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Investigation into preferential flow in natural unsaturated soils with field multiple-tracer infiltration experiments and the active region model

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ABSTRACT

Preferential flow in natural unsaturated soils is common, but difficult to characterize and predict. The major objective of this research is to investigate the preferential flow patterns with field-scale multiple-tracer infiltration experiments and to evaluate the capability of the active region model (ARM) in predicting the field-scale preferential flow and transport processes. For this purpose, the mixture solutions of iodine and bromide, iodine and nitrate, and again iodine and bromide, as the tracing solutes, were applied sequentially in two plots in natural unsaturated loam soil to illustrate the flow and transport processes. The distributions of soil water content and concentrations of applied tracing solutes (NO_3^- and Br^-) were measured after experiments and predicted using ARM and the mobile–immobile region model (MIM). The relative root mean square errors (RRMSE) between those predictions (from ARM and MIM) and measured results were calculated for quantitatively evaluating the prediction accuracy and comparing the modeling efficiency of the two models. Both field observations and the ARM predictions indicated that there were macropores in Plot 1 but not in Plot 2, and the macropores in Plot 1 were mainly in the top 20 cm soil layer. The mixture solutions transported in the top 20 cm soil layer in Plot 1 were mainly from the soil surface directly and less affected by the macropore flow, while the preferential flow in the soil layer below 20 cm was considerably affected by the macropores and more applied mixture solutions were delivered into the deep soil layer quickly. Compared to the mixture solutions applied in the first and third steps, more mixture solution applied in the second step was transported to the deep soil layer by macropores, corresponding to obvious peaks of soil water content and NO_3^- concentration distributions observed in the deep soil layer in Plot 1. On the other hand, unstable flow was the major preferential flow behavior in Plot 2, inducing no obvious peaks of soil water content and solutes (NO_3^- and Br^-) concentrations observed in the infiltrated soil profile. The comparisons between predicted and observed results in Plot 2 indicated that the ARM captured the overall behavior of unstable flow and associated tracer transport better than the MIM; however, to well characterize the macropore flow process, the ARM needs to be improved to include the effects of macropores.

1. Introduction

Preferential flow, which contributes to the rapid water flow and solute transport in unsaturated soils, is common rather than exceptional in the natural unsaturated soils (Bouma and De Laat, 1981; Quisenberry et al., 1994; Heppell et al., 2000). Preferential flow allows irrigated water and applied agriculture chemicals to move through unsaturated zone to groundwater table quickly with limited degradation and filtration (Glass et al., 1988; Gjettermann et al., 1997; Reichenberger et al., 2002; Morris and Mooney, 2004), increasing the losses of applied resources and energy (Yasuda et al., 2001), and making the groundwater under high contamination risks (Chen et al., 2002; Bachmair et al., 2009).

There are a number of factors to induce preferential flow. Soil marcropores, which cause considerably spatial and temporal variations of flow processes in unsaturated soils (Lennartz et al., 1997; de Rooij and Stagnitti, 2002; Wang et al., 2009), play a very important role in the preferential flow (Lin et al., 1996; Alaoui and Helbling, 2006). Although macropores always account for only a small portion of the total soil porosity, they provide pathways for rapid transport of water and dissolved or suspended constituents

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through the porous medium (Villholth et al., 1998; Alaoui and Goetz, 2008), and contribute to an important fraction of water and solute transported near saturation (Luxmoore, 1981; Alaoui and Helbling, 2006; Carey et al., 2007). Even for homogeneous soils, attributed to high non-linearity of unsaturated flow processes, an infiltration wetting front can become unstable and split into columns (fingers), resulting in preferential (unstable) flow (Glass et al., 1988; Wang et al., 1998; de Rooij, 2000). Because of its complexity and diversity, preferential flow and the associated solute transport are probably the most frustrating processes for the vadose zone studies (Šimůnek et al., 2003).

A variety of experimental approaches have been developed to evaluate the effects of macropores on preferential soil water flow and solute transport and the resulting contamination risks of groundwater. Since the natural macropore systems are too complicated to be characterized in field, most of the experimental studies are conducted in undisturbed soil columns (e.g. Haws et al., 2004; Morris and Mooney, 2004; Pot et al., 2005; Hincapié and Germann, 2009) or repacked soil columns with artificial macropores (e.g. Steenhuis et al., 1994; Buttle and Leigh, 1997; Allaire-Leung et al., 2000a; Akay and Fox, 2007). The breakthrough curves are often used in those studies to characterize the presence or absence of macropores in undisturbed soil columns (Ersahin et al., 2002; Lamy et al., 2009), or to address the effects of macropore characteristics (e.g. continuity and tortuosity) on soil water flow and solute transport in the repacked soil columns (Allaire-Leung et al., 2000a,b). However, as the flow heterogeneity varies considerably between different measurement scales (Hillel, 1987; Molz and Boman, 1993; Öhrström et al., 2002; Wang et al., 2006), it is still difficult to predict field-scale water flow and solute transport in natural soil from the laboratory column observations.

With the advantages of limited toxicity, distinct visibility, and high water solubility, tracing (e.g. dye tracing and iodine–starch staining tracing) experiments are increasingly applied to study the detail characteristics of preferential flow in both field and laboratory (e.g. Bouma and Anderson, 1975; Steenhuis et al., 1990; Flury et al., 1994; Morris and Mooney, 2004; Weiler and Flühler, 2004). As the dye is adsorbed by soils with high clay and low organic carbon contents (Ketelsen and Meyer-Windel, 1999; Kasteel et al., 2002; Öhrström et al., 2004), iodine–starch staining tracing experiment is determined as a much more effective technique to visualize preferential flow pathways as the anionic properties of iodide ion provide it with high mobility and low adsorption even in heavy clay soils (Sheng et al., 2009). Recently, multiple-tracer experiments, in which organic and/or inorganic tracers are applied simultaneously or sequentially, have been used to investigate the dynamics of water flow and solute transport in macropores (e.g. Reeves et al., 1996; Kätterer et al., 2001; Mayes et al., 2003; Öhrström et al., 2004; Wang and Zhang, 2011). The interrelation between water flow and transport process, the interaction between macropores and matrix, and the effects of macropores on preferential flow and transport can be further studied from the distributions of applied water and tracing solutes (Reeves et al., 1996; Öhrström et al., 2004).

Recent research results show that the preferential flow and solute transport in unsaturated soils and other porous media have fractal properties (e.g. Glass, 1993; Persson et al., 2001; Smith and Zhang, 2001; Liu et al., 2003; Wang et al., 2006; Sheng et al., 2009). Liu et al. (2005) indicated that the key to successfully characterize preferential flow was to be able to incorporate their fractal or multi-fractal patterns. Based on the fractal characteristics of preferential flow patterns, Liu et al. (2005) developed the active region model (ARM) to capture the macroscopic behavior of preferential flow and transport in unsaturated soil. Sheng et al. (2009) reported that the ARM is able to capture the major features of the observed flow patterns under different infiltration conditions, and the ARM parameter (γ, used for describing the preferential flow heterogeneity) is not scale dependent for their experimental conditions. This result is of practical importance as the estimated ARM parameter (γ) from small scale experiment could be used for large-scale problems. Based on the mass conservation principle and ARM, Sheng et al. (2011) derived the governing equations for preferential water flow and solute transport in unsaturated soils owing to wetting front instability. Compared to the widely used mobile–immobile region model (van Genuchten and Wierenga, 1976; Šimůnek et al., 2003), the ARM produced more accurate predictions in both infiltration depth and the distributions of soil water content and solute concentration (Sheng et al., 2011).

It may be useful to note that the ARM was originally developed from the active fracture model (AFM) for describing the preferential flow and transport through unsaturated fractured rock for the Yucca Mountain Project (Liu et al., 1998, 2003, 2005). (Yucca Mountain, Nevada, is the proposed national high-level nuclear waste disposal site in USA.) While the AFM has been intensively evaluated, as reviewed by Liu et al. (2003), and used as the base-case constitutive model for assessing the repository performance by the Yucca Mountain Project, studies related to evaluation of the ARM, a relatively simple, new, and potentially useful model for describing field-scale flow and transport processes in unsaturated soils, are very limited (e.g., Sheng et al., 2011). Thus, it is highly desirable to conduct further evaluations of ARM under a variety of field conditions.

The major objective of this study is to further investigate the effects of soil macropores and wetting front instability on preferential water flow and solute transport by means of field multiple-tracer infiltration experiments in a natural unsaturated loam soil, which is motivated by the importance of this issue to contaminant transport in the vadose zone. In addition, the usefulness of ARM in representing field-scale preferential flow and transport processes in natural unsaturated soil is evaluated. While some ARM evaluation results were previously reported in the literature (e.g., Sheng et al., 2011), the current study involves more complex test conditions and flow mechanisms, as will be discussed later.

2. Methods and materials

2.1. Field experiments

To visualize flow paths and investigate the effects of macropores and wetting front instability on preferential water flow and solute transport in natural unsaturated soil, field multiple-tracer infiltration experiments were conducted in two plots at a loam soil site in the summer of 2010 and 2011, respectively, in Wuhan (30°37′N, 114°20′E), China. Undisturbed soil samples of 100 cm^3 were collected at the depth intervals of 0–10, 10–20, 20–50, and 50–100 cm at the experiment site to measure soil properties in the laboratory (Dane and Topp, 2002), including the soil texture, bulk density, porosity, and saturated hydraulic conductivity (Sheng et al., 2009). Soil physical and hydraulic properties are listed in Table 1.

For each plot, two rectangular frames with the inner one as $1.0 \times 1.0\ m^2$ and the outer one as $2.0 \times 2.0\ m^2$ were concentrically embedded into the soil (Fig. 1) after the experimental surface was leveled. A three-step sequential infiltration experiment was carried out in each plot. In the first step, 20 mm of mixture solution of potassium iodide (KI) (20 g L^{-1}) and potassium bromide (KBr) (10 g L^{-1}) was applied to the inner frame, creating an instantaneous ponding infiltration condition. After the mixture solution (KI and KBr) completely infiltrated into the soil, 20 mm of another mixture solution of potassium iodide (KI) (20 g L^{-1}) and potassium nitrate (KNO_3) (10 g L^{-1}) was applied to the inner frame for the