Advances in Water Resources 65 (2014) 1–8

Contents lists available at ScienceDirect

Advances in Water Resources

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

Multiple pixel-scale soil water retention curves quantified by neutron radiography

M. Kang [a,b,*], E. Perfect [a], C.L. Cheng [a,e], H.Z. Bilheux [b], J. Lee [c], J. Horita [d], J.M. Warren [e]

[a] Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN, USA
[b] Chemical and Engineering Materials Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA
[c] Department of Biosystems Engineering and Soil Science, University of Tennessee, Knoxville, TN, USA
[d] Department of Geosciences, Texas Tech University, Lubbock, TX, USA
[e] Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

ARTICLE INFO

Article history:
Received 12 June 2013
Received in revised form 29 October 2013
Accepted 22 December 2013
Available online 8 January 2014

Keywords:
Point water retention curves
Neutron radiography
Quantification

ABSTRACT

The soil water retention function is needed for modeling multiphase flow in porous media. Traditional techniques for measuring the soil water retention function, such as the hanging water column or pressure cell methods, yield average water retention data which have to be modeled using inverse procedures to extract relevant point parameters. In this study, we have developed a technique for directly measuring multiple point (pixel-scale) water retention curves for a repacked sand material using 2-D neutron radiography. Neutron radiographic images were obtained under quasi-equilibrium conditions at nine imposed basal matric potentials during monotonic drying of Flint sand at the High Flux Isotope Reactor (HFIR) Cold Guide (CG) 1D beamline at Oak Ridge National Laboratory. All of the images were normalized with respect to an image of the oven dry sand column. Volumetric water contents were computed on a pixel by pixel basis using an empirical calibration equation after taking into account beam hardening and geometric corrections. Corresponding matric potentials were calculated from the imposed basal matric potential and pixel elevations. Volumetric water content and matric potential data pairs corresponding to 120 selected pixels were used to construct 120 point water retention curves. Each curve was fitted to the Brooks and Corey equation using segmented non-linear regression in SAS. A 98.5% convergence rate was achieved resulting in 115 estimates of the four Brooks and Corey parameters. A single Brooks and Corey point water retention function was constructed for Flint sand using the median values of these parameter estimates. This curve corresponded closely with the point Brooks and Corey function inversely extracted from the average water retention data using TrueCell. Forward numerical simulations performed using HYDRUS 1-D showed that the cumulative outflows predicted using the point Brooks and Corey functions from both the direct (neutron radiography) and inverse (TrueCell) methods were in good agreement with independent measurements of cumulative outflow determined with a transducer. Our results indicate that neutron radiography can be used to quantify the point water retention curve of homogeneous mineral particles. Further research will be needed to extend this approach to more heterogeneous porous media.

1. Introduction

Experimental techniques such as the hanging water column [1] and pressure cell apparatus [2] have been used to measure the water retention curve of soil. The data obtained with these methods correspond to the average volumetric water content for the entire soil column rather than the water content at a physical point. The resulting average water retention function has been assumed to be applicable to any physical point in a homogeneous porous medium when the column height is less than a few cm [3]. However, this assumption can be highly inaccurate for coarse-grained materials with low air entry values, tall columns, and/or fluids with low interfacial tensions because the capillary pressure varies with height within the porous medium. As a result, the volumetric water content at any point can deviate significantly from the measured average water content [4–6]. Thus, the use of average water retention data without correction can lead to inaccurate estimation of the hydraulic properties of variably-saturated porous media [7].

To improve prediction of unsaturated hydraulic properties, various computational procedures have been developed to extract the point water retention function from the measured average water retention function. Liu and Dane [5,8] developed an inverse

* Corresponding author at: Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN, USA. Tel.: +1 865 264 2685.
E-mail address: mkang9@utk.edu (M. Kang).

0309-1708/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.advwatres.2013.12.004

computational procedure and a FORTRAN program to account for variations in matric potential and the volumetric fluid content with column height. TrueCell [9], a Windows interface based on Liu and Dane's [8] FORTRAN program, was made available by this group and is widely used to extract point Brooks and Corey [10] function parameters from the average water retention curve. Schroth et al. [11] developed a numerical inversion procedure to obtain corrected parameters of the van Genuchten [12] equation to account for column height by subdividing the sample into a set of horizontal layers. Peters and Durner [13] also used a numerical integration method to take into account the nonlinearity of the vertical water content distribution in a soil column. Cropper et al. [14] employed a similar approach to inversely estimate point parameters for both the Brooks and Corey and van Genuchten equations from steady-state centrifugation data.

It should be noted that the above "extraction" methods are only as good as the underlying models used to represent the water retention curve and drainage process. Direct measurements of the point water retention curve are needed to provide model inputs and to evaluate the performance of these inverse procedures. Sakaki and Illangasekare [6] successfully compared Brooks and Corey parameters obtained using TrueCell with those estimated from data obtained by time domain reflectometry (TDR) at the midpoint of sample height in nine columns of sandy materials. Gamma beam attenuation [4], magnetic resonance imaging (MRI) [15], and X-ray computed tomography (CT) [16] have also been used to directly determine the water content distribution and point retention curves in porous media.

Neutron imaging is a particularly powerful tool for measuring soil water due to its transparency to heavy elements and high sensitivity to the hydrogen in water. Neutron imaging was first applied to soil in the 1970's when Wilson et al. [17] and Lewis and Krinitzsky [18] compared neutron radiographic images of soil with those determined using X-ray units. Since then neutron imaging has been employed to study both the statics [19–24] and dynamics [25–35] of soil water, either in two dimensions (radiography) or three dimensions (tomography). Most neutron imaging studies of soil water have employed thermal neutrons. D_2O is sometimes substituted for H_2O (e.g. [36]) because it attenuates neutrons ~7x less than normal water (H_2O), allowing for the use of thicker samples.

Neutron imaging has previously been employed to determine both average and point soil hydraulic properties under quasi-equilibrium and multi-step outflow conditions. Papafotiou et al. [36] successfully quantified the 3-D distribution of water in structured porous media after two successive drainage steps and tested the ability of neutron and synchrotron tomography to determine average hydraulic properties using numerical simulations. Schaap et al. [37] employed neutron tomography to map temporal changes in the water content distribution of an artificial heterogeneous medium during two drainage-wetting cycles. Vasin et al. [38] obtained average drainage curves for columns of coarse and fine sand, as well as for two heterogeneous sand columns comprised of these two sands packed in random and periodic grid arrangements, using neutron computed tomography. Deinert et al. [20] and Tumlinson et al. [22] extracted point water retention curves from single images of the quasi-equilibrium vertical distribution of water within sand columns acquired using neutron radiography and neutron computed tomography, respectively.

In our previous studies [24,39] we quantified average volumetric water contents and the hysteresis of average soil water retention curves using neutron radiography. Volumetric water contents from neutron radiography were obtained by calibration and showed good agreement with independent experimental data. There were no statistical differences between the neutron imaging and hanging water column methods in terms of parameter estimates describing the average soil water retention curves. In this study, we employed neutron radiography to map out the spatial distributions of water during a monotonic drainage cycle and determine multiple point (pixel-scale) soil water retention functions at different locations within a single soil column.

The main objectives of this research were to: (i) directly measure multiple point (pixel-scale) soil water retention curves using neutron radiography; (ii) compare the directly measured curves with the point water retention curve calculated by inverse modeling of the average water retention data using TrueCell; and (iii) compare cumulative outflows numerically simulated with HYDRUS 1-D [40] based on the Brooks and Corey [10] parameter estimates from the direct measurements and the inverse modeling with independent outflow data measured with a transducer.

2. Materials and methods

2.1. Hanging water column set-up

Flint sand, with grain diameters ranging from 0.11 to 0.60 mm and a median grain diameter of 0.56 mm, was used as the homogeneous porous medium (Flint #13, U.S. Silica Company, Berkeley Springs, WV). This material is mainly composed of quartz (99.8%) and has a particle density of 2.65 g cm^{-3} [41]. The saturated hydraulic conductivity of Flint sand, measured using the constant-head method implemented without a water tank [42], was determined to be $1.66 \pm 0.32 \times 10^{-4}$ m s^{-1}.

The hanging water column setup consisted of a cylindrical Al container (inner diameter = 2.56 cm, height = 10 cm) connected with Tygon tubing via an outlet at its base to a burette filled with distilled water. A pressure transducer (PX409USB, Omega®, Manchester, UK) was attached to the burette and recorded water level changes in the burette every second. The bottom of the Al container was covered with several layers of moist Whatman #4 filter paper (to provide a phase barrier) and any air bubbles in the hanging water column setup were removed by suction. Oven-dried sand (~50 g) was saturated with water and then incrementally packed into the Al container up to 5.6 (±0.1) cm. The bulk density (=mass of oven dry sand / total volume of the packed sand column) and porosity (=1 – bulk density/particle density) of the sand column were 1.74 (±0.03) g/cm^3 and 0.34 (±0.01), respectively. Prior to the drainage experiment, the sand column was fully saturated with water by raising the water level in the burette to a height approximately equal to the top of the sand pack and allowed to equilibrate overnight.

2.2. Neutron radiography

Neutron imaging was performed using cold neutrons at the High Flux Isotope Reactor (HFIR) Cold Guide (CG) 1-D beam line at Oak Ridge National Laboratory. Neutron attenuation by the sample was detected with a 25 μm LiF/ZnS scintillator and a charge coupled device (CCD) camera system (iKon-L 936, Andor Technology plc. Belfast, UK). The resulting field of view was ~7 × 7 cm with image resolution ~75 μm per pixel. The ratio of the distance between the aperture and the detector to its aperture diameter (the L/D ratio) was 625 and the neutron flux was 5×10^5 cm^{-2} s^{-1}.

The pre-saturated Flint sand column, and associated hanging water column setup, was transferred to the HFIR CG 1-D beamline. At the facility, the top of the Al cylinder was attached to the sample holder while allowing air to flow into the cylinder through small holes. The cylinder was placed 24 cm away from the detector to minimize any scattering effects due to the initial high water content of the Flint sand. The burette was placed outside of the