Journal of Hydrology 539 (2016) 319–329

Contents lists available at ScienceDirect

Journal of Hydrology

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

In-situ falling-head test for hydraulic conductivity: Evaluation in layered sediments of an analysis derived for homogenous sediments

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ARTICLE INFO

Article history:
Received 17 February 2016
Accepted 11 May 2016
Available online 20 May 2016
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Roseanna M. Neupauer, Associate Editor

Keywords:
Hydraulic conductivity
Permeameter
Sediments
Streambed
Numerical modeling
Groundwater–surface water interaction

SUMMARY

The hydraulic conductivity (K) of streambeds is a critical variable controlling interaction of groundwater and surface water. The Hvorslev analysis for estimating K from falling-head test data has been widely used since the 1950s, but its performance in layered sandy sediments common in streams and lakes has not previously been examined. Our numerical simulations and laboratory experiments show that the Hvorslev analysis yields accurate K values in both homogenous sediment (for which the analysis was originally derived) and layered deposits with low-K sand over high-K sand. K from the Hvorslev analysis deviated significantly from true K only when two conditions were present together: (1) high-K sand was present over low-K sand, and (2) the bottom of the permeameter in which K was measured was at or very near the interface between high-K and low-K. When this combination of conditions exists, simulation and laboratory sand tank results show that *in-situ* Hvorslev K underestimates the true K of the sediment within a permeameter, because the falling-head test is affected by low-K sediment outside of (below the bottom of) the permeameter. In simulation results, the maximum underestimation (occurring when the bottom of the permeameter was at the interface of high K over low K) was by a factor of 0.91, 0.59, and 0.12 when the high-K to low-K ratio was 2, 10, and 100, respectively. In laboratory sand tank experiments, the underestimation was by a factor of about 0.83 when the high-K to low-K ratio was 2.3. Also, this underestimation of K by the Hvorslev analysis was about the same whether the underlying low-K layer was 2 cm or 174 cm thick (1% or 87% of the domain thickness). Numerical model simulations were useful in the interpretation of *in-situ* field K profiles at streambed sites with layering; specifically, scaling the model results to the maximum measured K at the top of the field K profiles helped constrain the likely ratio of high K to low K at field locations with layered heterogeneity. Vertical K values are important in field studies of groundwater–surface water interaction, and the Hvorslev analysis can be a useful tool, even in layered media, when applied carefully.

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1. Introduction

The hydraulic conductivity (K) of streambeds is a critical variable controlling interaction of groundwater and surface water. The magnitude and spatial patterns of water and chemical fluxes through streambeds are related to the magnitude and spatial pattern of streambed K (Gilmore et al., 2016a; Kennedy et al., 2009b; Min et al., 2012; Sebok et al., 2014). In additional to spatial variation, streambed K may also vary in time in association with time-varying controls such as erosion, deposition, or temporal variation in biogenic gases in streambed sediments (e.g., Genereux et al., 2008; Cuthbert et al., 2010; Kurtz et al., 2012). A variety of *in-situ* approaches have been used to estimate streambed K, including falling head tests in field permeameters (Chen, 2000; Landon et al., 2001; Genereux et al., 2008), constant head injection tests, or "CHIT" (Cardenas and Zlotnik, 2003), slug tests (Cey et al., 1998; Springer et al., 1999; Sebok et al., 2014), and regressions based on grain size (Alayamani and Sen, 1993). Landon et al. (2001) offer a comparison of several methods. Lu et al. (2012) adapted a falling head permeameter approach to estimate anisotropy in streambed K. Ong and Zlotnik (2011) incorporated an air–water manometer for accurate measurement of head differences into their CHIT device for estimation of lakebed K. Other novel approaches include the small-scale pump tests and "piezo-seep meter" of Kelly and Murdoch (2003).

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http://dx.doi.org/10.1016/j.jhydrol.2016.05.030
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Often measurement of streambed K is motivated by the goal of determining water flux (v) through the streambed using K and associated measurements of vertical hydraulic head gradient in the streambed, J (i.e., $v = kJ$), and/or determining dissolved solute flux through the streambed as the product of v and solute concentration in the groundwater (for a gaining stream) or stream water (for a losing stream). The ideal K measurement for this flux application would be a value of vertical K measured over the same streambed depth interval as J, to give a consistent and meaningful pairing of K and J for estimation of v from Darcy's equation. In this regard, the field permeameter approach has an advantage over methods that yield measures of horizontal K, given that sediments are commonly layered and thus anisotropic to some degree (e.g., Lu et al. (2012)).

Field permeameter tests involve inserting a thin-walled pipe (the permeameter) into a streambed, filling the pipe with water, and observing the rate at which the water level in the pipe falls. An analysis originally proposed by Hvorslev (1951; solution E, page 44) and widely used since (e.g., Cedergren, 1989; McCarthy, 1998; Chen, 2000, 2004; Landon et al., 2001; Song et al., 2007; Lu et al., 2012) is most useful for data analysis when stated in the following form (Genereux et al., 2008):

$$\ln H = -\frac{K}{\left(\frac{\pi D}{11M} + L\right)} t + \ln H_0 \qquad (1)$$

where D is the permeameter diameter, L is the depth of penetration of the permeameter into the streambed (i.e., the length of the sediment column inside the bottom of the permeameter), M is the square root of the ratio of horizontal to vertical K, H is the water level inside the permeameter relative to the ambient water level (the subscript 0 refers to the start of the test), and t is time. In his original work, Hvorslev assumed the porous medium is homogeneous, the water and sediment are not compressible, friction losses due to the permeameter itself are negligible, and that Darcy's equation holds true. Horizontal K does appear in Eq. (1) (within M) but the analysis is very insensitive to horizontal K at high ratios of L to D (Chen, 2004). For example, assuming $M = \infty$ (extreme anisotropy) when M is actually 1 (isotropic sediment), or vice versa, results in less than 5% error in K when L/D is about 5 (Genereux et al., 2008). Thus, with adequate L/D (5 or more), the falling head test and Hvorslev analysis give the desired estimate of vertical K. In sandy streambeds the test is easy to perform and often many can be done in a single day.

A potential complication is that the Hvorslev analysis was developed for homogeneous porous media, but sediments are generally layered. In their analysis of the uncertainty in streambed K values derived from Eq. (1), Genereux et al. (2008) referred to the uncertainty arising from layering (i.e., the "model error" associated with using Eq. (1) in layered sediments) as the most difficult source of uncertainty to quantify in the Hvorslev analysis of falling-head field permeameter tests. To date, this source of uncertainty and the performance of Eq. (1) in layered sediments have not been directly assessed, despite widespread application of Eq. (1) since the 1950s.

The work reported here addresses two principal questions: First, how applicable is the Hvorslev analysis (Eq. (1)) when layered heterogeneity exists? Second, is there any practical guidance to help with interpretation of field K values from Eq. (1) in the presence of layered heterogeneity? We began with numerical simulations of falling-head tests to evaluate how well Eq. (1) would estimate the K of layered sediments. Then, results from falling-head tests in a laboratory sand tank where the location of a K boundary was designed and known were compared to the numerical simulation results. Finally, field measurements were done in two streams in eastern North Carolina to determine the degree of vertical variability in K due to layering and to assess whether results from numerical simulations could be used to help interpret field estimates of K from Eq. (1) in the presence of layered heterogeneity.

2. Methods

2.1. Numerical modeling

We used MODFLOW 2005 with its associated LAKE package (Merritt and Konikow, 2000) to model falling-head field permeameter tests in streambeds of known K (both homogeneous and layered) under different conditions, to predict the water level (i.e., the head) in the permeameter as a function of time. Head results from each simulated falling head test were then analyzed with Eq. (1), and the K value obtained was compared to the true K that we had assigned to the sediments in the model. Close agreement would indicate good performance of Eq. (1) in estimating K from falling head results. Eq. (1) predicts a linear relationship between ln$H$ and t, and K was calculated from the best-fit slope of this relationship, for model, laboratory sand tank, and field results:

$$K = -(slope)\left(\frac{\pi D}{11M} + L\right) \qquad (2)$$

Together, MODFLOW and the LAKE package represent a fully-coupled groundwater–surface water model capable of conserving water mass during transient simulations. In our work, the permeameter was modeled as a "lake" in a rectangular block of sandy sediment (Fig. 1). The initial permeameter head was assigned to

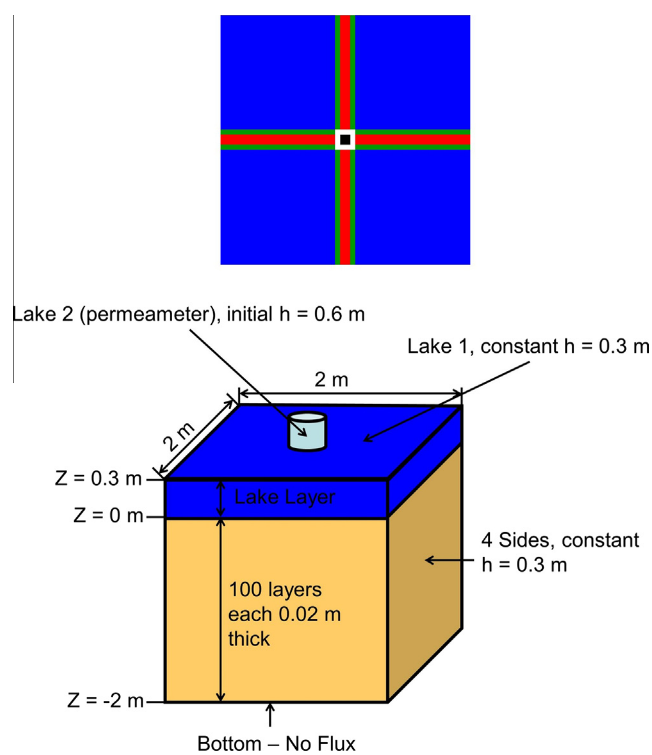

Fig. 1. Map view of the top layer (top), and overall schematic (bottom) of the model domain used to numerically simulate falling-head tests. The map-view image shows zones of different horizontal grid spacing: blue areas had the largest cells (1 cm × 1 cm), the black area in the center had the smallest cells (0.25 cm × 0.25 cm), and the white, green, and red areas had rectangular cells with lateral dimensions varying between 0.25 cm and 1 cm. The overall schematic shows the spatial extent and boundary conditions of the domain (h = hydraulic head). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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