturation (S_r). First proposals of water retention models (e.g. [17,3,4,46,12]) introduced a unique relationship between the amount of stored water (represented by S_r in this paper) and suction, which can be written as:

$$S_r = \Gamma(s) \tag{1}$$

where Γ is a function relating suction to degree of saturation.

These models are simple and empirical but well applicable expressions which allow the model to fit the experimental data with a limited number of parameters. However, the hysteresis associated with drying and wetting of the soil ascertained that there is no unique soil water retention curve. There are numbers of transitional drying and wetting scanning curves bounded between the main drying and main wetting curves. These scanning curves become asymptotic to the main bounding curves.

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Numerous models have been developed accounting for the hysteresis of soil water retention using the one-dimensional elasto-plastic framework in a way that the elastic (scanning) domain is bounded by the main curves, which act as yielding limits in the $S_r - s$ plane (e.g. [48,49,41,30,39]). Recent water retention models have been formulated with differential equations, which provide more capability to capture smooth nonlinear scanning curves without distinction between elastic and plastic zones (e.g. [24,31,25,54,45]). These models may be formulated in a rate form as below,

$$\dot{S}_r = \Gamma(s, \dot{s}) \tag{2}$$

Furthermore, the water retention behaviour depends also on mechanical variables (e.g. soil density or void ratio, volumetric strain, stress variable). Any change in these variables influences the amount of stored water, particularly in the low suction range, resulting mainly in changes in the air-entry value of the drying water retention curve or the air-occlusion value of the wetting water retention curve (e.g. [47,34,29,27,44]). Models have been proposed accounting for these effects (e.g. [14,40,30,42,28,53]); they can be written as:

$$S_r = \Gamma(s, \xi) \tag{3}$$

where ξ is a mechanical variable.

The mechanical dependency and the hysteresis of water retention indicated that the main drying and main wetting curves of deformable soils can be characterized by two surfaces in the $S_r - s - \xi$ space, namely, the main drying surface and the main wetting surface (e.g. [43,36,13]), as shown in Fig. 1, where the mechanical variable is assumed to be the void ratio (e). The intersection of the main drying and wetting surfaces with the $S_r - e$ plane at constant suction represents the main compression curve and the main swelling curve, respectively. On the other hand, the intersections with the $S_r - s$ plane at constant void ratio represent the main wetting curve and the main drying curve.

Gallipoli et al. [14] proposed a model which accounts for the mechanical dependency of the water retention behaviour by explicitly incorporating the effect of void ratio on the air-entry value, in which the degree of saturation can be computed depending on suction and void ratio,

$$S_r = \Gamma(s, e) = \left[1 + (ae^{\alpha}s)^n\right]^{-m} \tag{4}$$

where n and m are parameters of the Van Genuchten [46] model, and a and α are two additional parameters which introduce the dependency of the air-entry value on the void ratio. Therefore, the model can reproduce the main drying or main wetting curve (depending on which water retention curve the van Genuchten parameters are calibrated) and also the main compression curve. This results in the definition of a water retention surface in the $S_r - s - e$ space, which allows the model to predict irreversible changes of degree of saturation due to irreversible changes of void ratio. However, this model is not appropriate for problems involving significant hysteresis since the latter is not taken into account.

A general rate form expression for a WRM, which allows to account for mechanical dependency and hydraulic hysteresis, is:

$$\dot{S}_r = \Gamma(s, \dot{s}, \xi) \tag{5}$$

According to the most existing rate form WRMs, the scanning curves can be predicted by a data-fitting methodology, using the interpolation between the projections of suction or degree of saturation on the main drying and main wetting branches. These water retention models have been commonly derived by applying the capillary law to the cumulative distribution function of soil pores while the contact angle was assumed to be constant. Zhou [51] proposed a contact angle-dependent WRM interpreting the hydraulic hysteresis in terms of contact angle hysteresis. The proposed contact angle-dependent WRM also adopted the Van Genuchten [46] model to reproduce the main drying curve, whereas scanning and main wetting curves were predicted depending on the variation of contact angle. The model employs a single function including two incremental terms. The first one describes the direct

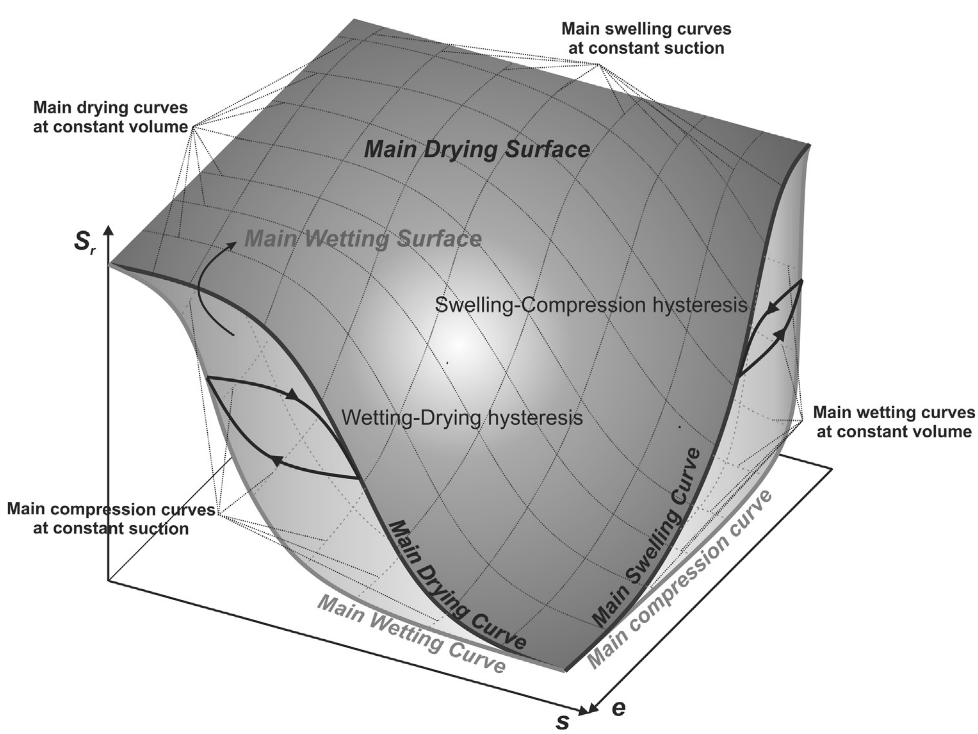

Fig. 1. Main drying and wetting surfaces and hysteresis induced by hydraulic and mechanical wetting-drying cycles.