Journal of Hydrology 511 (2014) 190–198

Contents lists available at ScienceDirect

Journal of Hydrology

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

Effect of injection screen slot geometry on hydraulic conductivity tests

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ARTICLE INFO

Article history:
Received 23 August 2013
Received in revised form 8 January 2014
Accepted 20 January 2014
Available online 28 January 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Jean-Raynald de Dreuzy, Associate Editor

Keywords:
Aquifer
Hydraulic conductivity
Non-ideal screen
Shape factor
Mixed type boundary value problem

SUMMARY

Hydraulic conductivity and its spatial variability are important hydrogeological parameters and are typically determined through injection tests at different scales. For injection test interpretation, shape factors are required to account for injection screen geometry. Shape factors act as proportionality constants between hydraulic conductivity and observed ratios of injection flow rate and injection head at steady-state. Existing results for such shape factors assume either an ideal screen (i.e., ignoring effects of screen slot geometry) or infinite screen length (i.e., ignoring effects of screen extremes). In the present work, we investigate the combined effects of circumferential screen slot geometry and finite screen length on injection shape factors. This is done in terms of a screen entrance resistance by solving a steady-state potential flow mixed type boundary value problem in a homogeneous axi-symmetric flow domain using a semi-analytical solution approach. Results are compared to existing analytical solutions for circumferential and longitudinal slots on infinite screens, which are found to be identical. Based on an existing approximation, an expression is developed for a dimensionless screen entrance resistance of infinite screens, which is a function of the relative slot area only. For anisotropic conditions, e.g., when conductivity is smaller in the vertical direction than in the horizontal, screen entrance losses for circumferential slots increase, while they remain unaffected for longitudinal slots. This work is not concerned with investigating the effects of (possibly turbulent) head losses inside the injection device including the passage through the injection slots prior to entering the porous aquifer.

1. Introduction

The hydraulic conductivity K $[L/T]$ is a fundamental hydrogeological parameter. For example, its effective value over large (e.g., >100 m) scales, directly influences the magnitude of natural or pumped groundwater flows in aquifers. Moreover, its spatial heterogeneity over smaller scales (e.g., <1 m) is of interest, as it determines the local properties of groundwater flow and solute transport (e.g., contaminant release from source zones and contaminant plume dispersion). Those are important pieces of information for a variety of hydrogeological problems (e.g., Sudicky, 1986; Sedighi et al., 2006). Under saturated conditions, i.e., below the water table of an aquifer, pump or slug tests are typically performed for investigations of K at different scales (Weight and Sonderegger, 2001). Accordingly, these tests may be performed on an entire well or on various portions of a well screen by use of single or double packer systems (Price and Williams, 1993; Butler et al., 2009). Different types of small diameter (i.e., <0.1 m) drive-point (also called push-in or direct-push) probes have also been proposed for quick and flexible investigation of K in unconsolidated media at small scales (Hinsby et al., 1992; Cho et al., 2000; Butler et al., 2007; Dietrich et al., 2008). A general relationship between injection head φ_0 $[L]$ and injection flow rate Q $[L^3/T]$ at steady-state is (Clark and Turner, 1983; Weight and Sonderegger, 2001)

$$\varphi_0 = \frac{Q}{KF} + CQ^2 \tag{1}$$

where the term Q/KF $[L]$ represents linear head losses due to laminar flow in the porous aquifer medium (potentially influenced by non-ideal screen geometry) and CQ^2 $[L]$ represents quadratic head losses due to turbulent flow along the well or injection device as well as across the screen openings prior to entering the aquifer. Coefficient C $[T^2/L^5]$ is hereby a proportionality constant and F $[L]$ is a shape factor accounting for the geometry of the imposed flow field in the aquifer. While well losses may be significant for production wells, small scale injection tests use relatively low values of Q,

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http://dx.doi.org/10.1016/j.jhydrol.2014.01.038

such that the quadratic term in Eq. (1) is small and sensitivity to aquifer properties (i.e., K) is maximized. Liu et al. (2012) propose a step drawdown procedure to estimate C, such that K may be estimated from a single steady-state injection test as

$$K = \frac{Q}{(\varphi_0 - CQ^2)F} \approx \frac{Q}{\varphi_0 F} \tag{2}$$

Here, φ_0 and Q are observed quantities at steady-state during an injection test and F needs to be determined for a given injection screen geometry (Hvorslev, 1951). The final expression in Eq. (2) applies when turbulent losses are negligible.

Numerous studies investigate the problem of quantifying F (or respective generalizations for transient conditions, such as type curves, for example) through different methods. A common feature of the most sophisticated approaches is to assume axi-symmetric potential flow imposed by a mixed type boundary condition along the injection well or probe (constant head along injection screen interval and impermeable casing above/below screen). Most recent results include the numerical work of Ratnam et al. (2001); Liu et al. (2008); Kobayashi et al. (2013) as well as the semi-analytical work based on integral transforms of Chang and Chen (2002); Perina and Lee (2006); Mathias and Butler (2007); Barua and Bora (2010). Furthermore, Chang and Yeh (2010) approach the mixed type boundary problem by solving a system of triple series equations, while Klammler et al. (2011) apply an approach related to trigonometric interpolation. Silvestri et al. (2011) quantify injection flow by conformal mapping in combination with a subsequent numerical integration to account for axi-symmetry of the problem (rather than plane two-dimensional). However, all of these and related studies treat the injection screen as a perfect (ideal) constant head boundary without accounting for the exact widths and separation distances of individual injection screen slots or perforations (Fig. 1). The goal of the present work is to investigate the effects of such non-ideal screens on injection test interpretation (i.e., on the value of F in Eq. (2)) for the purpose of (1) improving estimates of K and (2) assisting in injection screen slot design, such that existing results for the shape factor F for ideal screens remain applicable. The present work is not concerned with investigating the magnitude of the head losses inside the injection device including the passage through the injection slots prior to entering the porous aquifer (e.g., constant C in Eqs. (1) and (2)).

Work related to intake efficiency of non-ideal screens may be found in literature related to drainage pipes or tiles. Kirkham (1950) provides analytical solutions for upper and lower bounds based on geometric approximations of the boundary conditions near circumferential slots. Intake efficiency of circumferential slots was further investigated using the Gram-Schmidt method (Selim and Kirkham, 1974; including application to well pumping), by numerical solution of a Fredholm integral equation (Sneyd and Hosking, 1976) and by solution of dual trigonometric series (Prasad et al., 1981; Hazenberg and Panu, 1991). Nieuwenhuis and Wesseling (1979); Youngs (1980) study effects of filter materials around drains by exploring a conformal mapping solution of Widmoser (1966) for longitudinally slotted screens. Furthermore, Panu and Filice (1992) consider circular perforations in a dual trigonometric series approach and Dierickx and van der Molen (1981) refines a distributed line source and sink model for different slot and perforation geometries, which is validated by electrolytic experiments. However, consistent with the typically large extent of drainage pipes, results are not applicable to finite (short) screen lengths as customary for small scale injection tests using push-in probes, for example. In summary, hence, a need remains for investigating the combined effects of screen perforation/slotting and finite screen length on the hydraulic performance of an injection screen in terms of F. Since ideal screens of finite length possess flow singularities at their extremes (e.g., Sneyd and Hosking, 1976; Prasad et al., 1981; Mathias and Butler, 2007; Klammler et al., 2011), deviations from ideal screen geometry may have a significantly different impact on the performance of short screens than for screens of infinite length (or fully penetrating between confining layers, which do not possess flow singularities). For the purpose of measuring K by means of small scale injection tests, screen lengths may be at the order of the device radius and narrow screen slots are preferred over other types of perforation. Circular perforations, for example, may allow partial collapse of surrounding aquifer material into the screen. This may alter the geometry of the injection boundary condition with significant effects on the hydraulic behavior (Sneyd and Hosking, 1976).

In what follows we limit attention to injection screens possessing circumferential slots and apply the method of Klammler et al. (2011) to investigate the effect of screen slot geometry (slot width and separation distance) on screens of arbitrary lengths and in the absence of any nearby boundaries (as relevant for small scale injection tests, for example). The semi-analytical approach solves an axi-symmetric steady-state potential flow problem and honors the mixed type boundary condition along the injection probe at a finite but increasing number of control points, such that extrapolation to an exact solution (i.e., infinite number of control points) is possible. Thus, it is easily adapted for the present problem, where screen slotting represents a sequence of many constant head and impermeable boundary segments (Fig. 1b). The subsequent section briefly reviews the method applied and constructs a general solution. Results are then expressed in terms of a hydraulic screen

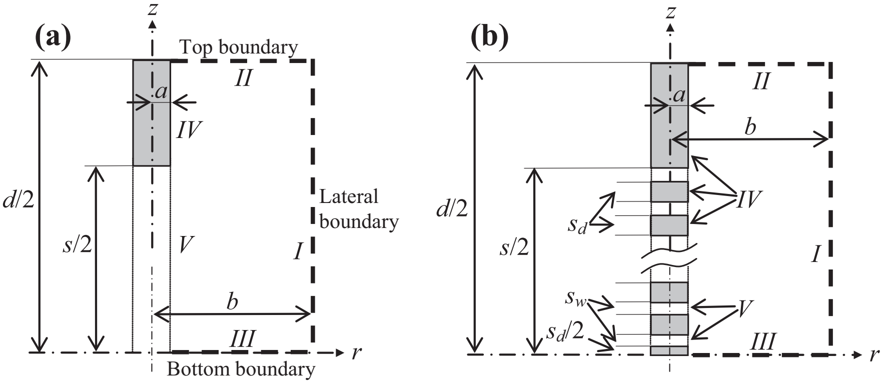

Fig. 1. Schematic of boundary conditions for upper half of (a) ideal and (b) non-ideal (circumferentially slotted) injection screen of uniform slot width s_w and uniform distance between slots s_d. Total screen length of n_s slots is $s = n_s(s_w + s_d) - s_d$, (b) is shown for even n_s, and modification to odd n_s is straight-forward.