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Using the double-exponential water retention equation to determine how soil pore-size distribution is linked to soil texture

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ABSTRACT

The link between soil particle arrangement and pore structures and its role in soil water retention is important. However, it is not completely determined. In this study, based on similarities and synchronizations between the three terms, i.e., residual, matrix, and structural porosities in a double-exponential water retention equation (DE) and the three soil separates (clay, silt and sand), we aimed to explore the link between soil particles and pores and to determine the causes of mono- and bi-modality in DE differential functions. For this purpose, 78 soil samples were selected from the Unsaturated Soil Hydraulic Database with a wide range of soil texture. Results showed that the DE fitted with the measured soil water retention curves well. Soil residual and structural pores could be reasonably predicted with clay and sand contents, respectively, via the derived linear functions. Soil texture reasonably influenced the modality of DE differential functions, particularly in the following situation. (1) When a soil separate (e.g., silt) occupied the absolute majority in soil particle size distribution, the DE differential function may tend to show a mono-peak, whereas the others may tend to be bi-peaked. (2) On the contrary, the matrix peak was significantly influenced by clay content, and the structural peak was greatly affected by sand content. (3) When the sand content was greater than 0.5, the curve of the DE differential function may tend to be bi-peaked, i.e., a high structural peak together with a low matrix peak. Further analyses, e.g., the technologies of X-ray and original SEM are needed to confirm the proposed soil structural model.

1. Introduction

Soil structure has traditionally been considered as one of the dominant attributes of soil quality, which critically influences the hydraulic properties of unsaturated media, such as soil water retention curves (WRCs; Nimmo, 1997). Soil macromorphology and micromorphology are closely linked to soil structure, and they are considered the basis of the explanation about the influence of soil structure on soil hydraulic functions (Kutílek, 2004). Although the processes that relate soil water fluxes to the macro- and micromorphological characteristics of soil structure have been identified (Lin et al., 1999; Vervoort and Cattle, 2003), the quantitative relationships between the morphologic characteristics of soil structure and soil hydraulic functions remain unclear.

In recent years, the soil particle size distribution (PSD) has been widely used to estimate the soil WRC. Arya and Paris (1981) developed a semi-empirical model (i.e., AP) to predict WRCs based on the similarity between shapes of the cumulative PSD and WRC. The AP and the modified AP model (Arya et al., 1999a,b) are most applicable to sandy soils (Hwang and Choi, 2006; Hwang and Powers, 2003). Haverkamp and Parlange (1986) estimated WRCs directly from the PSD data by assuming a lognormal distribution for both PSD and pore size distribution (POD) in sandy soils. Kosugi (1994) applied a three-parameter lognormal distribution function to the PODs of soils and developed a soil water retention model, which was further modified in his work in 1996 to be compatible with the model of Mualem (1976). The two lognormal functions described earlier are applicable to most soils. Moreover, many

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pedo-transfer functions based on soil texture have also been developed to predict WRCs (Botula et al., 2012; Hodnett and Tomasella, 2002; Oliveira et al., 2002).

Symmetrical or asymmetrical relationships may exist between the PSD and the POD of soils. Hwang et al. (2011) defined that the symmetry between PSD and POD means that the shape of POD curve is symmetric with respect to PSD curve. Therefore, POD curve can be superimposed on PSD curve except that the shape of POD is asymmetric to that of the PSD. Some researchers attempt to derive fractal WRC functions based on the symmetry of the relationship and most of their functions can be calculated from the PSD. Tyler and Wheatcraft (1990) introduced a fractal model for WRCs with the Sierpinski carpet model, which provides a theoretical basis for the Brooks and Corey (1964) model. Perrier et al. (1999) and Bird et al. (2000) developed a pore-solid fractal (PSF) model to estimate WRCs from the cumulative PSD data based on the assumption that the soil structure shows self-similarity. In addition, Hwang et al. (2011) modified the PSF model by considering the asymmetry between PSD and POD; the model hypothesizes that the microscopic arrangement of soil particles affects pore geometry and POD.

Many WRC functions, such as that of Rieu and Sposito (1991a,b), may perform well on some data sets, but not on others (e.g., dry range). This problem may arise from the insufficient attention that is paid to textural effects, which may dominate water retention beyond the wet range (Nimmo, 1997). Nimmo (1997) partitioned the pore space into two components, namely, textural and structural to model WRCs. On the basic of the laws of hydrostatics and hydrodynamics, Kutílek (2004) made a detailed classification of soil pores, namely, submicroscopic pores, micro-pores and macro-pores, where micro-pores include matrix pores (textural component) and structural pores. However, the structure of soil pores was mainly influenced by the soil solid phase. Moreover, how the soil separates (i.e., clay, silt and sand) affect these different soil pores is still unclear.

Dexter et al. (2008a) suggested that the compound particles hierarchy has three levels: groups of primary particles comprising micro-aggregates, groups of micro-aggregates comprising aggregates, and groups of aggregates comprising bulk soil. Every level of particles has a corresponding level of pores whose radii increase with the radii of particles. Accordingly, a pore space can be considered in terms of the void ratio (e_{total}), which consists of residual pores (e_{residual}), matrix pores (e_{matrix}), structural pores ($e_{\text{structural}}$), and macro-pores (e_{macro}). It is expressed as follows:

$$e_{\text{total}} = e_{\text{residual}} + e_{\text{matrix}} + e_{\text{structural}} + e_{\text{macro}} \quad (1)$$

For normal water retention experiments, only e_{matrix} and $e_{\text{structural}}$ are considered, and the segregation of pore space into these two categories produces what are called bi-modal PSDs (Dexter et al., 2008a; Omuto, 2009). The double-exponential water retention equation (DE) may then be expressed as follows:

$$w = C + A_1 e^{(-h/h_1)} + A_2 e^{(-h/h_2)} \quad (2)$$

where$w$ is soil volumetric water content; C is residual porosity i.e., residual water content defined as the water fraction that remains in the soil as the applied suction increases toward infinity (the asymptote of the equation, Dexter et al., 2008a); A_1 and A_2 are matrix and structural porosity, respectively; h_1 and h_2 are the characteristic pore suctions at which the matrix and structural pore spaces, respectively, are empty. Therefore, the second and third terms in Eq. (2) represent the variation in matrix and structural pore space with changing pore suction. DE not only provides a good fit to water retention data, but also accounts for how soil bulk density increases at the expense of structural porosity (Dexter et al., 2008a). Additionally, DE has been used to study the influence of the complex organic carbon on the smallest soil pores (residual plus textural) (Dexter et al., 2008b). The saturated hydraulic conductivity (Dexter and Richard, 2009a) and the optimum water content for tillage (Dexter and Richard, 2009b) have also been studied.

Interestingly, the DE partitions the corresponding soil pores into three components. Precise definitions are presented. The pore of C is so small that it may not be characterized in standard water retention experiments, which usually stop at the suction of 15,000 cm for WRC and not toward infinity.A_1 is the pore space among individual soil mineral particles. A_2 is the pore space among the micro-aggregates and among incipient aggregates. However, these definitions are predefined empirically. Moreover, a minor confirmation exists in terms of the physical meanings of DE parameters.

The differential function of WRC is related to the POD function or pore capillary pressure distribution function (Kosugi, 1994). Soil POD can be reflected by the mono-modality, bi-modality or even tri-modality (Dexter and Richard, 2009,b; Dexter et al., 2008a; Kutílek, 2004; Kutílek et al., 2006). However, the causes for either the mono- or bi-modality of DE differential function are poorly understood. We speculate that the various DE differential functions, i.e., mono- or bi-modality, can be explained by using the soil texture and whether or not the three soil pore types established by the DE can be linked to the soil separates (i.e., clay, silt, and sand). Based on soil samples with a wide range of soil textures selected from UNSODA, we aimed (i) to explore the relationships between the three soil separates and the three soil porosities (i.e., residual, matrix, and structural porosities) based on DE; (ii) to use soil texture explaining the different modalities of DE differential curves.

2. Theory

2.1. Pore classification by soil texture

In this study, we mainly focused on the packing pattern of soil particles. We considered that the packing pattern of soil aggregates be similar with that of soil particles. We also assumed that soils are formed naturally and have no artificial compaction. Pore spaces can be understood well when the soil structure is considered a hierarchy of compound particles (Dexter, 1988). Accordingly, the idea of pore classification based on soil texture emerged from the observed similarities between the three parameters$C$, A_1, and A_2 of the DE (i.e., residual, textural, and structural pores) and the three

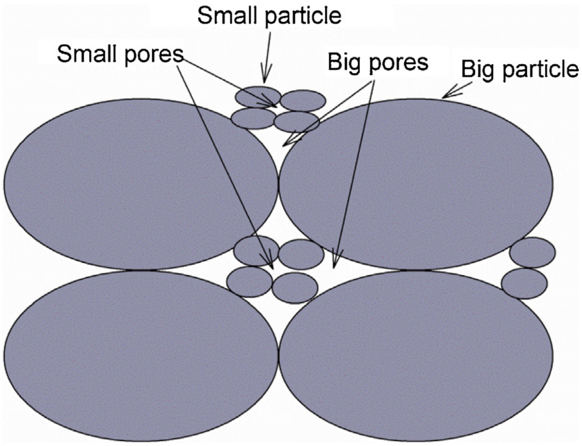

Fig. 1. Packing pattern of soil particles, where the mean size of the pores around particles is assumed to increase progressively with the particle size.