Journal of Hydrology 496 (2013) 195–204

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Hydraulic profiling with the direct-push permeameter: Assessment of probe configuration and analysis methodology

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A R T I C L E I N F O

Article history:
Received 15 November 2012
Received in revised form 17 May 2013
Accepted 20 May 2013
Available online 28 May 2013
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Christophe Darnault, Associate Editor

Keywords:
Direct-push permeameter
Hydraulic conductivity
Numerical simulation
High-resolution profiling
Site characterization

S U M M A R Y

The characterization of hydraulic conductivity (K) variations in heterogeneous aquifers has proven to be a significant challenge. Recent field and numerical assessments, however, have demonstrated the considerable potential of direct-push profiling for characterization of vertical K variations at the resolution needed for contaminant site investigations. The direct-push permeameter (DPP), in particular, has been found to be an effective characterization tool (0.4-m resolution in current configuration) over the K range expected in aquifers. The potential of this tool is explored further here through numerical simulations to assess the probe configuration and the analysis approach that are most appropriate for profiling in highly permeable heterogeneous systems. A probe configuration with transducers placed between 0.1 and 0.4 m from the injection screen appears to be most suitable for general field applications, as it can yield a reasonable resolution (few decimeters) in the presence of a typical level of sensor noise. DPP data are commonly analyzed using the spherical form of Darcy's Law. Although this approach will provide reliable K estimates in many situations, it can introduce error in the presence of thin (relative to the distance between injection screen and transducers) layers of vastly differing K. Simultaneous numerical inversion (under steady-shape conditions) of all DPP tests in a profile can yield improved results if information about aquifer structure is available. DPP K estimates have little sensitivity to the zone of compaction created during probe advancement, but estimates are sensitive to channeling along the probe surface. Proper probe design (probe shape and position of transducers) and test procedures (low injection rates) can reduce the potential for and impact of such channeling. These points are demonstrated using K data from an outcrop study in which K varies by orders of magnitude on the scale of a few decimeters.

1. Introduction

Spatial variations in hydraulic conductivity (K) can have a large impact on the fate and transport of solutes in the subsurface (e.g., Sudicky, 1986; Zheng and Gorelick, 2003). Characterizing those variations at the scale (centimeter to decimeter) needed for investigations at sites of groundwater contamination, however, has proven difficult. This has resulted in highly uncertain descriptions of K variations, which have led to problematic transport predictions and ineffective remediation systems.

The most widely used methods for estimation of K are not capable of reliably resolving K variations on the scales needed for many practical investigations. Commonly used field methods, such as pumping or slug tests, are of limited effectiveness due to scale and procedural issues (Butler, 2005), while methods based on estimation of K from sieve statistics are extremely time consuming and use empirical expressions that are highly site specific (e.g., Vienken and Dietrich, 2011). New approaches are needed to improve transport predictions and increase the efficacy of remediation systems.

Recently developed methods based on direct-push technology have great potential for characterization of K variations in near-surface, unconsolidated aquifers (see review in Liu et al., 2012). In particular, three direct-push probes have proven to be effective in characterizing vertical K variations in a practically feasible manner. The direct-push injection logger (DPIL) can provide information about relative variations in K on the cm-scale through determination of a specific-capacity-like parameter during continuous or near-continuous advancement (Dietrich et al., 2008; Liu et al., 2009). The direct-push permeameter (DPP), on the other hand, can provide reliable K estimates (resolution of current tool ~0.4 m) through the performance of formal hydraulic tests (Lowry et al., 1999; Butler et al., 2007). Finally, the high-resolution K (HRK) tool combines the DPIL and DPP probes to yield K estimates at the cm-scale (Liu et al., 2009, 2012). Extensive field and numerical

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0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.05.036

assessments have demonstrated the quality of the information that these probes can provide (Butler et al., 2007; Dietrich et al., 2008; Liu et al., 2008; Bohling et al., 2012).

The HRK tool can provide information on K variations at the resolution and accuracy required for transport investigations in heterogeneous aquifers (Bohling et al., 2012), but the tool is currently limited to a K range from about 2.0×10^{-8} m/s to 7×10^{-4} m/s (Liu et al., 2012). Although the upper K limit can undoubtedly be raised somewhat through use of larger diameter tools and refined field and analysis procedures, prospects for raising the limit much beyond 2×10^{-3} m/s are dim. The DPP will therefore be the primary means of acquiring quantitative information about K variations in highly permeable formations (>2×10^{-3} m/s). However, the probe configuration and analysis methodology most appropriate for use in heterogeneous aquifers have yet to be thoroughly evaluated. The assessment of those issues is the primary objective of this paper.

In the following sections, we present a theoretical assessment of the DPP that builds on the earlier simulation assessment of Liu et al. (2008). The basic issues we address are those of the probe configuration and analysis methodology that are most appropriate for profiling in highly permeable heterogeneous aquifers. We use high-resolution forward modeling of DPP tests in idealized layered aquifers to examine probe performance at the interface between layers and to assess the impact of thin layers and of channeling along the probe body. We then use the K data from an outcrop that was previously investigated in an aquifer analogue study (Tronicke et al., 2002) to simulate DPP tests in the presence of K variations over several orders of magnitude on the scale of decimeters. Finally, on the basis of this assessment, we present recommendations for the most appropriate tool design and analysis methodology to use for DPP profiling in highly heterogeneous aquifers.

2. DPP overview

The DPP has been previously described in several publications (Lowry et al., 1999; Butler et al., 2007; Liu et al., 2008, 2012), so only a brief overview will be given here. Typically, the tool consists of two pressure transducers inset into the probe a short distance above a screened section (a few cms in length) through which water is injected (Fig. 1). As the probe is advanced, water is continuously injected at a low rate to prevent screen clogging. After reaching the desired depth for a K estimate, probe advancement and water injection cease and the pressure heads are allowed to recover. A series of injection tests are then performed in a stepwise sequence (injection rate varying between tests with first and last tests having the same rate). In each test, the injection-induced pressure responses are recorded at the two transducers and K is then estimated from these responses using the spherical form of Darcy's Law (Lowry et al., 1999; Butler et al., 2007):

$$K = \frac{Q}{4\pi(\Delta h_1 - \Delta h_2)}\left(\frac{1}{l_1} - \frac{1}{l_2}\right), \quad (1)$$

where Q is the injection rate [L^3/T], Δh_i is the injection-induced pressure head change at transducer i [L], and l_i is the distance between transducer i and the center of the injection screen [L]. The key feature of Eq. (1) is that the injection-induced pressure gradient is used to estimate K. This approach thus only requires steady-shape (constant induced gradient) conditions; steady-state flow is not necessary (Butler et al., 2007]. In this paper, we use the term pole–dipole (PD) to refer to the test configuration for Eq. (1). This term is borrowed from geophysics where it refers to a gradient measurement between two observation points (dipole) in a potential (in this case, pressure head) field produced by a source (pole) injection.

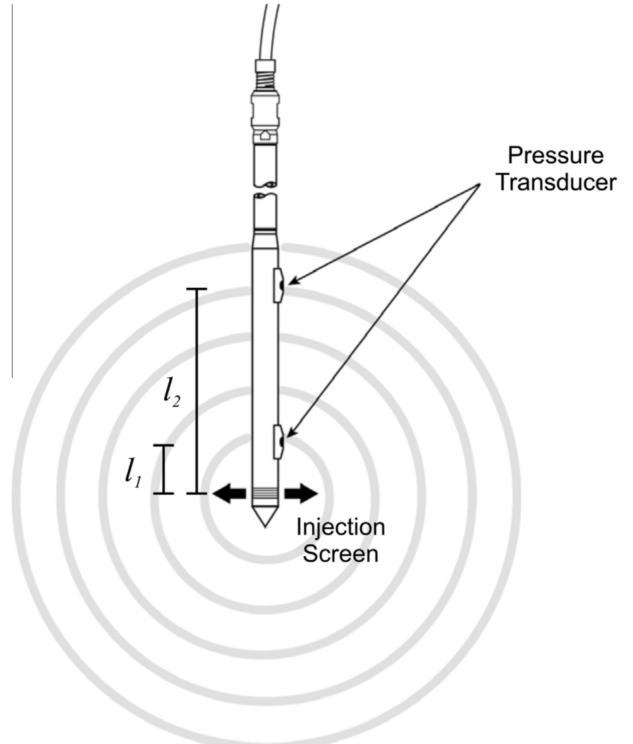

Fig. 1. Schematic sketch of the DPP probe (modified after Butler et al., 2007). Although not shown, the diameter of the probe increases slightly above the injection screen to diminish the potential for short circuiting flow along the probe.

As explained by Butler et al. (2007), an alternative approach to estimate K is to use the head change at a single transducer:

$$K_i = \frac{Q}{4\pi l_i(\Delta h_{i_{ss}})}, \quad (2)$$

where $\Delta h_{i_{ss}}$ is the injection-induced head change at transducer i at steady state. We use the term pole–pole (PP), again borrowed from geophysics, to refer to the test configuration for Eq. (2). This approach can be used as a backup in case a pressure transducer malfunctions during profiling. However, in contrast to the pole–dipole configuration of Eqs. (1) and (2) does require steady-state conditions. In media with low K, the test duration required to reach steady state can be long relative to that required for steady-shape conditions (e.g., Fig. 7 in Liu et al., 2008). If steady state is attained during a test, analysis of the individual transducer measurements can be useful in identifying the presence of thin layers between the DPP transducers (Butler et al., 2007; Liu et al., 2008).

Eqs. (1) and (2) are based on an idealized conceptualization of the injection-induced flow system (spherical flow in a homogeneous aquifer). The assumed conditions are never perfectly met, so, in certain situations, the accuracy of the resulting K estimates can be significantly affected. In particular, as we show in later sections, thin layering can introduce considerable uncertainty into the DPP K estimates.

3. Theoretical evaluation of DPP K range and sensitivity to noise

Given that Eqs. (1) and (2) are the primary means to estimate K from DPP test data, these equations are used here to assess the dependence of the measurable K range and the sensitivity of the K estimates to sensor noise on the positions of the two transducers (henceforth, probe configuration). In order to facilitate this assessment, the equations can be rewritten in a form that consists of a