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An analytical model for solute transport in an infiltration tracer test in soil with a shallow groundwater table

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SUMMARY

It is recommended that an in-situ infiltration tracer test is considered for simultaneously determining the longitudinal and transverse dispersion coefficients in soil. Analytical solutions have been derived for two-dimensional advective–dispersive transport in a radial geometry in the literature which can be used for interpreting the result of such a tracer test. However, these solutions were developed for a transport domain with an unbounded-radial extent and an infinite thickness of vadose zone which might not be realistically manifested in the actual solute transport during a field infiltration tracer test. Especially, the assumption of infinite thickness of vadose zone should be invalid for infiltration tracer tests conducted in soil with a shallow groundwater table. This paper describes an analytical model for interpreting the results of an infiltration tracer test based on improving the transport domain with a bounded-radial extent and a finite thickness of vadose zone. The analytical model is obtained with the successive application of appropriate integral transforms and their corresponding inverse transforms. A comparison of the newly derived analytical solution against the previous analytical solutions in which two distinct sets of radial extent and thickness of vadose zone are considered is conducted to determine the influence of the radial and exit boundary conditions on the solute transport. The results shows that both the radial and exit boundary conditions substantially affect the trailing segment of the breakthrough curves for a soil medium with large dispersion coefficients. Previous solutions derived for a transport domain with an unbounded-radial and an infinite thickness of vadose zone boundary conditions give lower concentration predictions compared with the proposed solution at late times. Moreover, the differences between two solutions are amplified when the observation positions are near the groundwater table. In addition, we compare our solution against the approximate solutions that derived from the previous analytical solution and has been suggested to serve as fast tools for simultaneously estimating the longitudinal and transverse dispersion coefficients. The results indicate that the approximate solutions offer predictions that are markedly distinct from our solution for the entire range of dispersion coefficient values. Thus, it is not appropriate to use the approximate solution for interpreting the results of an infiltration tracer test.

1. Introduction

Most severe chemical threats to groundwater quality originate from incidental surface releases of various types of wastes and products generated by the industrial, agricultural and public sectors. These harmful chemicals can permeate unsaturated soil to enter the underlying aquifer system. The contaminant transport processes in unsaturated soil play a crucial role in determining groundwater quality. Concerns with deteriorating groundwater quality have underlined the need to understand the movements of these pollutants through unsaturated soil.

Conducting effective soil concentration measurements for characterizing the extent of a contaminant plume is both expensive and time-consuming, therefore, analytical or numerical models based on advection–dispersion equations (ADEs) are increasingly being used for forecasting contaminant migration and understanding the effect of the various transport processes that occur in unsaturated soil on solute transport. Several analytical models have been reported for simulating the transport of various contaminants

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(Barry and Sposito, 1988; Batu, 1989, 1993, 1996; Chen et al., 2008a,b, 2012a,b,c; Gao et al., 2010, 2012, 2013; Leij et al., 1991, 1993; Hunt, 1998, 2002; Parlange et al., 1992; Pang and Hunt, 2001; Park and Zhan, 2000; Pérez Guerrero et al., 2010, 2013; van Genuchten and Alves, 1982; Yeh, 1981a,b; Zhan et al., 2009). Several numerical models have been developed in the past decades. The most widely popular models include FEMWATER (Yeh and Ward, 1980; Lin et al., 1997), MT3DMS (Zheng and Wang, 1999), RT3D (Clement et al., 1998), HYDRAUS 2D/3D (Šimůnek et al., 2006), HYDROGEOCHEM (Yeh et al., 2004) and TOUGHREACT (Xu et al., 2004). A comprehensive review on numerical models can be found in Kitanidis and McCarty (2012).

In ADEs, the dispersion coefficients are generally known to be important parameters for predicting the extent of the pollutant's plume. The longitudinal dispersion coefficient delineates the spread of the contaminant plume along the flow direction, whereas the transverse dispersion coefficient accounts for the plume's distribution in the direction normal to the flow direction. It is accepted that tracer test is a very efficient method to characterize the dispersion coefficients. Ptak et al. (2004) gave a comprehensive review on the tracer experiments. Theoretically, dispersion coefficients in both longitudinal and transverse directions, can be determined from laboratory- or field-controlled tracer tests by using at least two breakthrough curves (BTCs) observed at distinct observation positions. Significant contributions on determining longitudinal and transverse dispersion coefficients in aquifer from various types of tracer tests include Sauty (1980), Sudicky et al. (1983), Moltyaner and Killey (1988), Zou and Parr (1993, 1994), Chen et al. (1999), Klenk and Grathwohl (2002) and Rahman et al. (2005).

Compared with the longitudinal dispersion coefficients reported in the literature for laboratory- and field-scale studies, there is paucity of data on transverse dispersion coefficients. Moreover, according to Vanderborght and Vereeken (2007), it is the transverse dispersion coefficient that controls the shape of the contaminant plume in unsaturated soil with a higher value indicating a larger plume distribution. In addition to the longitudinal dispersion coefficient, the transverse dispersion coefficient is crucial for predicting contaminant migration. Recently, various field and laboratory methods have been developed for simultaneously determining the longitudinal and transverse dispersion coefficients in unsaturated soil. Massabò et al. (2007) proposed a technique for determining the longitudinal and transverse dispersion coefficients from the BTCs of a laboratory-scale column experiment. Massabò et al. (2006) developed an analytical solution for two-dimensional advective–dispersive transport in a radial geometry for interpreting the results of laboratory-scale column experiments. They specified the instantaneous slug input as a Dirac delta function and considered the transport domain to be infinite ($-\infty \leqslant z \leqslant +\infty$). An infinite transport system enables the upward movement of the tracer mass and causes a backward dispersion at the inlet boundary. Commenting on the work of Massabò et al. (2007) and Chen et al. (2012a) argued that their analytical solution is unsuitable for interpreting their two-dimensional radial column experiment because it inadequately describes the actual solute transport process in the soil column.

Zhang et al. (2006) described an in-situ infiltration tracer test for simultaneously estimating the longitudinal and transverse dispersion coefficients and derived an analytical solution to a 2D ADE in cylindrical coordinates. Zhang et al. (2006) further reduced the derived solutions to an approximate expression to facilitate rapid determination of the longitudinal and transverse dispersion coefficients, postulating two assumptions which a sampling point is distant from the soil surface and the injected tracer source over a circular area can be approximated as a point source. In an analytical model, Zhang et al. (2006) considered a transport system with an unbounded-radial extent and infinite thickness of vadose zone. However, in reality, the tracer should move in a flow domain with a bounded radial extent during an infiltration tracer test. Moreover, a mathematical model with an infinitely thickness of vadose zone might be invalid when the infiltration tracer test is performed in soil with a shallow groundwater table. Thus, a new analytical solution for tracer test modeling with a bounded-radial extent and a finite thickness of vadose zone is needed.

A novel analytical solution for 2D radial solute transport is presented in this paper which are developed by considering the transport domain with a bounded-radial extent and finite thickness of vadose zone. The objectives of this study are two-fold. First of all, the influence of the presence of a shallow water table on tracer transport in an infiltration tracer test is investigated by comparing the BTCs obtained from Zhang et al. (2006) and the newly derived solutions. Secondly, we examine the validity of the approximate solutions which has been simplified from Zhang et al.'s (2006) analytical solution.

2. Analytical model

Zhang et al. (2006) conducted a field tracer tes for simultaneous determination of the longitudinal and transverse dispersion coefficients and developed a simplified analytical solution to interpret the results of the tracer test. The instruments consisted of a triple-ring infiltrometer, Marriot water tanks, and suction cup samplers as shown in Fig. 1. Prior to the start of the test, the suction

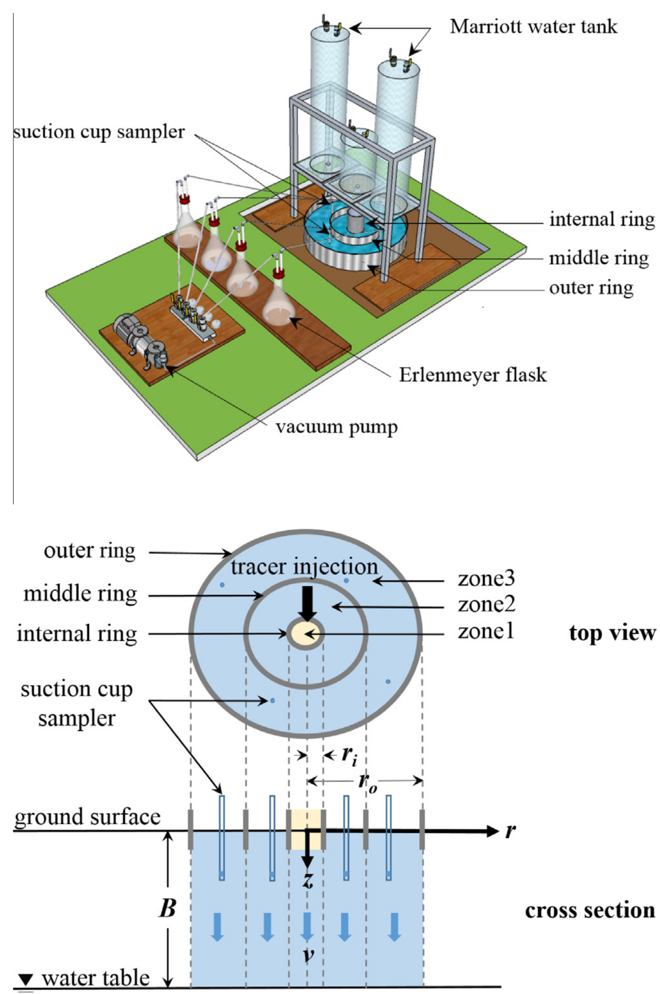

Fig. 1. Schematic diagram of the instruments and solute transport in an infiltration tracer test.