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Estimation of laboratory-scale dispersivities using an annulus-and-core device

Christophe C. Frippiat [a,c,*], Patrick Conde Pérez [b], Alain E. Holeyman [c]

[a] *Center for Experimental Study of Subsurface Environmental Processes (CESEP), Colorado School of Mines, 1500 Illinois Street, Golden, CO 80401, USA*
[b] *SECO S.C., Brussels, Belgium*
[c] *Department of Civil and Environmental Engineering, Université catholique de Louvain, Louvain-la-Neuve, Belgium*

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Summary This paper investigates the use of two-dimensional radial column experiments to estimate longitudinal and transverse dispersivity at the laboratory scale. The experimental device is an ''annulus-and-core'' device: it is based on a classical column system, of which the inlet reservoir is divided into three independent concentric zones, allowing non-uniform tracer injection. The outlet reservoir is similarly adapted, so that information on the radial distribution of concentration becomes available through mean effluent concentration measurements in each annular zone. In this study, we only investigated continuous tracer injections through the central inlet zone. An analytical solution to a similar problem was available in the literature, and was adapted to compute effluent concentrations. The influence of the simplified boundary conditions of the solution was assessed by means of a numerical model. A general methodology is suggested to obtain transport parameters from breakthrough curve analysis, involving (i) the determination of effective porosity and longitudinal dispersivity from the full averaged breakthrough curve using classical one-dimensional tools and (ii) the determination of transverse dispersivity from the breakthrough curves recorded in the annular zones. Preliminary experiments were performed on a glass bead porous medium, on a gravel sand and on a natural medium sand. It is found that the rapidity of the test, its low cost, and the ability to simultaneously estimate three transport parameters comes at the price of potentially larger experimental errors. Transverse dispersivities were found to be higher than values previously reported in the literature, probably as a result of plume meandering, which cannot be detected nor corrected when using annulus-and-core devices.

* Corresponding author. Address: Center for Experimental Study of Subsurface Environmental Processes (CESEP), Colorado School of Mines, 1500 Illinois Street, Golden, CO 80401, USA. Tel.: +1 303 384 2237.
E-mail address: cfrippia@mines.edu (C.C. Frippiat).

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Introduction

Longitudinal dispersivity has been a major research topic in subsurface hydrology for a few decades and a great amount of data is currently available in the literature (see e.g. the recent compilations by Schulze-Makuch (2005) and by Bromly et al. (2007)). By contrast, few measures of transverse dispersivity have been made, even though it has crucial importance when modeling transport in physically heterogeneous media (Gelhar et al., 1979), multispecies transport (Cirpka et al., 2006), multiphase transport (Oostrom et al., 1992, 1999a,b; Seagren et al., 1999) or microbial activity in aquifers (Cirpka et al., 1999).

Existing methods to estimate transverse dispersion are usually based either on tracer tests (either at the laboratory or at the field scale) or on dissolution tests (at the laboratory scale). Dissolution tests generally imply groundwater flow along a stagnant zone containing constant concentration gas (Klenk and Grathwohl, 2002; McCarthy and Johnson, 1993), NAPL (Oostrom et al., 1999a,b; Pearce et al., 1994) or solid (Guedes de Carvalho and Delgado, 1999, 2000; Delgado and Guedes de Carvalho, 2001). Transverse dispersivity can then be inferred from the rate of dissolution of the third phase, which is obtained through solute breakthrough curve measurements at the laboratory model outlet.

Most of the tracer tests designed to determine transverse dispersion coefficients are performed in a uniform flow at constant mean velocity. Blackwell (1962) and Hassinger and von Rosenberg (1968) used the so-called ''annulus-and-core'' approach, in which the inlet and the outlet cross-sections of a column are divided into two concentric zones. The concentration of the solution flowing in the inner inlet zone (the core) is rapidly increased, while the solution in the outer inlet zone (the annulus) is kept solute-free. Transverse dispersivity is computed by comparing the steady-state concentration of effluent solutions in the outlet annulus and core zones. Divided inlets were also adopted in several other column studies involving intrusive local concentration measurements (Bruch, 1970; Grane and Gardner, 1961; Han et al., 1985; Harleman and Rumer, 1963; Perkins and Johnston, 1963; Zhang et al., 2006). Grid lysimeter devices, used to study water flow and solute transport in the vadose zone, have a divided outlet. A sampling grid is installed at the bottom of the lysimeter, allowing local surface-averaged measurements of water fluxes and solute concentrations (e.g. de Rooij and Stagnitti, 2002). Other authors preferred point injection, either in column (Olsson and Grathwohl, 2007; Pisani and Tosi, 1994; Robbins, 1989) or in the field (Jiao, 1993; Kelly et al., 1994; Zou and Parr, 1993, 1994). A few specific devices imply non-uniform flow: Cirpka and Kitanidis (2001) and Benekos et al. (2006) investigated flow and transport in a helix and in a cochlea to determine transverse dispersivity. Kim et al. (2004) determined local longitudinal and transverse dispersivities in a laboratory aquifer model with a local recharge zone.

In this paper, we use an ''annulus-and-core'' method similar to that of Blackwell (1962) and Hassinger and von Rosenberg (1968). We have modified the device by dividing inlet and outlet flasks into three concentric zones rather than two (Fig. 1). Recently, Massabo et al. (2006) have proposed a set of analytical solutions for two-dimensional advection–dispersion problems in axisymmetrical geometries of finite lateral extent. These solutions include among others concentration distributions resulting from the continuous injection of tracer in a circular zone centered on the longitudinal axis of the column. That particular solution was adapted to interpret effluent concentration data recorded in the three outlet zones. It must be noted that Massabo et al. (2006) have developed these solutions within the framework of similar experiments, based however on non-intrusive electrical measurements along the column body. As an example of application, three porous materials are tested: glass beads, a gravel sand and a natural medium sand.

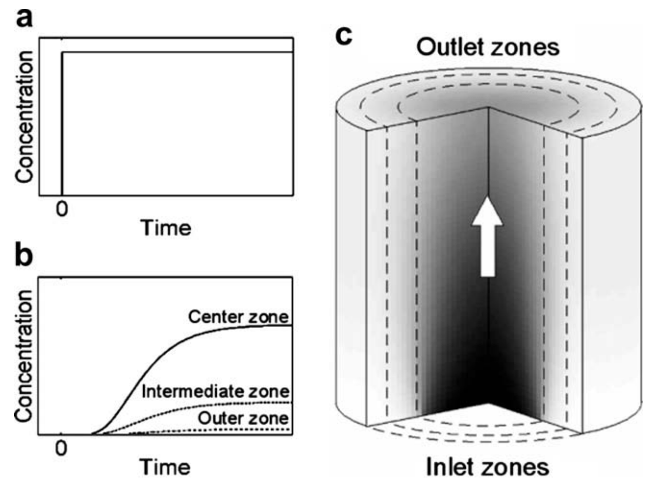

Figure 1 Concentration distributions within an annulus-and-core device with three inlet and outlet zones. (a) Continuous injection through the central inlet zone. (b) Resulting breakthrough curves in the three outlet zones. (c) Three-dimensional spatial distribution of concentration within the column at an intermediate time.

Experimental setup and materials

The experimental setup is based on a classical column system used to determine longitudinal transport properties. The setup is illustrated in Fig. 2. The column consists of a Plexiglas pipe of length $L = 11.63$ cm and of inner diameter $D = 10.14$ cm (radius $R = 5.07$ cm). The inlet reservoir is divided into three independent concentric zones in order to perform two-dimensional tests. Each zone has an equal cross-sectional surface area and is supplied with two specific tubes allowing solution feeding and pressure measurement. The central circular zone has a radius $R_1 = 2.93$ cm and the intermediate annular zone has an outer radius $R_2 = 4.14$ cm. The pipe is covered with a thin layer of silicon grease to minimize wall effects resulting from the higher porosity close to the lateral boundaries. The inlet boundary is made of stainless steel (quality AISI 316L) screened with 80 holes of 3-mm-diameter evenly distributed along the surface of each zone. Additional filters are also used to prevent finest grains from flowing out of the column. The mesh size of the filters is adapted to the particle size distribution of the material tested. The outlet reservoir is similarly modified, so that the concentration responses of the system partitions can be individually recorded. It must be noted that