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The use of soil water retention curve models in analyzing slope stability in differently structured soils

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ABSTRACT

This study analyzes whether and at what rate the parameterization of the Soil Water Retention Curve (SWRC) affects the analysis of shallow slope stability for differently structured unsaturated soils. Advanced empirical or physically-based equations of SWRCs have been proposed in literature to describe soil systems characterized by the so-called bimodal porous domain. In unsaturated soils, SWRC affects the stability assessment in two ways. It influences the resistance properties in terms of shear strengths, which depend on the soil water suction; and it affects the hydrological process modeling (e.g. infiltration) directly influencing soil moisture patterns and indirectly influencing slope stability. Most of the formulations proposed to predict the shear strength of unsaturated soils require the definition of an χ parameter that tunes the contribution of the suction effect to a rate proportional to the saturation conditions. In this study, a set of experiments was carried out in order to analyze both the mechanical and hydrological effects of SWRC on slope stability. First, three SWRC models were calibrated on different soil textures. Then, slope stability analyses were carried out on a synthetic hillslope supposed to be characterized alternatively and homogenously by the different soils. The factor of safety (FS) of the slope was computed first, at given states of hydrological conditions (i.e., fixed soil moisture), and then at dynamic hydrological conditions simulated by solving the 1D Richards's equation. Two different formulations of the χ parameter were also used. Finally, a sensitivity analysis of the SWRC models and the χ formulations for slope stability were evaluated for different slope angles and mechanical properties.

The results indicated that for clayey (and bimodal) soils, changes in FS obtained with different SWRC models can be significant, especially at soil moisture values close to the residual zone. In sandy (and unimodal) soils, the choice of χ formulations can be more important. The variation of FS decreases as the slope angle increases or the friction angle decreases.

1. Introduction

The role of water infiltration in causing slope instability has been analyzed and reviewed in many scientific studies (Montgomery and Dietrich, 1994; Iverson, 2000; Mukhlisin et al., 2011; Arnone et al., 2011, 2016a). Rainwater infiltration into unsaturated soil increases the degree of saturation, hence affecting the shear strength properties and the probability of slope failure. It has been widely proved that shear strength properties change with soil water suction (i.e. negative pore water pressure or matric suction) in unsaturated soils; therefore, accuracy in predicting the relationship between soil water content and soil water matric suction, parameterized by the Soil Water Retention Curve (SWRC), has significant effects on the slope stability analysis (Mukhlisin et al., 2011).

Several semi-empirical functions have been proposed in recent years to predict the shear strength of unsaturated soils using the soil water characteristic curve (Vanapalli and Fredlund, 2000; Sheng et al., 2011). Most of these are based on the Bishop (1955) approach, which proposed a shear strength equation derived from the extension of Terzaghi's principle of effective stress for saturated soils.

Bishop's equation introduces the soil suction term as stress variables and a parameter χ, which tunes the contribution of the suction effect in a rate proportional to the saturation conditions (Lepore et al., 2013). For many years, the use of Bishop's approach was abandoned due to inconsistencies observed in cases of soil compression (Alonso and Cardoso, 2010) and the difficulties in evaluating the χ parameter, which is affected by different factors (e.g., type of soil, wetting-drying history, void ratio and the structure of the soil) (Rojas et al., 2011; Sheng et al., 2011). Many authors have proposed different relationships to define

Abbreviations: AIC, Akaike Information Criterion; C(i), cohesion configuration (i); DE, Dexter et al. (2008) model; F(i), fiction angle configuration (i); FS, Factor of Safety; L(i), slope angle configuration (i); MAE, Mean Absolute Error; PSD, Pore Space Distribution; RMSE, Root Mean Square Error; RS, Ross and Smettem (1993) model; S(i), soil texture (i); SWRC, Soil Water Retention Curve; vG, van Genuchten (1980) model.

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the value of χ (Oberg and Sallfors, 1997; Vanapalli et al., 1996; Rojas, 2008a,b), which have been either empirical or derived from the SWRC models. The most popular of these relationships makes use of one or more parameters of SWRC as the air entry value and/or the residual water content. The problem of a proper evaluation of Bishop's χ parameter is still under discussion.

Therefore, to predict unsaturated soil properties, correctly reproducing the water content/suction description of natural soils is crucial in order to reduce further uncertainties. Several empirical and physically-based equations have been proposed to describe the SWRC (Gardner, 1958; Brooks and Corey, 1964; Campbell, 1974; van Genuchten, 1980; Fredlund and Xing, 1994; Kosugi, 1996; Kutílek, 2004; Groenevelt and Grant, 2004). All of these models assume that the soil is characterized by a unimodal distribution of the soil pore size, i.e. a single continuous pore domain.

Most current approaches to the parameterization of the complex porous media conceptualize the porous space as portioned into two subsystems: one is related to macropores or non-capillary pores, while the other comprises the capillary pores distinguished into intra-aggregate pores inside the aggregates (matrix porosity) and inter-aggregate pores between the aggregates (structural porosity). This concept gives rise to the so-called bimodal domain (Dexter et al., 2008). Many studies have discussed the implications that the nature of the bimodal porous systems might have on the description of the retention curve. Some authors (Othmer et al., 1991; Durner, 1992; Ross and Smettem, 1993, Coppola, 2000; Kutílek and Jendele, 2008; Dexter et al., 2008; Omuto, 2009; Romano et al., 2011) have proposed a methodological approach to quantify both the distribution of the pores in soil aggregates and the degree of interaction between the two domains (macro and micro- pores) and its preferential flow in macropores. Models that use a bimodal approach that are based in the overlap of two unimodal curves derived from various types of unimodal SWRCs have been observed to produce a good description of the retention curve. Starting from the bimodal lognormal model developed by Romano et al. (2011) and from the suction stress framework of Lu and Likos (2006), Ciervo et al. (2015) proposed an analytical approach to describe the bimodal suction stress and its effects on shear strength. The approach was tested on data collected from literature, and it provided a discrepancy between the model descriptions and the experimental data collected in higher fine soils.

In this study, we investigate how the characterization of the SWRC of differently structured unsaturated soils may affect the analysis of shallow landslides. Two bimodal models describing the soil water retention curve have been used; one is empirical and the other is physically-based. The Ross and Smettem (1993) formulation has been selected among the empirical models, since it is derived from the most widely-used van Genuchten (1980) model; whereas, the Dexter et al. (2008) model has been chosen from the physically based models, due to its user-friendly equation in which all the terms can be related to a distinct physical meaning.

In this context, this study aims to accomplish two main targets: first, (1) calibrating and evaluating the performances of the two bimodal SWRCs (i.e. Ross and Smettem, 1993; Dexter et al., 2008) and the traditional unimodal van Genuchten (1980) model on seven samples representative for seven soil types that differ in terms of structure and texture. Secondly, (2) evaluating the effect of the use of the three SWRCs on slope stability analysis throughout a synthetic case study. For each soil type and SWRC model, the stability conditions of a hypothetical hillslope, with a given geometry and geotechnical properties, have been analyzed using Taylor's (1948) simple infinity slope model, which is suitable to analyze translational slides typical of shallow failures. Two formulations (Oberg and Sallfors, 1997; Vanapalli et al., 1996) of the χ term of Bishop's equation have been used in combination with the SWRCs. Three types of experiments have been carried out on the slope domain using the 1D Richards equation to simulate the infiltration process: (i) analysis at steady hydrological conditions (i.e. at given states of soil moisture) to evaluate the mechanical effects of the combination SWRCs-χ parameterization on slope stability; (ii) sensitivity analysis of the stability condition to the SWRC and χ parameterization at varying mechanical properties and slope geometry (at steady hydrological conditions); (iii) analysis at dynamic hydrological conditions to evaluate first the effects of SWRCs on hydrological modeling and then the effects of the combination SWRCs-χ on slope stability.

2. Methods and materials

2.1. Soil water retention models

Dexter et al. (2008) (hereinafter DE), introduced a double exponential equation with 5 parameters and the water content being expressed in gravimetric terms, w [g g^{-1}]:

$$w = C + A_1 e^{\left(-\frac{h}{h_1}\right)} + A_2 e^{\left(-\frac{h}{h_2}\right)} \tag{1}$$

where h is the soil water suction [cm], (i.e. the opposite of matric potential); C is the residual water content [g g^{-1}] (i.e., the water content as $h \rightarrow \infty$); A_1 is the textural pore space [g g^{-1}]; h_1 is the soil water suction characteristic for displacing water from the textural pores [cm]; A_2 is structural pore space [g g^{-1}]; h_2 is the soil water suction characteristic for displacing water from the structural pores [cm]. Each term of the equation has a physical meaning: the first term represents the residual water content, the second term describes the drainage of the "textural porosity" and the third term describes the drainage of the "structural porosity". Moreover, the function may provide useful information on the structure of the soil that can contribute to the interpretation and prediction of other aspects of the soil's physical behavior, e.g., the compaction that occurs at the expense of structural porosity (Dexter et al., 2008) or the effects of organic matter content and bulk density on textural porosity (Dexter et al., 2008).

van Genuchten (1980) and Ross and Smettem (1993) (hereinafter vG and RS) expressed the water content in terms of effective saturation:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2}$$

where θ_s and θ_r represent the volumetric water content at saturation and the residual water content respectively. The vG model describes the SWRC as follows:

$$S_e = \left[\frac{1}{1 + (\alpha h)^n}\right]^m \tag{3}$$

where α [cm^{-1}] corresponds approximately to the so called "air entry pressure", n [−] and m [−] are curve-fitting parameters.

The RS model is built by assuming the existence of two independent pore space distributions, each of them characterized by its own function of water retention; one is described by a van Genuchten curve, whereas the other (i.e. the macroporosity system) is described through the following equation:

$$S_e = (1 + \alpha h) e^{(-\alpha h)} \tag{4}$$

The linear combination of the two curves leads to the following final retention curve:

$$S_e = \varphi_1 (1 + \alpha_1 h) e^{(-\alpha_1 h)} + \varphi_2 \left[\frac{1}{1 + (\alpha_2 h)^n}\right]^m \text{ with } \quad \varphi_1 + \varphi_2 = 1 \tag{5}$$

where φ_1 and φ_2 are the weights of the total pore space fraction to be attributed to each sub-curve and α_1, α_2, n and m are the fitting parameters.