ARTICLE IN PRESS

Journal of Hydrology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

A mathematically continuous model for describing the hydraulic properties of unsaturated porous media over the entire range of matric suctions

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ARTICLE INFO

Article history:
Received 17 May 2016
Received in revised form 21 June 2016
Accepted 29 July 2016
Available online xxxx
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Rao S. Govindaraju, Associate Editor

Keywords:
Soil hydraulic model
Film flow
Unsaturated porous media
Bimodal model

ABSTRACT

Recent studies suggest that water flow in unsaturated porous media extends beyond the commonly known capillary-driven regime into the film regime. There is a need to develop the unsaturated hydraulic properties over the entire range of matric suctions to capture both flow regimes. In this study, Fredlund and Xing model is modified to represent the soil water retention curve from saturation to oven dryness. The new function is mathematically differentiable. The hydraulic conductivity function is composed of the capillary-driven term and film associated term, which is easy to apply. The new model has capacity to represent the bimodal hydraulic properties that are often present in structured and aggregated soils. Testing with the published data of sixteen soils shows good performance for both the water retention curve and the hydraulic conductivity function. For most soils, the new model results in a better agreement with observations than a published model. The result also indicates a possibility to improve the previously published film-associated hydraulic conductivity function.

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1. Introduction

The unsaturated zone supports terrestrial ecosystems. It lies between surface and groundwater systems, influencing groundwater recharge and quality. Thus modeling water flow and solute transport in the unsaturated zone is always an important research subject in hydrological and ecological studies. Solutions to the Richards' (1931) equation, the most widely used model for simulating water flow and associated solute transport in variably saturated media, require the soil water retention curve (SWRC) $h(\theta)$ and the hydraulic conductivity curve $K(h)$.

The commonly used SWRC functions (e.g., Brooks and Corey, 1964; van Genuchten, 1980) and soil hydraulic conductivity functions (e.g., Mualem, 1976a) are based on the capillary theory (Mualem, 1976a; Tuller and Or, 2001). This theory conceptualizes pore space into a bundle of cylindrical capillaries (Millington and Quirk, 1961; Mualem, 1976a). Water is supposed to move only when the capillary pendular rings are continuous in the pores (Tokunaga, 2009), with an assumption that the meniscus of water is axially symmetric or nearly so (Orr et al., 1975; Bear et al., 2011). The water content at the stage with broken pendular rings is defined as the residual water content (θ_r), representing the moisture beyond the capillary influence. This water is assumed to be hydraulically immobile according to the capillary theory.

However, previous studies have found that the conventional SWRCs and soil hydraulic conductivity functions often do not accurately simulate flow processes that occur under conditions of low soil water contents (e.g., Rossi and Nimmo, 1994; Silva and Grifoll, 2007). Water moving along thin liquid films on the particle surfaces can be significant under dry conditions (Li and Wardlaw, 1986; Lenormand, 1990; Toledo et al., 1990; Tuller et al., 1999; Tuller and Or, 2001; Wang et al., 2013), which is, however, neglected in the commonly used soil hydraulic models (Lebeau and Konrad, 2010). The impact from three-dimensional pore network (e.g., pore connectivity and air entrapment) further complicates unsaturated water flow modeling, which is not considered here.

To describe the soil hydraulic properties from saturation to oven dryness, one needs to extend the soil hydraulic models from the capillary-dominated suctions to film-dominated suction range.

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http://dx.doi.org/10.1016/j.jhydrol.2016.07.046
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Please cite this article in press as: Wang, Y., et al. A mathematically continuous model for describing the hydraulic properties of unsaturated porous media over the entire range of matric suctions. J. Hydrol. (2016), http://dx.doi.org/10.1016/j.jhydrol.2016.07.046

Nomenclature

Notation

A	the specific perimeter per unit area of the porous media (L L^{-2})
b	the parameter vector used for optimization
α	fitted parameter (L^{-1})
β	capillary model parameter
$C(h)$	correction function in the Fredlund and Xing (1994) model
c	scaling factor (=0.01)
dh/dx	the matric suction gradient
e	is Euler's number (the e constant)
f	film thickness (L)
f_r	film thickness at S_r (L)
$f(S)$, $f(1)$ and $f(y)$	the integrated functions of the capillary model
$F(y)$	the integrated part of the capillary model in the EMFX model
$F_{VG}(y)$	the integrated part of the capillary model in the VG model
$\Gamma(h)$	correction function in the EMFX model
$\Phi(b)$	objective function for optimization
g	the acceleration due to gravity (L T^{-2})
θ	volumetric water content (L^3 L^{-3})
θ_r	residual water content (L^3 L^{-3})
θ_f	water content associated with the film force (L^3 L^{-3})
θ_s	saturated water content (L^3 L^{-3})
$\widehat{\theta}_i$	model estimated water content (L^3 L^{-3})
h	matric suction (L)
h_r	matric suction corresponding to the residual water content (L)
h_0	matric suction where water content is zero (L)
h_a	the critical matric suction in the PDI model, equals $1/\alpha$ (L)
$h(S)$	matric suction as a function of S
k	capillary model parameter
K	the total hydraulic conductivity (L T^{-1})
K_c	capillary conductivity (L T^{-1})
K_f	film conductivity (L T^{-1})
$K_f(S)$	film conductivity as a function of saturation (L T^{-1})
K_f^r	film conductivity at S_r (L T^{-1})
$\widehat{K}_i$	model estimated conductivity values (L T^{-1})
K_s	saturated hydraulic conductivity (L T^{-1})
l	capillary model parameter
l_1	fitted parameter
λ	grain diameter (L)
m	fitted parameter
n	fitted parameter
n_K	the number of conductivity data used for optimization
n_θ	the number of retention data used for optimization
μ	viscosity of the fluid (M L^{-1} T^{-1})
$\Pi(h)$	the unscaled capillary saturation in the VG model
Π_0	the capillary saturation at the suction of h_0 in the VG model
Q_c	the specific volumetric flux associated with the capillary force (L T^{-1})
Q_f	the specific volumetric flux associated with the film force (L T^{-1})
ρ	density of the fluid (M L^{-3})
RMSE$_\theta$	root mean squared error for water content
RMSE$_{logKr}$	root mean squared error for log-scale conductivity
S	saturation degree
S_c	the effective saturation where the capillary force dominates
S_r	the saturation degree at the residual water content
S_f	the film saturation degree
τ	exponent in the film conductivity model
v_f	the film thickness averaged film velocity (L T^{-1})
w	weight factor for the conductivity in the PDI model
w_θ	weight for the water content
w_k	weight for the conductivity data
X_m	scaling factor for the film water retention curve in the PDI model
y	variable used for deriving the capillary conductivity, equals $S^{1/m}$
δ	surface tension (N L^{-1})
SWRC	soil water retention curve
FX model	the model developed by Fredlund and Xing (1994)
EMFX model	the proposed model as an extension and modification of the FX model
PDI model	the model developed by Peters (2013) and improved by Iden and Durner (2014)
VG model	the model developed by van Genuchten (1980)

Depending whether the van der Waals forces or the electrical double-layer forces are the dominant contribution to film thickness, two hydraulic conductivity models were developed to simulate film flow by Tuller and Or (2001) and Tokunaga (2009), respectively. The model proposed by Tuller and Or (2001) accounts for both capillary and film forces. This model must be used in conjunction with the water retention model of Or and Tuller (1999), which often fails to fit experimental data in the intermediate saturation range (Lebeau and Konrad, 2010). Additionally, the electrical double-layer force is considered more important at the intermediate values of matric potential (Tokunaga, 2011). By combining an existing capillary conductivity model (e.g., van Genuchten (1980) model) with Tokunaga (2009) film model that accounts for electrical double-layer forces, a series of models have been developed to describe the soil hydraulic conductivity from saturation to oven dryness (Lebeau and Konrad, 2010; Zhang, 2011; Peters, 2013). Two problems exist in these models. First, the film conductivity model presented by Tokunaga (2009) relies on the smooth sphere grain assumption, its validation for different soils needs to be examined. Secondly, for the SWRCs, these models often have the "mathematical discontinuity" problem (Iden and Durner, 2014). This problem results from that the water content is divided into the capillary and film components. The SWRCs that account for film flow (e.g., Campbell and Shiozawa (1992) model) are not differentiable over the entire range of suctions. This can lead to a numerical problem (Iden and Durner, 2014). A smoothing strategy may solve this problem, but it makes the model mathematically more complex.

Fredlund and Xing (1994) adapted a different approach. They describe the SWRC from saturation to oven dryness without partitioning water into the capillary and adsorptive components, so the equation is differentiable over the entire matric suction range. However, there is no closed-form solution for the hydraulic conductivity function, and film flow contribution is not considered.

In this paper, a modification of Fredlund and Xing (1994) model is provided to describe the SWRC over the suction range from saturation to oven dryness. The model is mathematically continuous and easy to use. Based on the modified model, an approximately

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