Engineering Geology 185 (2015) 10–19

Contents lists available at ScienceDirect

Engineering Geology

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

A generalized variable-head borehole permeameter analysis for saturated, unsaturated, rigid or deformable porous media

W.D. Reynolds *

Greenhouse and Processing Crops Research Centre, Agriculture and Agri-Food Canada, 2585 County Road 20, Harrow, Ontario N0R 1G0, Canada

ARTICLE INFO

Article history:
Received 25 January 2014
Received in revised form 17 October 2014
Accepted 29 November 2014
Available online 9 December 2014

Keywords:
Permeability
Hydraulic conductivity
Capillarity
Falling-head test
Rising-head test
Numerical simulation

ABSTRACT

The variable-head borehole permeameter (VHBP) method is a long-standing international standard for in-situ measurement of field-saturated hydraulic conductivity, K_{FS}, in natural and engineered porous media. Its applicability is restricted, however, because traditional VHBP theory does not apply for unsaturated or deformable porous media, and because precise knowledge of the boundary condition on the interface of the borehole outlet (screen) is required for accurate K_{FS} determination. This study extends the traditional VHBP theory to include saturated, unsaturated, rigid and deformable porous media, and also clarifies the boundary condition at the screen interface. Using a recent VHBP analysis developed for rigid, unsaturated porous media, it is shown (via flow conservation and the total increment theorem) that change in porous medium water content, $\Delta\theta$, can be extended to include change in porosity (deformation) as well as change in degree of saturation. It is also shown that the appropriate boundary condition on the borehole screen is antecedent pore water pressure head, H_a, for saturated porous media, but effective wetting front pressure head, ψ_f (or sorptive number, α^*), for unsaturated porous media. The K_{FS}, $\Delta\theta$, H_a, and ψ_f (or α^*) parameters can be determined using numerical optimization (e.g. "Solver" in the Excel spreadsheet) to curve-fit the extended VHBP analysis directly to borehole head versus time measurements; however, fitting to the velocity graph (borehole head plotted against change in head with time) is generally less problematic. In a cursory assessment of the extended VHBP analysis, K_{FS} was determined with ≤7% error, $\Delta\theta$ with ≤15% error, H_a with ≤1.4% error, and ψ_f with ≤0.5% error, which is more than sufficient accuracy for most applications. It was concluded that the VHBP method was successfully extended for application to saturated, unsaturated, rigid and deformable porous media.

1. Introduction

The variable-head borehole permeameter (VHBP) is one of the so-called "single borehole", "single well", "monitoring well", "piezometer", "well permeameter", or "slug test" methods for in-situ measurement of field-saturated hydraulic conductivity, K_{FS} [LT^{-1}], in natural and engineered porous media (e.g. Reynolds, 2013). The method involves boring a hole into a porous medium; constructing a water outlet or inlet zone of known dimensions in the bottom of the hole; inducing a sudden change (increase or decrease) in borehole water level from its initial level; and then monitoring the over-damped (monotonic) change in borehole water level as water flows through the outlet/inlet zone (Figure 1). The outlet/inlet zone is usually constructed by attaching a perforated pipe section or packer assembly to the bottom of a solid-wall pipe, and the zone may or may not include a bentonite-sealed "gravel pack" or "lantern" (Chapuis, 2001; Figure 1). The method has appeared for decades in many national standards (e.g. Highway Research Board, 1958; CAN-BNQ, 1988, 2008; AFNOR, 1992); and it is used world-wide for design and performance assessment of reservoirs, embankments, earthen dams, waste impoundments, runoff retention ponds, groundwater recharge facilities, irrigation and drainage systems, etc. (e.g. Freeze and Cherry, 1979; Reddi, 2004). The VHBP method appears to have been first developed for geotechnical applications by Lefranc (1936), for soil applications by Kirkham (1946), and for groundwater applications by Hvorslev (1951).

Despite its long and wide-spread use, continuing difficulties that affect the method's applicability and accuracy include: i) invalidity of VHBP theory for unsaturated and/or deformable porous media; and ii) requirement in the VHBP analysis for appropriate and accurate knowledge of the boundary condition in the porous medium at the outlet/inlet zone (hereafter referred to as the "screen", Figure 1). The objectives of this study were consequently to present: i) approximate VHBP theory that applies for saturated, unsaturated, rigid and deformable porous media; and ii) VHBP analysis procedures that provide accurate and appropriate estimates of the porous medium boundary condition at the screen. We first describe traditional VHBP theory, analyses and limitations, then proceed to enhancements that circumvent the limitations, and finally provide a few illustrative examples of how the enhanced analysis might be applied and interpreted.

* Tel.: +1 519 738 1265; fax: +1 519 738 2929.
E-mail address: dan.reynolds@agr.gc.ca.

http://dx.doi.org/10.1016/j.enggeo.2014.11.019

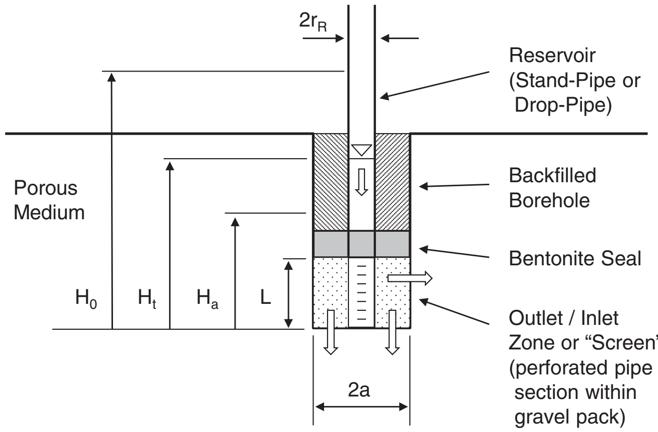

Fig. 1. Schematic of a variable-head borehole permeameter (VHBP) test in a saturated porous medium; falling-head version with the borehole outlet/inlet zone or "screen" formed by a gravel pack beneath a bentonite seal. The water level is raised suddenly in the permeameter reservoir at time, t = 0, to initial level, $H = H_0$, and water level decline with time, H_t vs. t, is then monitored. r_R = reservoir inside radius; H_a = antecedent pore water pressure head in the porous medium adjacent to the screen; L = screen length; a = screen radius. Block arrows indicate directions of water flow.

2. Traditional VHBP theory, analyses and limitations

The traditional VHBP analysis for monotonic water level response in rigid porous media can be written as (e.g. Kirkham, 1946; Hvorslev, 1951):

$$\ln\left[\frac{H_t-H_a}{H_0-H_a}\right] = CK_{FS}t; \quad t\geq 0 \tag{1}$$

where H_t [L] is the water pressure head in the screen at time, t [T], H_0 [L] is the initial pressure head in the screen at t = 0 (i.e. start of test immediately after the induced sudden change in water level), H_a [L] is the water pressure head (assumed constant) in the porous medium adjacent to the screen (boundary condition at screen), C [L^{-1}] is a "shape factor", and K_{FS} [LT^{-1}] is the field-saturated hydraulic conductivity of the porous medium near the screen, where the term "field-saturated" acknowledges that pore water flow may be impeded by entrapped air or exsolved gas (Figure 1). The datum for measuring H_t, H_0 and H_a is most conveniently set at screen base (Kirkham, 1946; Figure 1), but may also be the top or mid-elevation of the screen, the ground surface, or some other arbitrary elevation (e.g. Hvorslev, 1951; Chapuis, 1999, 2001; Chiasson, 2005; Chapuis et al., 2012). The shape factor (C) accounts for various conditions associated with the test (e.g. screen or gravel pack geometry, reservoir size, porous medium boundaries or layers of contrasting permeability at some distance from the screen); and can be written in the form:

$$C = \pm\frac{c}{S_{inj}} = \pm\frac{4r_S}{r_R^{\,2}} \tag{2}$$

where c [L] is a screen geometry factor, S_{inj} [L^2] is the reservoir cross section, r_S [L] is the "effective" radius of the screen, r_R [L] is the inside radius of the variable-head water reservoir which is frequently referred to as the "stand-pipe" or "drop-pipe" (Figure 1), and the sign on C is negative (−) if H_t decreases with time (falling-head test) or positive (+) if H_t increases with time (rising-head test).

The effective screen radius (r_S) usually assumes that the surface area of the borehole outlet/inlet zone, A_{Screen} [L^2], can be represented mathematically as an "equivalent sphere" or "equivalent ellipsoid". For an equivalent sphere surface, A_{Sphere} [L^2] (e.g. Lefranc, 1936; Kirkham, 1946; Philip, 1993; Reynolds, 2011, 2013):

$$A_{Sphere} = 4\pi r_S^{\,2} = A_{Screen}. \tag{3.1}$$

Hence, for vertical flow through a circular "end-of-pipe" screen of radius, a:

$$r_S = \frac{a}{2}; \tag{3.2}$$

for radial flow through a blind-ended cylindrical screen (e.g. well/drive point, straddle packer) of length, L, and radius, a:

$$r_S = \left(\frac{aL}{2}\right)^{1/2}; \tag{3.3}$$

and for combined vertical and radial flow through a cylindrical screen with permeable base (e.g. gravel pack or lantern) of length, L, and radius, a:

$$r_S = \left(\frac{a^2}{4}+\frac{aL}{2}\right)^{1/2} \tag{3.4}$$

where L [L] and a [L] are the height and radius, respectively, of the screen, and it is understood that the screen is continuously submerged during the test (i.e. $0 \leq L \leq H_t$) (Figure 1). It should also be understood that alternative analytical solutions or electric analogue values may be more accurate than equivalent spheres or ellipsoids for certain screen geometries (e.g. Chapuis, 1989; Reynolds, 2013); and that certain flow domain boundary effects may require r_S values determined using image theory or numerical simulations (e.g. Chapuis, 1989; Chapuis and Chenaf, 2008; Chapuis et al., 2012). For example, a slightly more accurate version of Eq. (3.2) used by Hvorslev (1951) and others for end-of-pipe flow in saturated porous media is given by:

$$r_S = \frac{a}{2.284} \tag{3.5}$$

which was obtained using 3-D electric analogue methods (Chapuis, 1989).

The K_{FS} value is often obtained using the "basic time lag" analysis of Hvorslev (1951), or simply by:

$$K_{FS} = \frac{S_{LN}}{C} \tag{4}$$

where S_{LN} [T^{-1}] is the slope of the best-fit straight line through linear (or "linearized") $\ln[(H_t - H_a) / (H_0 - H_a)]$ vs. t data (e.g. Line 1, Figure 2a). Both approaches (i.e. basic time lag analysis and Eq. (4)) can yield accurate K_{FS} values, provided that certain assumptions implicit in Eq. (1) are met; namely, saturated flow in a saturated, rigid porous medium, and H_a accurately known. Unfortunately, one or more of these assumptions are frequently violated in field environments — i.e. the porous medium may be unsaturated, tension saturated, or deformable near the screen; and H_a must usually be guessed or assumed, as it almost never equals the antecedent water level in the borehole due to leakage past packers or bentonite seals (Figure 1), hydraulic head gradients, and various time lag effects (Chapuis, 1998, 2001, 2009; Chapuis et al., 2012). Underestimation of the actual H_a typically causes convex $\ln[(H_t - H_a) / (H_0 - H_a)]$ vs. t plots (Line 2, Figure 2a), while overestimation of H_a causes concave plots (Line 3, Figure 2a) (Chapuis, 2001). In either case, application of Eq. (4) by fitting a straight line through some or all of the curvilinear $\ln[(H_t - H_a) / (H_0 - H_a)]$ vs. t data can yield K_{FS} results that are non-unique and/or incorrect by more than an order of magnitude (e.g. Figure A7 and associated discussion in Chapuis, 1998, 1999, 2001; Chiasson, 2005).

The so-called "velocity graph" or "velocity plot" analysis originally proposed by Schneebeli (1954) can provide accurate determinations of both K_{FS} and H_a under certain conditions (e.g. Chapuis, 1999, 2001; Chiasson, 2005, 2012; Chapuis et al., 2012). Here, dH_t/dt of Eq. (1) is plotted against borehole head, H_t, to obtain:

$$H_t = \frac{1}{CK_{FS}}\left(\frac{dH_t}{dt}\right) + H_a, \tag{5}$$