Journal of Hydrology 428–429 (2012) 182–190

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

Effects of free convection and friction on heat-pulse flowmeter measurement

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ARTICLE INFO

Article history:
Received 28 June 2011
Received in revised form 4 January 2012
Accepted 1 February 2012
Available online 9 February 2012
This manuscript was handled by Philippe Baveye, Editor-in-Chief, with the assistance of Renduo Zhang, Associate Editor

Keywords:
Flowmeter
Calibration
Hydraulic conductivity
Flow velocity
Diverter

SUMMARY

Heat-pulse flowmeter can be used to measure low flow velocities in a borehole; however, bias in the results due to measurement error is often encountered. A carefully designed water circulation system was established in the laboratory to evaluate the accuracy and precision of flow velocity measured by heat-pulse flowmeter in various conditions. Test results indicated that the coefficient of variation for repeated measurements, ranging from 0.4% to 5.8%, tends to increase with flow velocity. The measurement error increases from 4.6% to 94.4% as the average flow velocity decreases from 1.37 cm/s to 0.18 cm/s. We found that the error resulted primarily from free convection and frictional loss. Free convection plays an important role in heat transport at low flow velocities. Frictional effect varies with the position of measurement and geometric shape of the inlet and flow-through cell of the flowmeter. Based on the laboratory test data, a calibration equation for the measured flow velocity was derived by the least-squares regression analysis. When the flowmeter is used with a diverter, the range of measured flow velocity can be extended, but the measurement error and the coefficient of variation due to friction increase significantly. At higher velocities under turbulent flow conditions, the measurement error is greater than 100%. Our laboratory experimental results suggested that, to avoid a large error, the heat-pulse flowmeter measurement is better conducted in laminar flow and the effect of free convection should be eliminated at any flow velocities. Field measurement of the vertical flow velocity using the heat-pulse flowmeter was tested in a monitoring well. The calibration of measured velocities not only improved the contrast in hydraulic conductivity between permeable and less permeable layers, but also corrected the inconsistency between the pumping rate and the measured flow rate. We identified two highly permeable sections where the horizontal hydraulic conductivity is 3.7–6.4 times of the equivalent hydraulic conductivity obtained from the pumping test. The field test results indicated that, with a proper calibration, the flowmeter measurement is capable of characterizing the vertical distribution of preferential flow or hydraulic conductivity.

1. Introduction

The hydraulic conductivity of an aquifer plays an important role in groundwater flow and contaminant transport. An equivalent hydraulic conductivity of the aquifer is commonly obtained by the conventional hydraulic testing. Nevertheless, most aquifers are somewhat heterogeneous in nature due to the spatial variation of deposition, weathering and deformation. Hydraulic conductivity may vary in both vertical and lateral directions (Rubin, 1982). Field techniques for estimating hydraulic conductivity at various depths have been studied by Molz et al. (1990, 1994), Taylor et al. (1990), Kabala (1993), Young et al. (1998), and Paillet (2000). Double-packer tests can be used to measure the hydraulic conductivity interval by interval in an open-hole (Braester and Thunvik, 1984), but the operation is time-consuming (Borgne et al., 2006). An impeller flowmeter can be used to measure the borehole flow continuously (Molz et al., 1989; Hanson and Nishikawa, 1996), but the instrument only for rapid flow conditions, and requires frequent maintenance and calibration (Molz and Young, 1993). Electromagnetic flowmeter was developed to improve the resolution of borehole flow measurement in medium to high velocity conditions (Molz et al., 1994; Dinwiddie et al., 1998; Ruud et al., 1999; Arnold and Molz, 2000; Crisman et al., 2001).

Heat-pulse flowmeter is a promising tool that can be used to measure the flow velocity at a stationary position in the borehole under low to medium flow velocity conditions. By integrating the velocities measured at various depths by the flowmeter and the equivalent hydraulic conductivity estimated by the hydraulic test, one can then establish the vertical profile of horizontal hydraulic conductivity in a heterogeneous aquifer (Molz et al., 1989; Kabala, 1994). However, the accuracy of calculated hydraulic conductivity could be affected by flowmeter measurement. Negative values of hydraulic conductivity were often reported in field applications

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doi:10.1016/j.jhydrol.2012.02.001

(Paillet, 2000), but the mechanism behind the measurement error of the heat-pulse flowmeter remains unclear. Hess (1986) presented a calibration curve for heat-pulse flowmeter measurements, but did not provide detailed data at low velocities. Correction processes under various borehole conditions have been suggested for the heat-pulse and electromagnetic flowmeter measurement based on field practices by Paillet (2004).

However, the lack of rigorous laboratory experimental test data and analysis of the measurement error in the previous studies may lead to improper use of the heat-pulse flowmeter or difficulties in data analysis and interpretation in the field. Here we conduct a laboratory test of flow through a carefully designed water circulation system for evaluating the error and precision of measured flow velocity using the heat-pulse flowmeter. The physical mechanism of the measurement error is discussed and an empirical formula for calibrating the measured flow velocity was developed. A field test was then conducted to demonstrate the application of the flowmeter measurement to characterization of the vertical distribution of hydraulic conductivity in an alluvial aquifer. Calibration against the effect of free convection and friction loss was performed to improve the accuracy in hydraulic conductivity of individual sections and to correct the inconsistency between the pumping rate and the measured flow rate.

2. Laboratory measurement

A circulation system is established in the laboratory for measuring water flow velocity by heat-pulse flowmeter. The system is designed to minimize the influence of environmental factors and provides a stable condition for analyzing measurement data.

2.1. Heat-pulse flowmeter

The heat-pulse flowmeter adopted in this study is manufactured by the Robertson Geologging Ltd. The instrument, approximately 2.24-m long and 5.0-cm in diameter, is designed for measuring vertical flow velocity at a stationary position in a borehole. The flow-through cell is located near the bottom of the heat-pulse flowmeter. It contains a heating wire-grid and two thermistors located 5 cm above and below the grid (Fig. 1a). As water flows through the grid, a pulse of heat is produced by controlled electric current, heating water in the vicinity of the grid. The heated water is then transported 5 cm in distance toward the thermistor where it is detected.

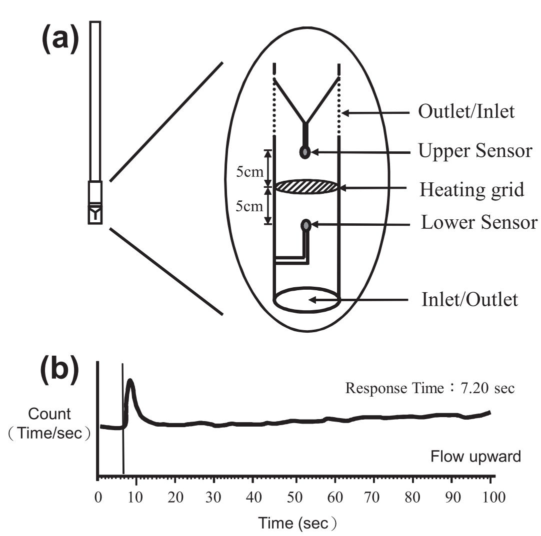

Fig. 1. (a) Schematic illustration of inner components of the heat-pulse flowmeter probe; (b) typical heat-pulse flowmeter response curves.

The data logger measures the elapsed time from heat injection to detection of the temperature difference by the thermistor. The plot of differential temperature between the two thermistors versus elapsed-time for the heat-pulse flowmeter measurement is shown in Fig. 1b. Time resolution is 0.06 s. The flow direction can be identified by the upward or downward direction of heat-pulse as implied by the temperature change. Based on the direction of heat pulse and the elapsed time of the warm fluid front detected by thermistors, the vertical flow velocity can be estimated.

2.2. Experimental setting

The laboratory testing system is designed to accommodate flowmeter measurement at various inflow rates and to minimize the error due to artificial effects. The system consists of three components: heat-pulse flowmeter, electronic equipment, and circulation components (Fig. 2). The heat-pulse flowmeter measures water flow velocity. The electronic equipment includes data logger, computer, and plotter to process the heat command and to convert flowmeter signals to elapsed time readings.

A 94-mm diameter transparent acrylic pipe was chosen to simulate a well, and a 20-cm thick layer of pebbles was placed at the bottom of the test pipe to reduce the turbulent instabilities near the inlet. The flow velocity is anticipated to be interfered by the placement of the instrument. The inlet of flow-through cell blocks about 4% of the cross section area of the pipe. It is possible to slightly reduce the flow velocity at the central position of the pipe (Fig. 1a). In order to minimize the instability of inflow rate caused by the pump, the inflow rate in our experimental setting was driven by the difference in elevation head and was controlled by a throttling pressure valve at the bottom of the pipe. The system allows water overflow to maintain a constant hydraulic gradient, and we collect overflowed water to measure the discharge rate. The flow system contains a pump and two vessels. The upper vessel receives the pumped water and provides hydraulic gradient to drive water flow to the overflow gate, and the lower vessel receives overflowed water from the acrylic pipe and keeps pumping water to the upper vessel to maintain a stable circulation system. The inflow rate ranges from 750 ml/min to 5700 ml/min.

Furthermore, we designed a diverter to increase the velocity of the flow passing through the flow-through cell by reducing the flux area. The diverter assembly is a collar consisting of a sponge cylinder sandwiched between two rubber gasket rings that encircled the flowmeter as shown in Fig. 3. The rubber gasket is completely sealed between the flowmeter and the pipe. The lower limit of inflow rate can thus be extended to 210 ml/min. This setting with a diverter is then used to evaluate the performance of velocity measurement under high flow rate conditions and the tests with packers in the field.

2.3. Measurement error and precision

Fig. 4 illustrates the average flow velocity, measured flow velocity, Coefficient of variation (CV), and measurement error of heat-pulse flowmeter measurements at different inflow rates. These tests results were obtained when the flowmeter was positioned at the center of pipe. The average flow velocity (V_a) in the pipe is defined as the inflow rate per unit area which can be obtained by

$$V_a = Q/A = 4Q/\pi D^2 \tag{1}$$

where Q is the inflow rate, A is the cross-sectional area of the pipe, and D is the pipe diameter. The inflow rate is supposed to be equal to the measured discharge rate. According to the inflow rates in Fig. 4, the calculated average flow velocity ranges from 0.18 to 1.37 cm/s. The traveling time of the warm water front from the