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Evaluation of dispersivity coefficients by means of a laboratory image analysis

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ABSTRACT

This paper describes the application of an innovative procedure that allows the estimation of longitudinal and transverse dispersivities in an experimental plume devised in a laboratory sandbox. The phenomenon of transport in porous media is studied using sodium fluorescein as tracer. The fluorescent excitation was achieved by using blue light and the concentration data were obtained through the processing of side wall images collected with a high resolution color digital camera. After a calibration process, the relationship between the luminosity of the emitted fluorescence and the fluorescein concentration was determined at each point of the sandbox. The relationships were used to describe the evolution of the transport process quantitatively throughout the entire domain. Some check tests were performed in order to verify the reliability of the experimental device. Numerical flow and transport models of the sandbox were developed and calibrated comparing computed and observed flow rates and breakthrough curves. The estimation of the dispersivity coefficients was carried out by analyzing the concentration field deduced from the images collected during the experiments; the dispersivity coefficients were evaluated in the domain zones where the tracer affected the porous medium under the hypothesis that the transport phenomenon is described by advection–dispersion equation (ADE) and by computing the differential components of the concentration by means of a numerical leap-frog scheme. The values determined agree with the ones referred in literature for similar media and with the coefficients obtained by calibrating the numerical model. Very interesting considerations have been made from the analysis of the performance of the methodology at different locations in the flow domain and phases of the plume evolution.

1. Introduction

Aquifers are a vital water resource whose quality characteristics must be safeguarded or, if damaged, restored. The extent and complexity of aquifer contamination is related to characteristics of the porous medium, the influence of boundary conditions, and the biological, chemical, and physical processes. To simplify and understand the influence of these various factors on aquifer contamination, it is common for researchers to use controlled laboratory conditions. For example, contaminant transport has been studied in aquifer models constructed in sandboxes; these allow control of porous medium structure, boundary conditions and reactions (e.g. Bruch, 1970; Goswami and Clement, 2007; Silliman and Zheng, 2001; Sternberg, 2004; Yeh and Liu, 2000; Yin and Illman, 2009). One very important physical process that affects contaminant transport and has been studied extensively in sandboxes is contaminant dispersion.

Two main measurement approaches for measuring contaminant dispersion in model aquifer sand tanks are reported in the literature. The first approach uses in situ probes to measure the concentration of a conservative tracer. For example, salt is commonly used and is detected by means of

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in situ conductivity probes (Aksoy and Guney, 2010; Kim et al., 2004; Silliman et al., 1987; Sternberg, 2004). Even though this approach is inexpensive and allows continuous monitoring, it is invasive, can potentially disturb flow, and typically limited to monitoring in only a few locations. The second approach is based on image analysis, which allows time-lapse images of a tracer to be taken in 2D transparent sand tanks without disturbing the plume evolution. In most cases, tracer evolution was monitored using black and white cameras with low (compared to the present technology) spatial resolution (Aeby et al., 2001; Catania et al., 2008; Gimmi and Ursino, 2004; Huang et al., 2002), or with color digital cameras, but only analyzing the most sensitive color (McNeil et al., 2006) and, later, each color channel (Barrero et al., 2010; Capilla Romá and Sánchez Fuster, 2012a, 2012b; Castro-Alcala et al., 2012; Persson, 2005; Sánchez Fuster, 2011; Sánchez Fuster et al., 2008). In some cases, tracer experiments were performed using potentially harmful UV light to excite a fluorophore (Barns et al., 2012; Catania et al., 2008; Huang et al., 2002) or using hazardous substances such as Oxazione 170 perchlorate, Methyl Blue, Thymol Blue or Rhodamine (Aeby et al., 2001; Aureli et al., 2011; Castro-Alcala et al., 2012; Cirpka et al., 2006; McNeil et al., 2006). Over the last fifteen years, digital photography, digital storage capacity, and digital analyses have improved exponentially. This has paved the way for enhancements in imaging tracer dispersion that are the focus of this work.

In the hydraulic laboratory of the Department of Civil, Environmental and Land Engineering and Architecture (DICATeA) of the University of Parma, we set up an aquifer model sandbox and next generation imaging system to perform groundwater transport tests, including the measurement of dispersion. In previous efforts, longitudinal dispersivity was determined from one-dimensional transport experiments (Silliman et al., 1987; Sternberg, 2004) and transverse dispersivity has been determined by assuming a fixed ratio of longitudinal to transverse dispersivity (Aksoy and Guney, 2010; Capilla Romá and Sánchez Fuster, 2012a, 2012b; Kim et al., 2004). In other efforts, transverse dispersivity was determined from experiments (Benekos et al., 2006; Chiogna et al., 2010; Cirpka et al., 2006; Klenk and Grathwohl, 2002; Olsson and Grathwohl, 2007; Rolle et al., 2012) making assumptions on the longitudinal dispersivity. None of the aforementioned procedures simultaneously estimated both longitudinal and transverse dispersivities. All the previous studies, except Capilla Romá and Sánchez Fuster (2012a, 2012b) that used a numerical discretization of the advection dispersion equation, estimated the dispersivity coefficients by fitting the experimental data to analytical solutions available in literature.

In the literature of the imaging systems, there is very little documentation on strategies for monitoring negative effects of the experimental limitations, such as photobleaching, quenching, side-walls effects, local heterogeneities, non-homogeneous lightening etc., that cannot be totally eliminated but, at least, they can be quantified.

In the present paper we report on our efforts to:

1. develop a non-invasive monitoring system with respect to the flow and concentration field;
2. analyze whether the present potential of digital photography (color camera with high resolution) improves the detection of concentration in terms of reading and spatial detail;
3. implement experimental runs by adopting substances and methodologies harmless for both the people and the environment;
4. develop a method that monitors the experimental errors in order to validate the data collected;
5. test a new procedure for estimating the dispersivity coefficient values in sand-box experiment.

We describe materials and methods of the laboratory experiments in Section 2, the procedure for estimating the dispersivity coefficients in Section 3, the numerical model developed to validate the results of the procedure in Section 4 and the results of a relevant test case in Section 5. Finally, in Section 6, we discuss the outcomes of the study and draw our conclusions.

2. Materials and methods

2.1. Sandbox

The transport experiments were performed in a sandbox (Fig. 1) built with Polymethyl methacrylate (PMMA) plates with 0.02 and 0.03 m thickness for, respectively, the lateral and the bottom sides. The external dimensions of the sandbox are 1.20 m × 0.73 m × 0.14 m. Along the longest axis, the sandbox is made up of three parts (Fig. 2): two tanks (upstream and downstream) which allow the regulation of the water level and, consequently, of the flux, and a central chamber (length $L = 0.954$ m, height $H = 0.70$ m and thickness $T_H = 0.10$ m) which contains the porous medium. The boundary between the tanks and the porous medium is a pierced (1 mm diameter) iron plate covered with brass wire gauze; two weirs control the water level in the upstream and downstream tanks in order to maintain the same boundary conditions without oscillations. A small tank ($70°10^{-3}$ m^3) and a centrifugal pump, which circulates the water through the device, are located on a shelf below the sandbox. The water that flows through the porous medium can be conveyed either to the sewage system or back to the lower tank for recirculation. The water discharge is monitored with a flow meter that works in the range $6.5°10^{-6}$ to $250°10^{-6}$ m^3/s with an accuracy of ±0.4% of the full-scale value. Although an iron bar installed on the top of the box limits the deformation of the sandbox due to the weight of the glass beads (about 981 N as a whole), the deformation in each point of the box's sidewalls was measured through a photogrammetric survey. The survey reported a maximum deformation in the center of the sidewalls, which was quantified to be 0.5 cm.

The porous medium was chosen to be inert and to allow a total reset of the system at the end of a transport experiment. The medium consisted of glass beads with diameter in the range between 0.75 and 1 mm with a density of 1480 kg/m^3 composed by 72% SiO_2, 13% Na_2O, and 9% CaO. The material was packed in order to avoid non-uniformity of the media. The porosity of the medium was estimated at 37% through several tests carried out by using a Tempe pressure cell; the bulk hydraulic conductivity K was assessed after a series of tests