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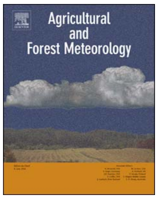

A binary mixing model for characterizing stony-soil water retention

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ABSTRACT

A century of research focused primarily on agricultural soils has largely ignored stony soils, which dominate some forests and are poorly understood in terms of the stone influence on soil hydraulic properties. Motivated by this knowledge gap, we quantified the influence of soil-containing stone fragments on bulk soil hydraulic properties by determining the water retention curve (WRC) of soil, stone and stone-soil mixtures with varied volumetric stone content. The measured WRC for seven different stone types based on their composition showed maximum and minimum saturated water contents of 0.55 $m^3\,m^{-3}$ in pumice and 0.025 $m^3\,m^{-3}$ in fine sandstone, respectively. The stony soil water retention function was measured using the simplified evaporation method. Contrasting scenarios were studied considering a broad range of stone inclusions; (*i*) negligibly porous, (*ii*) significantly porous but less porous than the background soil, (*iii*) more porous than the background soil. An averaging scheme to describe the WRC of stony soil was proposed based on the individual WRC of the background and stone inclusion which was in good agreement with the experimental data. The HYDRUS-3D model was also employed to simulate the evaporation experiment used for the WRC measurements. The model simulations supported the basic assumptions of the proposed averaging scheme.

1. Introduction

Hydraulic properties of unsaturated soils, namely soil water retention characteristic (WRC) and unsaturated hydraulic conductivity, are critical physical aspects to model and study the dynamics of flow and transport in soil (Coile, 1953; Cousin et al., 2003; Elliott et al., 1999; Low, 1954; Sauer and Logsdon, 2002; Schneider et al., 2006; Šimůnek et al., 1998; Yang et al., 2013 e.tc.). Soil hydraulic properties are mainly affected by the pore-size distribution, which is dictated by the soil particle size distribution (Jones and Or, 1998; Sakaki and Smits, 2015). Stone inclusions embedded in a background soil matrix will likewise alter the bulk hydraulic properties as a result of their pore-size distribution. With an emphasis on arable soils, the soil physics literature has largely focused on the properties of the soil matrix (i.e. particles passing through the 2-mm sieve), neglecting the influence of stones and rock fragments which are quite common in non-arable soils.

Soil containing over 35% stones by volume, i.e., soil particles larger than 2 mm, are classified as stony soil (Jahn et al., 2006; Tetegan et al., 2011; 2015a; Hlavacikova et al., 2016). Unlike agricultural soils, most non-arable soils commonly have a significant stone content as a result of their formation process and shallow depth underlain by bedrock (Lv et al., 2017; Novák and Šurda, 2010; Poesen and Lavee, 1994; Stendahl et al., 2009). Surface soils are commonly formed by the weathering of rock such as limestone, sandstone and quartzite, whose occurrence is spatially variable, both laterally and vertically.

As compared to the soil matrix, stones typically have lower water retention capacity and hydraulic conductivity, depending on their formation processes (Ma and Shao, 2008; Ma et al., 2010; Parajuli et al., 2015). The porosity and the density of different rock types are widely varied (Flint and Childs, 1984). For example, the porosity of sandstone may vary an order of magnitude between 0.03 to around 0.35 (Manger, 1963; Parajuli et al., 2016). There are rocks such as pumice, which exhibit porosities greater than 80% that may significantly increase the water holding capacity of the soil (Blonquist et al., 2006; Parajuli et al., 2016) and may augment the water flow through the soil (Coile, 1953; Cousin et al., 2003; Ma et al., 2010). Some studies have shown stone fragments are capable of holding significant amounts of water available to plants (Coile, 1953; Flint and Childs, 1984; Ugolini et al., 1998). Flint and Childs (1984) found that stone fragments contributed an average of 15% to the total available water over the range of 1.6% to 52.1%. Tetegan et al. (2015a,b) reported that the available water content was underestimated by 15% when the hydraulic characteristics of stones were not accounted for and emphasized that stone fragments can store water for root water uptake. Apart from the water retention capacity, the stone fragments can alter the soil water movement by increasing the tortuosity and reducing the available soil-

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volume for the flow (Childs and Flint, 1990; Ma and Shao, 2008; Mehuys et al., 1975). On the other hand the water holding capacity rises with increase in lacunar pore volume between stone-soil interface with increased stone content (Wang et al., 2013).

Several researchers examined the impact of stones on soil hydraulic properties (e.g. Reinhart, 1961; Bouwer and Rice, 1984; Childs and Flint, 1990; Fies et al., 2002; Poesen and Lavee, 1994; Sauer and Logsdon, 2002; Tokunaga et al., 2002, 2003; Cousin et al., 2003; Novák et al., 2011; Boateng et al., 2013; Wang et al., 2013). These studies suggest significant descrepancies in measured and modeled soil water content due to the variability in stone content and the effective volume of stony-soil considered (Al-Yahyai et al., 2006; Coppola et al., 2013). The modelling and measurement of stone content impact on saturated hydraulic conductivity has received greater attention than stony soil water retention (Dunn and Mehuys, 1984; Hlaváčiková et al., 2016; Koltermann and Gorelick, 1995; Lewandowska et al., 2004; Rucker et al., 2005; Zhang and Ward, 2011). A number of studies also focused on the effect of packing density on porosity and overall hydraulic conductivity in stony soil with varying stone shapes and sizes (Kwan et al., 2015; Koltermann and Gorelick 1995; Sakaki and Smits., 2015). However, less attention has been paid to creating a predictive model for the hydraulic properties of stony soils. Very few of the studies focussed primarily on the hydraulic properties of the stones and their impact on the water retention of stony soils (Tetegan et al., 2015b; Wang et al., 2013 Wang et al., 2013). This study is a step toward developing a simple model for estimating the unsaturated hydraulic properties of a soil-stone binary porous medium. The main objective of this paper was to quantify the impact of stone fragments on the WRC using laboratory measurement techniques and numerical modelling. Three different classes of stone inclusions were examined; (*i*) low porosity (fine sandstone), (*ii*) medium porosity, i.e., porosity below the background soil matrix (coarse sandstone), (*iii*) high porosity, i.e., porosity above the background soil matrix (pumice).

2. Theory

The van Genuchten (1980) model is assumed here to continuously represent the discrete WRC data for both the background soils and stone inclusions:

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha h)^n]^{-m} \tag{1}$$

where S [−] is the effective degree of saturation, θ [L^3L^{-3}] is the volumetric water content, h [L] is the matric potential (absolute values are used here for convenience), θ_r and θ_s are the residual and saturated volumetric water contents, respectively, α [L^{-1}] is the scaling parameter and n [−] and m [−] are the shape parameters, assumed to be related as $m = 1-1/n$ (Van Genuchten, 1980). In the following, the volumetric water content (θ) is distinguished between background soil, stone inclusion and soil-stone mixture as θ_{soil}, θ_{stone} and θ_{mix}, respectively. Similarly, other variables and parameters are distinguished between different media with subscripts *soil*, *stone* or *mix*.

Our proposed averaging scheme is based on a correction to the following equation, proposed by Bouwer and Rice (1984):

$$\theta_{mix} = (1 - v)\theta_{soil} \tag{2}$$

where v [L^3L^{-3}] is the volumetric stone content.

Eq. (2) neglects the porosity of stone fragments, in spite of the fact that some types of stone (e.g., coarse sandstone, pumice) exhibit high porosity and water retention capacity (Ma et al., 2010; Novak et al., 2011; Wang et al., 2013). Hence, we here correct Eq. (2) to account for the stone porosity:

$$\theta_{mix} = (1 - v)\theta_{soil} + v\theta_{stone} \tag{3}$$

To solve for the WRC of the soil-stone binary mixture, we assume that the matric potential between the background and inclusions is in equilibrium. This assumption is later evaluated using numerical simulations. Accepting the equilibrium assumption, the WRC of the mixture is obtained using Eq. (3) at any given h:

$$\theta_{mix}(h) = (1 - v)\theta_{soil}(h) + v\theta_{stone}(h) \tag{4}$$

Eq. (4) in conjunction with Eq. (1) can be written in the form of Durner's (1992, 1994) dual-porosity soil WRC:

$$S_{mix} = w_{soil}S_{soil} + w_{stone}S_{stone} = w_{soil}[1 + (\alpha_{soil}h)^{n_{soil}}]^{-m_{soil}} + w_{stone}[1 + (\alpha_{stone}h)^{n_{stone}}]^{-m_{stone}} \tag{5}$$

where the weighting factors for soil and stone fractions, w_{soil} and w_{stone}, can be solved analytically using Eq. (3) at saturation:

$$w_{soil} = \frac{(1 - v)\theta_{s,soil}}{(1 - v)\theta_{s,soil} + v\theta_{s,stone}} \tag{6}$$

$$w_{stone} = \frac{v\theta_{s,stone}}{(1 - v)\theta_{s,soil} + v\theta_{s,stone}} \tag{7}$$

Eq. (5) offers a simple averaging scheme to estimate the WRC of the soil-stone mixture by knowing the individual WRC for soil and stone. Based on the mass balance, the averaging scheme would be physically valid when the soil and stone are in equilibrium (i.e., identical matric potential). Therefore, Eq. (5) is assumed to be applicable to static (i.e. no flow) condition. For the dynamic case, the validity of Eq. (5) will depend on the h distribution within the mixture. The equilibrium assumption during soil evaporation processes will be discussed later.

As discussed in Gerke and van Genuchten (1993), stony soil may behave as a dual porosity medium in which water from the macro-pores drain earlier, at less negative potentials, than from the micro-pores. However, stony soil may contain a significant overlapping pore-domain, described by Gerke and van Genuchten (1996), where both soil and stone concurrently release water from the mixture. Eqs. (5)–(7) provide an analytical approach to the empirical coefficients of the mixture WRC, rather than a regression analysis which requires laborious measurements of the soil-stone mixture WRC for any given volumetric stone content, v.

3. Materials and methods

3.1. Porous materials evaluated

Various types of stone inclusions, including dolostone (DS), limestone (LS), two coarse sandstones (CSS1 and CSS2), two fine sandstones (FSS1 and FSS2) and pumice (PM), embedded in two different background soils, Millville silt loam (sand, 29%; silt, 55%; clay, 16%) and Wedron Silica sand (silica, 99.65%) were studied. The physical properties such as bulk density and saturated water content of these materials are presented in Table 1.

To determine the bulk density of the stone samples, they were submerged in water for 48 h followed by exposure to vacuum (0.85 bar) saturation for 30 min to enhance the release of entrapped air inside the pores. After being submerged in water for another 24 h, the saturated mass of stone samples were obtained. Once the saturated mass was recorded, the stones were placed in an oven at 110 °C for 48 h to obtain the dry mass. The bulk density of each stone sample was computed as:

$$\rho_b = \frac{M_s}{V_t} \tag{8}$$

where ρ_b [ML^{-3}] is the bulk density, M_s [M] is the mass of oven dried sample, and V_t [L^3] is the total volume of the sample. The saturated water content of the stone samples were calculated as:

$$\theta_s = \frac{\rho_b}{\rho_w}\left(\frac{M_{sat} - M_s}{M_s}\right) \tag{9}$$

where M_{sat} [M] is the mass of the vacuum saturated stone sample and ρ_w [ML^{-3}] is the density of water.