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An assessment of borehole infiltration analyses for measuring field-saturated hydraulic conductivity in the vadose zone

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ABSTRACT

Single-borehole infiltration tests are widely used for in-situ measurement of field-saturated hydraulic conductivity, K_{fs}, in the vadose or unsaturated zone. United States Bureau of Reclamation (USBR) methods are used extensively in geologic and water management engineering to analyse single-borehole infiltration data, while borehole permeameter (BP) methods are preferred in the environmental and agricultural sciences. Little is known about how well the USBR and BP analyses correspond; hence, the objectives of this study were to compare and provide usage recommendations for some of the most common constant head and falling head USBR and BP analyses in terms of range of validity and accuracy for K_{fs} determination. HYDRUS-2D numerical simulations of variably saturated, axisymmetric flow for a range of specified K_{fs} values, porous media capillarities (as represented by sorptive number, α^*, and change in water content, $\Delta\theta$) and outflow geometries (as represented by length, L, and radius, a, of borehole discharge zone) were used to generate perturbation-free borehole test data for use in the USBR and BP analyses. The numerically generated test data consisted of steady borehole discharge rate, Q_S, versus steady ponded head, H, for the constant head borehole tests, and ponded head, H_t, versus time, t, for the falling head borehole tests. The constant head USBR estimates of K_{fs} were generally accurate (≤25% error) when $H/a \geq 10$, $\alpha^* \geq 12\ m^{-1}$, $a \geq 10$ cm and $L/a \geq 10$, but could overestimate or underestimate by more than an order of magnitude when the above parameters were outside those ranges. The falling head USBR analysis appeared to always overestimate or underestimate K_{fs} (>25% error), and the overestimates could be more than an order of magnitude when early-time H_t vs. t data were used. The constant head and falling head BP analyses, on the other hand, provided accurate K_{fs} estimates (≤26% error) for all test scenarios. The BP analyses were therefore recommended for all tested borehole configurations and porous medium characteristics, while the USBR analyses were recommended only for constant head tests when $H/a \geq 10$, $L/a \geq 10$, $\alpha^* \geq 12\ m^{-1}$, and $a \geq 10$ cm.

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1. Introduction

Various single-borehole infiltration methods are used for in-situ measurement of field-saturated hydraulic conductivity, K_{fs} [LT^{-1}], in the vadose or unsaturated zone. The methods involve drilling or augering a single borehole to the desired depth, ponding water in the borehole, and monitoring the discharge of water out of the borehole and into the surrounding unsaturated porous medium under constant head or falling head conditions. The borehole may be uncased (open) if the porous medium is cohesive (Figure 1a,b), or cased (lined) if the porous medium is un-cohesive (Figure 1c,d). In uncased boreholes, the water discharge (outflow) zone may be defined by the depth of ponded water (Figure 1a), or by installation of a packer connected to a water delivery or "drop pipe" reservoir (Figure 1b). In cased boreholes, the water discharge zone may be defined by the open base of the casing (Figure 1c); by a perforated or slotted section in the casing; by a "well screen" attached to the base of the casing; or by an open section below the casing which may or may not be backfilled with fine gravel or coarse sand (Figure 1d). Single-borehole infiltration tests are employed widely for characterizing water seepage and leachate movement, especially in the design, construction and assessment of canals, reservoirs, earthen dams, irrigation and drainage systems, waste impoundments, landfills, and waste water leach fields (e.g. Elrick and Reynolds, 1986; USBR, 1995, 2001; Reddi, 2004; Chiasson, 2005).

In geologic and water management engineering, the most commonly used analyses of borehole infiltration data from the vadose zone are variously known as "pressure permeability", "gravity permeability", "shallow well pump-in" and "percolation" tests; and they appear in many international texts and handbooks, such as the American "United States Bureau of Reclamation" (USBR) method manuals (e.g. USBR, 1974, 1995, 1998, 2001), the British "Soil and Environmental Analysis" handbook (Youngs, 2001), the Australian

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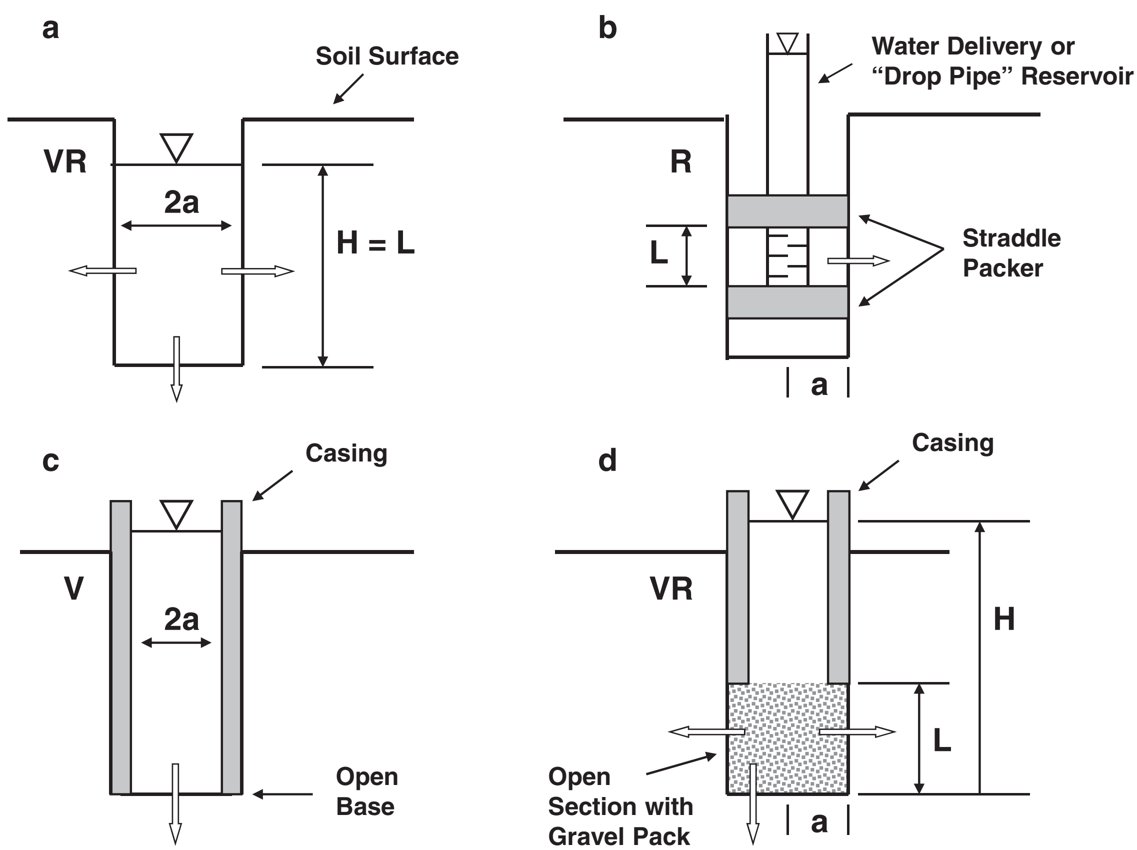

Fig. 1. Common borehole configurations for conducting single-borehole infiltration tests: a) combined vertical and radial water discharge (VR) from an uncased (open) borehole; b) radial water discharge (R) through a straddle packer installed in an uncased borehole; c) vertical water discharge (V) from a fully cased borehole; and d) combined vertical and radial discharge (VR) from a cased borehole with a basal gravel pack. H = water ponding depth; L = length of water discharge zone; a = radius of water discharge zone. Block arrows indicate directions of water outflow through discharge zone.

"Soil Physical Measurement and Interpretation for Land Evaluation" manual (Mackenzie, 2002), and the Czech-American text "Soil Hydrology" (Kutilek and Nielsen, 1994). For simplicity, these analyses will be referred to as "USBR tests", with the understanding that they are widely applied throughout the world in geologic and water management engineering. In environmental and agricultural science, on the other hand, alternative analyses are more commonly used (e.g. Reynolds and Elrick, 2002; Reynolds, 2008, 2010, 2011); and these are often referred to as "borehole permeameter" (BP) tests. The two sets of tests differ primarily in their analyses of soil water flow, and in the dimensions of the borehole. Specifically, the USBR analyses are based on saturated flow theory (Laplace equation) and consider only the hydrostatic pressure component of discharge from the borehole (e.g. Zangar, 1953). The BP analyses, on the other hand, are based on variably saturated flow theory (Richards equation) and include the hydrostatic pressure, capillarity and gravity components of borehole discharge (e.g. Reynolds et al., 1985; Reynolds, 2008, 2010, 2011). Additionally, the diameter and length of borehole discharge zone used in the USBR tests tend to be on the order of 10–20 cm and ≥100 cm, respectively (e.g. USBR, 2001), while those used in the BP tests tend to be on the order of 3–10 cm and 5–50 cm, respectively (e.g. Reynolds, 2008).

Given the differences in theory and application, one might expect USBR and BP analyses to yield greatly different K_{fs} estimates under certain conditions, and this has indeed been found (e.g. Philip, 1985; Reynolds et al., 1985). To the author's knowledge, however, the two sets of analyses have never been rigorously compared in terms of accuracy or range of validity. Hence, the objectives of this study were to: i) use numerical and analytical methods to compare the most common USBR and BP analyses in terms of range of validity and accuracy for K_{fs} determination; and ii) provide recommendations for use of the USBR and BP analyses.

2. Materials and methods

2.1. USBR analyses

The USBR analyses considered here include the constant head and falling head "pressure permeability" tests (e.g. Fig. 17–5 and p. 165, respectively, in USBR, 2001), and the constant head "gravity permeability" tests (e.g. Fig. 17–10, Fig. 17–11 and Fig. 17–12 in USBR, 2001). These tests apply for homogeneous vadose zones with deep (non-interfering) water tables (i.e. "Zone 1" in Fig. 17–5 and Fig. 17–6 in USBR, 2001); and as mentioned above, they assume that discharge from the borehole is due entirely to the hydrostatic pressure of the ponded water.

2.1.1. Constant head USBR analyses

The analyses for the constant head tests are usually based on (Ahrens and Barlow, 1951; Zangar, 1953):

$$K_{USBR} = \frac{Q_S}{C_U a H} \tag{1.1}$$

where K_{USBR} [LT^{-1}] is the USBR estimate of porous medium field-saturated hydraulic conductivity, Q_S [L^3T^{-1}] is the measured steady discharge out of the borehole and into the porous medium, a [L] is the effective radius of the water discharge zone in the borehole

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