Improved Description of the Hydraulic Properties of Unsaturated Structured Media Near Saturation

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Abstract

Dual-porosity and dual-permeability models for preferential flow in unsaturated structured media (macroporous soils, fractured rock) generally assume that the medium consists of two interacting pore regions, one associated with the macropore or fracture network, and one with micropores inside soil aggregates or rock matrix blocks. A simple but effective approximation of preferential flow results when a single Richards equation is still used in an equivalent continuum approach, but with composite (bimodal type) hydraulic conductivity curves, rather than a single unimodal curve used in most traditional analyses. Field data indicate that the macropore conductivity is generally about one order of magnitude larger than the matrix conductivity at saturation. Neural-network analysis of the UNSODA unsaturated soil hydraulic database revealed a similar difference between the macropore and matrix saturated hydraulic conductivities. Further analysis of the database shows that a piece-wise log-linear function can be used for the macropore hydraulic conductivity between pressure heads of 0 and -40 cm. Results significantly improve the description of the hydraulic properties of structured field soils.

Introduction

This paper focuses on the problem of preferential flow, a major challenge when dealing with flow and contaminant transport in the vadose zone. Preferential flow is caused by a broad range of processes. In structured or macroporous soils water may move through interaggregate pores, decayed root channels, earthworm burrows, and drying cracks. Similar processes occur in unsaturated fractured rock where water may move preferentially through fractures, thus bypassing much of the rock matrix.

Process-based descriptions of preferential flow generally are based on dual-porosity or dual-permeability models which assume that the soil consists of two interacting pore regions, one associated with the macropore or fracture network, and one with micropores inside soil aggregates or rock matrix blocks. Different formulations arise depending upon how water and/or solute movement in the micropore region is modeled, and how water and solutes in the micropore (matrix) and macropore (fracture) regions are allowed to interact.

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Application of dual-porosity or dual-permeability models requires estimates of the hydraulic properties of the fracture pore network, the matrix region, or some composite of these. Dual-permeability models typically contain two water retention functions, one for the matrix and one for the fracture pore system, and two or three conductivity functions in terms of their local pressure heads, h, i.e., $K_f(h_f)$for the fracture network, $K_m(h_m)$ for the matrix, and possibly a separate conductivity function $K_a(h_a)$ for the fracture/matrix interface (e.g., Gerke and van Genuchten, 1993). Of these functions, K_f is determined primarily by the structure of the fracture pore system (i.e., the size, geometry and continuity of the fractures, and possibly the presence of fracture fillings). Similarly, K_m is determined by the hydraulic properties of single matrix blocks, and the degree of hydraulic contact between adjoining matrix blocks during unsaturated flow.

A simple but still effective approximation of flow in structured media results when a single Richards equation is used in an equivalent continuum approach, but with composite (bimodal type) hydraulic conductivity curves rather than a single unimodal curve used in most traditional analyses of variably-saturated flow. Measurements of the composite (fracture plus matrix) hydraulic properties are greatly facilitated by the use of tension infiltrometers. An advantage of tension infiltrometer methods is that negative soil water pressures at the soil-infiltrometer interface can be maintained very close to zero, and that they can be decreased in small increments to yield well-defined conductivity functions near saturation (e.g., Mohanty et al., 1997). In several studies the composite hydraulic properties of structured soils and rocks have been modeled using sums of two or more van Genuchten-Mualem type functions or similar formulations (e.g., Peters and Klavetter, 1988; Durner, 1994; Mohanty et al., 1997).

Hydraulic Property Description Near Saturation

Evidence from field measurements suggests that the macropore conductivity of soils generally is about one order of magnitude larger than the matrix conductivity at saturation. We revisited this finding, as well as the general shape of the unsaturated conductivity function near saturation, using a detailed neural network analysis of the UNSODA unsaturated soil hydraulic database (Leij et al., 1996; Nemes et al., 2001; www.ussl.ars.usda.gov/models/unsoda.htm). Our analysis also addressed the issue of second-order continuity of the soil water retention curve $\theta(h)$ at h=0. Second-order continuity is not satisfied when the exponent n in the soil hydraulic model of van Genuchten (1980) becomes less than 2. The discontinuity in the second derivative of $\theta(h)$ may lead to extremely nonlinear $K(h)$ functions for fine-textured (clay) soils, especially when n becomes less than about 1.1 (thus approaching its lower limit of n=1 when the van Genuchten-Mualem formulation is used). Following Vogel et al. (2000), we used a slightly modified hydraulic model that incorporates a small air entry pressure (h_s) into the water retention curve (referred to by Vogel et al. as the minimum capillary height). This modification only minimally affects the water retention curve, but avoids numerical instabilities in simulations when n becomes less than about 1.1 or 1.2. A recent analysis (Schaap and van Genuchten, 2004) of the UNSODA database showed that the air-entry value of the fracture hydraulic conductivity should be about - 4 cm.

The model of Vogel et al. (2000) was further modified to account for the effects of soil structure. For this purpose we first determined the matrix saturated hydraulic conductivity K_{ms}, which should be much smaller than the measured saturated (matrix plus fracture) soil hydraulic conductivity, K_s. The matrix saturated conductivity may be viewed as a parameter that is extrapolated from unsaturated conductivity data associated with mostly soil textural (matrix) properties. The soil structural part of the conductivity function (associated with the fractures and macropores) in the near-saturation range was analyzed in terms of scaled conductivity residuals as follows

$$R(h) = \frac{\log K(h) - \log K_m(h)}{\log K_s - \log K_m(h)} \tag{1}$$

where $K_m(h)$ is the matrix conductivity function modified according to Vogel et al. (2000) using an air-entry value of -4 cm. Eq. (1) shows that $R(h)$ varies between 0 in the dry range when the effects of macroporosity are no longer present, to 1.0 when the medium is saturated (h=0).

Hydraulic Conductivity Optimization Results

The residuals $R(h)$ of Eq. (1) were analyzed using 235 UNSODA data sets that had at least six θ-h pairs and at least five K-h pairs. Results indicate that $R(h)$ decreases from 1.0 at h=0 cm to 0 at approximately h=-40 cm. The data revealed a relatively sharp decrease in R near saturation and a slower decrease afterwards. A two-element piecewise linear function was used to describe this pattern, with R=0 at h=-40, a change in slope at -4 cm and R=1 at h=0 cm. The change in slope was purposely located at -4 cm to be consistent with the second-order continuity modification of the van Genuchten-Mualem model, as found earlier. A least-squares analysis of the residuals produced the following approximation for $R(h)$:

$$R(h) = \begin{cases} 0 & h < \text{-40 cm} \\ 0.2778 + 0.00694h & -40 \le h < \text{-4 cm} \\ 1 + 0.1875h & -4 \le h \le 0 \text{ cm} \end{cases} \tag{2}$$

Given Eq. (2), the conductivity function now applicable to all pressure heads (matrix and fracture regions) is given by Eq.(1), which can be rearranged to give

$$K(h) = \left(\frac{K_s}{K_m(h)} \right)^{R(h)} K_m(h) \tag{3}$$

We refer to Schaap and van Genuchten (2004) for a detailed analysis and discussion of Eqs. (2) and (3).

Equation (3) was next fitted to all available hydraulic conductivity data in the UNSODA database for the purpose of comparing the fitted matrix saturated conductivities, K_{ms}, with independently measured (fracture plus matrix) saturated conductivities, K_s. This analysis also allowed adjustment of the tortuosity factor L in the soil hydraulic equations of van Genuchten (1980) and Vogel et al. (2000). The ratio of measured (K_s) and extrapolated (K_{ms}) values was found to be larger than those obtained earlier by Schaap and Leij (2000), mostly because the micropore (matrix) and macropore (fracture) contributions to the overall conductivity function were now analyzed independently in terms of Eqs. (2) and (3). The average Root-Mean-Square Error ($\mathrm{RMSE_K}$) of the fitted log hydraulic conductivity data using Eq. (3) with fitted K_{ms} and L values was found to be 0.261, which is substantially lower that the average $\mathrm{RMSE_K}$ value (1.301) of the original van Genuchten model with fitted K_{ms} (but with L fixed at 0.5), and also lower when L was allowed to vary ($\mathrm{RMSE_K}$=0.410). The very low $\mathrm{RMSE_K}$ for Eqs. (2) and (3) reflects the substantially better description of unsaturated conductivity data we obtained with this model in the near-saturated region. Also, as opposed to previous van Genuchten-Mualem type formulations with and without fitted K_{ms} and L values, Eqs. (2) and (3) were found to produce very small systematic errors across the entire pressure range between 0 and -150 m.

We further found that the average fitted $\mathrm{RMSE_W}$ values associated with water retention data differed only marginally between the original and modified approaches. This shows that it is possible to immediately use the original van Genuchten retention parameters instead of needing to fit the more complicated retention model of Vogel et al. (2000) to the data. However, it is still necessary to use the modified retention model in calculations of variably-saturated flow in structured media.

Concluding Remarks

Our analysis of the UNSODA unsaturated soil hydraulic database shows that a piece-wise log-linear function can be used to represent the soil macropore contribution to the overall hydraulic conductivity function, $K(h)$. While the macropore contribution is most significant between pressure heads 0 and -4 cm, its influence on the conductivity function was found to extend to pressure heads as low as -40 cm. The analysis leads to Eq. (3) for $K(h)$, with $R(h)$ as defined by Eq. (2). We emphasize that these equations define a composite hydraulic conductivity model that lumps the contributions of the matrix and the fractures into one equation. When used in conjunction with the traditional Richards equation, the resulting formulation is unable to distinguish between flow in the matrix and the fractures. The model hence still generates a uniform moisture front, and as such cannot reproduce non-uniform moisture distributions typical of preferential flow. Dual-porosity or dual-permeability models are required to generate such non-uniform flow. Still, deconvolution of the bimodal conductivity functions discussed in this paper may well provide useful guidance to estimating separate matrix and fracture conductivities for use in such dual-permeability flow models.

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