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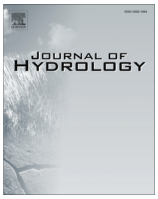

Hydraulic properties of coarsely and finely ground woodchips

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SUMMARY

Recent evidence suggests that leachate from woodchips stockpiled at recycling facilities could negatively impact water quality. Models that can be used to simulate water movement/leachate production require information on water retention and hydraulic conductivity functions of the stockpiled material. The objectives of this study were to (1) determine water retention and hydraulic conductivity functions of woodchips with particle size distributions (PSDs) representative of field stockpiled material by modeling multistep outflow and (2) assess the performance of three pore structure models for their ability to simulate outflow. Six samples with contrasting PSDs were assessed in duplicate. Samples were packed in cylindrical columns (15.3 cm high, 12.1 cm wide) to measure saturated hydraulic conductivity (K_s), cumulative outflow and water content at equilibrium with pressure potentials of -2, -10 and -40 cm. Water retention at pressure potentials between -200 and $-10{,}000$ cm were obtained using pressure plate extractors and used to supplement data from the outflow experiment. Hydraulic parameters of the pore models were derived from these measurements using HYDRUS-1D run by DREAM$_{(ZS)}$. K_s was independent of PSD with values between 55 and 80 cm/h. Cumulative outflow at each pressure potential was correlated with the PSD geometric mean diameters, and was best predicted by a model having two interacting pore domains, each with separate hydraulic conductivity and water retention functions (DPeM). Unsaturated conductivities were predicted to drop on an average to 0.24 cm/h at -10 cm and 3×10^{-3} cm/h at -50 cm for the DPeM model, suggesting that water would move slowly through stockpiles except during intense rainfalls.

1. Introduction

About 9.7 million metric tons of unpainted and non-chemically treated woody yard waste generated in the United States in 2010 was recovered for reuse and recycling (Falk and McKeever, 2004; USEPA, 2010). Wood recycling facilities processing wood for use as mulch typically grind the incoming material twice, and stockpile it outdoors for weeks to months depending on the demand. Woodchips ground once are considered coarse while those ground twice are regarded as fine, although sizes of coarsely and finely ground woodchips vary between facilities. Leachate generated from stockpiled woodchips is potentially harmful to aquatic life possibly because of its low pH and high concentrations of oxygen depleting organic compounds, as well as the presence of potentially toxic constituents such as tannin, lignin, tropolone, terpene and lignan (Hedmark and Scholz, 2008; Tao et al., 2007). The residence time of rain water within a stockpile as well as the amount of leachate generated from it are likely functions of the particle sizes of woodchips.

Numerical models have been used to simulate the flow, transport and distribution of water and contaminants, as well as to provide guidance on the design of leachate control and collection systems for land-filled solid waste and stockpiled waste rock from mines (Fala et al., 2005; Johnson et al., 2001; Khire and Mukherjee, 2007; Molson et al., 2005; Safari et al., 2012). These modeling exercises are not common with source separated organic wastes such as woody materials and only few examples are found in the literature (e.g. Ferrero et al., 2009; Seng et al., 2012).

Modeling water movement through unsaturated porous media such as woodchip stockpiles requires information on the hydraulic properties i.e., the water retention and hydraulic conductivity functions of packed woodchips of mixed sizes. Such information is not available in the literature, in particular for the range of sizes found in stockpiles at recycling facilities. Information on packed woodchips is limited to porosity and saturated hydraulic conductivity measurements (Christianson et al., 2010; Chun et al., 2009; Ima and Mann, 2007; van Driel et al., 2006).

Recently, hydraulic parameters for solid waste samples have been determined by modeling data of cumulative drainage from saturated columns induced by increasing pressures applied in multiple steps (Han et al., 2011; Scicchitano, 2010). This technique is

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Pore models

α	parameter in the single porosity van Genuchten (1980) model (cm^{-1})
α_1, α_2	parameters in the Durner (1994) bimodal pore model for the 1st (1) and 2nd (2) subsystem of pores (cm^{-1})
α_M, α_m	parameters in the dual permeability model for the macropore (M) and matrix (m) domains (cm^{-1})
K_s	saturated hydraulic conductivity (cm/h)
K_{sM}, K_{sm}	saturated hydraulic conductivities for the macropore (M) and matrix (m) domains in the dual permeability model (cm/h)
l	tortuosity parameter in the single porosity and dual porosity models (non-dimensional)
l_M, l_m	tortuosity parameters of the macropore (M) and matrix (m) in the dual permeability model (non-dimensional)
n	parameter in the van Genuchten (1980) unimodal pore model (non-dimensional)
n_1, n_2	parameters in the Durner (1994) bimodal pore model for the 1st (1) and 2nd (2) subsystem of pores (non-dimensional)
n_M, n_m	parameters in the dual permeability model for the macropore (M) and matrix (m) domains (non-dimensional)
θ	volumetric water content (cm^3/cm^3)
θ_r, θ_s	residual (*r*) and saturated (*s*) volumetric water contents (cm^3/cm^3)
θ_{rM}, θ_{sM}	residual (*rM*) and saturated (*sM*) volumetric water contents of the macropore region (cm^3/cm^3)
θ_{rm}, θ_{sm}	residual (*rm*) and saturated (*sm*) volumetric water contents of the matrix region (cm^3/cm^3)
w_1, w_2	weight of the 1st (1) and 2nd (2) subsystem of pores in the Durner (1994) bimodal pore model (non-dimensional)
w_M, w_m	weight of the macropore (M) and matrix (m) pore domains in the dual permeability model (non-dimensional)

Others

A	cross-sectional area of the flow cell (cm^2)
d	opening diameter in a sieve (mm)
d_g	geometric mean diameter (mm)
d_{gi}	geometric mean of the *i*th and ($i+1$)th sieves (mm)
f_i	mass fraction of the material retained between the *i*th and ($i+1$)th sieves (non-dimensional)
h	pressure potential (cm)
L	height of the flow cell (cm)
Q	flow rate (cm^3/h)
S_o	sorting coefficient (non-dimensional)

particularly appropriate for mixes of woodchips of different sizes because it allows the hydraulic properties of material with large pores to be characterized with transient data (Laloy et al., 2010). The selection of the water retention and hydraulic conductivity functions should reflect the nature of the pore system of the material studied. The unimodal pore model proposed by van Genuchten (1980) has been widely used to describe the hydraulic properties of a multitude of materials from soils to stockpiled waste rocks (Fala et al., 2005; Kazimoglu et al., 2006; Londra, 2010; Naasz et al., 2005; Scicchitano, 2010). However, models incorporating a dual subsystem of pores with uniform flow (Durner, 1994) and dual interacting pore domains with non-equilibrium flow (Gerke and van Genuchten, 1993) also have to be considered when modeling porous media such as packed woodchips that contain a wide range of inter-particle pore sizes and where the woodchip themselves are porous. All the pore models mentioned are implemented in the hydrologic software HYDRUS (Šimůnek et al., 2009) which has been used to predict water flow and determine hydraulic properties of porous materials (Fala et al., 2005; Han et al., 2011; Molson et al., 2005; Scicchitano, 2010).

Model calibration by optimization algorithms may result in several feasible parameter sets, especially for complex models. Optimization algorithms using local gradient-based search strategies such as the one employed in HYDRUS-1D are influenced by the initial values of the parameter set and often terminate their search on encountering local optimum values, thus missing the exploration of a global optimum solution (Vrugt et al., 2008a). On the other hand, optimization techniques based on the Markov Chain Monte Carlo (MCMC) approach treat parameters as probabilistic variables, and determine the posterior or target distributions of model parameters from prior information on the distribution of those parameters and a measured response. The MCMC scheme adaptively updates the evaluation of the target distributions based on the statistical convergence of the Markov chains, and is, therefore, robust enough to provide accurate target parameter distributions even with the input of biased prior distributions. The MCMC scheme is utilized in the **D**iffe**R**ential **E**volution **A**daptive **M**etropolis (DREAM) algorithm (Vrugt et al., 2008b, 2009) which, among other applications, has been used to run HYDRUS-1D (Laloy et al., 2010).

The objectives of this work were to: (1) determine water retention and hydraulic conductivity functions of woodchips with particle size distributions representative of field stockpiled material by modeling multistep outflow data from columns packed with woodchips, and (2) assess the performance of models of pore structure for their ability to simulate outflow. The selected models were run in HYDRUS-1D coupled with DREAM$_{(ZS)}$ (Laloy and Vrugt, 2012; Vrugt et al., 2008b, 2009) for optimization of model parameters. For all models, the strategy was to reduce the number of parameters to be optimized by fixing some of them with measured values and to check for: (a) consistency between predictions using optimized parameters and properties not used directly in the optimization process such as water retention, and (b) potential relationships between optimized parameter values and particle size distribution (PSD).

2. Materials and methods

A total of 30 samples consisting of both coarsely and finely ground woodchips were obtained from stockpiles at three wood-recycling facilities in New Jersey. The facilities accept whole trees, tree parts and woody yard waste from mixed tree species native to New Jersey. The types of wood and chemically untreated wood products accepted at different recycling facilities vary. Each woodchip sample was a composite of thoroughly mixed material from the top middle, and bottom of a stockpile. Samples were allowed to air-dry for one month at laboratory conditions.

2.1. Bulk density and particle size distribution

Bulk density (ρ_b) of packed material was determined in triplicate for each of the 30 samples by dropping a calibrated container with one kilogram of loosely packed air-dried material 15 times from a height of 15 cm (ASAE, 1998) onto a rubber mat. The average depth of the settled material after the 15th drop was used to calculate the volume and from it estimate bulk density. The