Journal of Hydrology 540 (2016) 736–743

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

A semi-analytical generalized Hvorslev formula for estimating riverbed hydraulic conductivity with an open-ended standpipe permeameter

Sergey P. Pozdniakov [a], Ping Wang [b,*], Mikhail V. Lekhov [a]

[a] Department of Hydrogeology, Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow 119899, Russia
[b] Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A, Datun Road, Chaoyang District, Beijing 100101, PR China

ARTICLE INFO

Article history:
Received 26 January 2016
Received in revised form 4 June 2016
Accepted 27 June 2016
Available online 28 June 2016
This manuscript was handled by C. Corradini, Editor-in-Chief, with the assistance of Philip Brunner, Associate Editor

Keywords:
Surface-groundwater exchange
Hydraulic conductivity
Slug tests
Riverbed sediments
Hydraulic resistance
Superposition

ABSTRACT

The well-known Hvorslev (1951) formula was developed to estimate soil permeability using single-well slug tests and has been widely applied to determine riverbed hydraulic conductivity using in situ standpipe permeameter tests. Here, we further develop a general solution of the Hvorslev (1951) formula that accounts for flow in a bounded medium and assumes that the bottom of the river is a prescribed head boundary. The superposition of real and imaginary disk sources is used to obtain a semi-analytical expression of the total hydraulic resistance of the flow in and out of the pipe. As a result, we obtained a simple semi-analytical expression for the resistance, which represents a generalization of the Hvorslev (1951). The obtained expression is benchmarked against a finite-element numerical model of 2-D flow (in *r-z* coordinates) in an anisotropic medium. The results exhibit good agreement between the simulated and estimated riverbed hydraulic conductivity values. Furthermore, a set of simulations for layered, stochastically heterogeneous riverbed sediments was conducted and processed using the proposed expression to demonstrate the potential associated with measuring vertical heterogeneity in bottom sediments using a series of standpipe permeameter tests with different lengths of pipe inserted into the riverbed sediments.

1. Introduction

The exchange processes between surface water and groundwater are significant not only in riverbank water resource management (Chen and Chen, 2003; Winter et al., 1998) but also in water quality considerations (Calver, 2001) associated with biogeochemical interactions between streams and surrounding aquifer systems (Hiscock and Grischek, 2002). Riverbed hydraulic conductivity (K) is one of the key factors controlling the magnitude and spatial distribution of surface-groundwater exchange processes (Genereux et al., 2008; Landon et al., 2001), and it may vary over more than eight orders of magnitude, ranging from below 1.0×10^{-9} m/s to above 1.0×10^{-2} m/s (Calver, 2001), depending on the riverbed sediment materials and textures (Min et al., 2013; Taylor et al., 2013).

Although numerous approaches (e.g., grain-size distribution analysis, Darcy's law-based in-stream tests, environmental tracer experiments, water balance techniques, integrated surface-groundwater numerical modeling, etc.) have been widely applied to investigate the hydraulic properties of riverbed sediments (Cheong et al., 2008; Kalbus et al., 2006; Wang et al., 2015), the accurate estimation of riverbed K values remains a challenge. One of the challenging aspects of estimating riverbed K is associated with its high spatial and temporal variability across measurement scales due to heterogeneity in the riverbed sediments (Chen et al., 2010), scouring and depositional processes during flooding events (Dunkerley, 2008; Hatch et al., 2010), and diurnal and seasonal changes in stream flow temperature (Constantz, 1998). Additionally, the successful application of the aforementioned methods is highly dependent on the assumptions and limitations of the applied methods, the specific equipment, and the design of the measurements (Shanafield and Cook, 2014). Therefore, to estimate riverbed K, multiple methods are recommended to reduce the method uncertainties involved in many field studies (Fleckenstein et al., 2010).

Field methods, including slug tests, in situ permeameter tests, and seepage-meter measurements, have been widely applied to determine the hydraulic properties of riverbeds. For studying riverbed vertical heterogeneity, a light-oil piezomanometer, which allows to measure very small head differences between surface water and underlying groundwater, was developed by Kennedy

* Corresponding author.
E-mail address: wangping@igsnrr.ac.cn (P. Wang).

http://dx.doi.org/10.1016/j.jhydrol.2016.06.061
0022-1694/

et al. (2007). Recently, a new type of permeameter was designed to measure two parameters, i.e., vertical flux and hydraulic gradient, simultaneously on site (Lee et al., 2015). These methods are relatively quick, inexpensive and allowing for numerous measurements to be made at many locations (Landon et al., 2001). The falling head slug tests, in which a standpipe (well or piezometer) is filled with river water and the raised water level in the standpipe is immediately allowed to fall while assuming that the general river water level remains constant (Baxter et al., 2003; Hvorslev, 1951), are considered to be a more practical in-stream approach than a permeameter for determining the riverbed K because of their ability to measure much deeper sediments (Landon et al., 2001). Another important advantage of falling head slug tests is that this type of test can evaluate the anisotropy of riverbed sediments using the L-shaped standpipe method (Chen, 2000), which provides in situ measurements of riverbed K in different directions.

Hvorslev (1951) conducted detailed interpretations of field standpipe permeameter tests using different types of piezometers and provided corresponding formulas to calculate the hydraulic conductivity. Hvorslev's falling-head analysis generated accurate vertical hydraulic conductivities of the riverbed in homogenous sediments and layered deposits of low-K sand over high-K sand (Burnette et al., 2016). The analytical solution produced by Hvorslev (1951) highly depends on the shape factor of the installed piezometer (F), which is considered a function of the geometric constants, i.e., the length-to-diameter ratio, of the piezometer (Silvestri et al., 2012). As indicated by Klammler et al. (2011), most existing approaches used to determine F are based only on geometric or mathematical simplifications that neglect the effects of the boundaries of the flow domain. Therefore, the objectives of this study are to: (1) develop a semi-analytical expression for hydraulic resistance of an open-ended standpipe permeameter in the vicinity of a constant head boundary; (2) validate the obtained expression using numerical simulations of the falling head tests in the standpipe permeameter; (3) examine the influence of the natural vertical flow gradient in bottom sediments and medium elastic storage on the falling head test results; and (4) analyse the possibility of determining the hydraulic conductivity profiles of layered bottom sediments using falling head tests in a standpipe permeameter.

2. Development of an analytical model

2.1. A semi-analytical solution for hydraulic resistance

As shown in Fig. 1, an open-ended cylindrical pipe has a diameter d and a penetration length into the riverbed sediments L. Let us assume that the initial water level in the pipe $H_{pipe}(0)$ is equal to the river water level H_{riv}, i.e., $H_{pipe}(0) = H_{riv}$. The water level in the pipe is instantaneously raised to S_0 above the river water level H_{riv}, and the subsequent raised water level in the pipe relative to the initial water level in the pipe $H_{pipe}(0)$ is $S(t)$.

A semi-infinite medium with an origin in cylindrical coordinates (r, z) is placed at the upper boundary of the sediments in the centre of the pipe with diameter d. The riverbed sediments are assumed to be horizontally anisotropic media, i.e., the saturated hydraulic conductivity at each field point can be characterized by the radial horizontal (K_r) and vertical (K_z) components of hydraulic conductivity tensor **K**. The coefficient of anisotropy of conductivity can be defined as follows: $\alpha^2 = K_z/K_r$.

The equation of unsteady state flow in an anisotropic medium from the pipe into the riverbed sediments, in cylindrical coordinates (r, z), is written as follows, using superposition principles in terms of changes in hydraulic head (Neuman, 1975):

$$S_s\frac{\partial s}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} rK_r\frac{\partial s}{\partial r} + K_z\frac{\partial^2 s}{\partial z^2}, \tag{1}$$

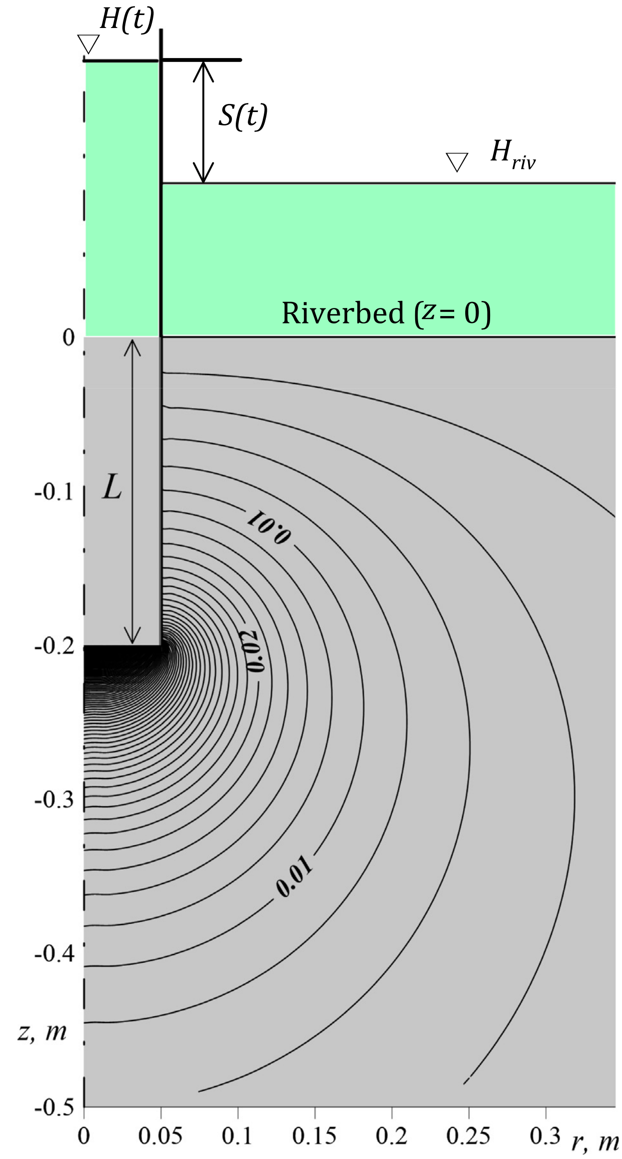

Fig. 1. Cylindrical pipe installed in riverbed sediments with equipotential of groundwater head change in the sediments. H_{riv} is the river level, $H(t)$ is the water level in the pipe, and $S(t)$ is raised over the H_{riv} water level in the pipe.

where S_s is specific storage, and $s(r, z, t) = H(r, z, t) - H(r, z, 0)$ is the change in hydraulic head $H(r, z, t)$, i.e., its increase above the initial head $H(r, z, 0)$.

The initial condition of Eq. (1) is $s(r, z) = 0$ for $r > d/2$, and $s = S_0$ for $z = 0$ and $r < d/2$ at $t = 0$. S_0 is the instantaneous change in the water level inside the pipe above the river water level at $t = 0$. The boundary conditions at the wall of the pipe are no-flow conditions. At the top of the sediments inside the pipe, i.e., $z = 0$ and $r < d/2$, the hydraulic head change in the sediments is $s(r, 0, t) = S(t)$. The flow rate from the pipe Q is system-dependent, and it can be found by equating the flow in the pipe to the flow in the medium:

$$Q = -\frac{\pi d^2}{4}\frac{dS}{dt} = 2\pi\int_0^{d/2} rK_z\frac{\partial s}{\partial z}\Big|_{z=0} dr \tag{2}$$

At the surface $z = 0$ outside the pipe ($r > d/2$), two types of boundary conditions can generally be considered: a) a no-flow boundary and b) a constant-head ($s = 0$) boundary. Note that the no-flow boundary at the top of the bottom sediments is not