An assessment of the single-head analysis for the constant head well permeameter

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Reynolds, W. D., Vieira, S. R. and Topp, G. C. 1992. **An assessment of the single-head analysis for the constant head well permeameter.** Can. J. Soil Sci. **72**: 489-501. An in-situ constant head well permeameter (CHWP) method employing three or more ponded heads per well was used to establish relationships between field-saturated hydraulic conductivity (K_{fs}), matric flux potential (ϕ_m), the alpha parameter (α^*), soil texture, and soil structure. The relationships were then used to evaluate a single-head CHWP technique which employs representative mean α^* values in the determination of K_{fs} and ϕ_m. The measurements were made at several depths on four soils which ranged in texture from loamy sand to silty clay, and in structure from single grain to strong, fine subangular blocky. The K_{fs} and ϕ_m results obtained from the multiple-head CHWP measurements were found to be highly variable within and between soils, yielding within-soil ranges as high as 3.5 orders of magnitude and standard deviation factors (SDF) as high as 5.1. The geometric mean (GM) K_{fs} and ϕ_m values were also highly variable between soils, but they were controlled primarily by soil structure rather than by soil texture or other factors. The α^* values, on the other hand, were relatively consistent both within and between soils, yielding an overall SDF of only 1.2 and an overall GM of 11 m^{-1}. Use of $\alpha^* = 11\ m^{-1}$ in the single-head CHWP technique yielded K_{fs} and ϕ_m values which were usually accurate to within a factor of 2, and often accurate to within ±25%. These levels of accuracy are within acceptable limits for a field method, considering the many potential sources of error and the extreme range and variability of K_{fs} and ϕ_m normally encountered in the field.

Key words: Constant head well permeameter, hydraulic conductivity, matric flux potential, alpha parameter, soil texture, soil structure, single-head analysis

Reynolds, W. D., Vieira, S. R. et Topp, G. C. 1992. **Évaluation de l'analyse sur charge unique pour les mesures au perméamètre à charge constante.** Can. J. Soil Sci. **72**: 489-501. Une méthode d'observation in situ au perméamètre à charge constante, utilisant trois charges d'eau ou davantage par tube, a servi à établir les rapports entre la conductivité hydraulique à saturation (K_{fs}), le potentiel de flux matriciel (ϕ_m), le paramètre alpha (α^*), la texture et la structure du sol. Ces rapports ont ensuite servi à évaluer la technique à charge unique qui utilise des valeurs α^* moyennes représentatives dans la détermination de K_{fs} et de ϕ_m. Les mesures étaient faites à plusieurs profondeurs sur quatre sols allant du loam à l'argile limoneux et de la structure granulaire à la structure polyédrique subangulaire fine, forte. Les valeurs K_{fs} et ϕ_m obtenues pour les mesures à charge multiple se sont révélées très variables, tant dans un sol que d'un sol à l'autre, donnant des écarts intra-sol pouvant aller à des ordres de grandeur de 3,5 et des écarts-types pouvant atteindre 5,1. La moyenne géométrique (GM) des valeurs K_{fs} et ϕ_m montrait également de grandes variations d'un sol à l'autre, mais elles étaient commandées davantage par la structure du sol que par la texture ou par d'autres facteurs pédologiques. En revanche, les valeurs α^* étaient relativement constantes, tant dans un même sol que d'un sol à l'autre, donnant des écarts types de seulement 1,2 et une moyenne géométrique générale de 11/m. L'application de la valeur $\alpha^* = 11$/m à la technique à charge unique réduisait l'élément erreur dans les valeurs K_{fs} et ϕ_m à un facteur habituellement inférieur à 2 et souvent inférieur à ± 25%. Ces niveaux de justesse se situent dans les limites acceptables pour une méthode de terrain, compte tenu des nombreuses sources d'erreur potentielles ainsi que de l'amplitude et de la variabilité extrêmes des valeurs K_{fs} et ϕ_m normalement observées sur le terrain.

Mots clés: Perméamètre à charge constante, conductivité hydraulique, potentiel de flux matriciel, paramètre, texture du sol, structure du sol, analyse sur charge unique

Reynolds et al. (1985) proposed a constant head well permeameter technique for simultaneous in-situ measurement of the soil hydraulic properties, field-saturated hydraulic conductivity (K_{fs}) and matric flux potential (ϕ_m). In their method, two or more heads (H) are ponded sequentially in a well augered into unsaturated soil and the relationship,

$$Q_s = [(2\pi H^2/C) + \pi a^2]K_{fs} + (2\pi H/C)\phi_m \quad (1)$$

is solved for K_{fs} (ms^{-1}) and ϕ_m ($m^2\ s^{-1}$) using simultaneous equations (two heads ponded) or least squares regression (two or more heads ponded) (Reynolds et al. 1985; Reynolds and Elrick 1986). In Eq. 1, Q_s ($m^3\ s^{-1}$) is the steady flow rate out of the well, H (m) is the steady depth of ponding (head) in the well, a (m) is the well radius, and C is a dimensionless shape factor.

Although this "multiple-head" procedure (known as the "Richards" analysis (Reynolds and Elrick 1986)) works well in uniform, structureless soils (Richards 1987), heterogeneity in the forms of layering, cracks, worm holes, root channels, etc. can result in a high percentage of invalid (i.e., negative) K_{fs} and ϕ_m values (Vieira et al. 1988; Wilson et al. 1989). This problem is further compounded by ill-conditioning of the simultaneous equations and least squares coefficient matrices (Philip 1985; Elrick et al. 1989). In a highly structured loam soil, Vieira et al. (1988) obtained a "success" rate (i.e. when both K_{fs} and ϕ_m are positive) of only 27% for the simultaneous equations procedure, and only 17% for the least squares procedure. The data currently available suggest that success rates in the order of 20–70% can generally be expected in most structured soils (Bradshaw 1986; Richards 1987; Vieira et al. 1988; Wilson et al. 1989).

To avoid the problem of negative values, Elrick et al. (1989) proposed a single-head well permeameter technique for determining K_{fs} and ϕ_m. Their approach involves rewriting Eq. 1 in the form (Elrick et al. 1989),

$$K_{fs} = CQ_s/[2\pi H^2 + C\pi a^2 + (2\pi H/\alpha^*)] \quad (2)$$

$$\phi_m = CQ_s/[(2\pi H^2 + C\pi a^2)\alpha^* + 2\pi H] \quad (3)$$

where α^* (m^{-1}) is defined by

$$\alpha^* = K_{fs}/\phi_m \quad (4)$$

Values of K_{fs} and ϕ_m are then obtained by substituting into Eqs. 2 and 3 a "site estimated" α^* value, obtained by visually estimating into which one of four "porous media" categories (Table 1) the material at the field site fits. Because the value of α^* is selected a priori in this technique (using Table 1), Eqs. 2 and 3 can obviously be solved using Q_s from only one ponded head (H), and thus negative K_{fs} and ϕ_m values are avoided.

The physical basis of the single-head technique is the linkage between the magnitude of α^*, soil capillarity and the type of porous medium. The α^* value indicates the relative importance of the field-saturated and unsaturated, or "capillarity", components of flow in the soil surrounding the permeameter well (Reynolds and Elrick 1987). The field-saturated component of flow is represented by the first two terms on the right of Eq. 1 (i.e., the K_{fs} terms), and the capillarity component is represented by the third term on the right (i.e., the ϕ_m term) (Reynolds et al. 1985). The smaller the α^* value (i.e. the smaller the K_{fs}/ϕ_m ratio in Eq. 4), the greater the proportion of the steady flow out of the permeameter well (i.e. Q_s in Eq. 1) that is due

Table 1. Porous media categories used for estimating α^* in the single-head well permeameter analysis of Elrick et al. (1989)

Porous media category	Corresponding α^* value (m^{-1})
Compacted, structureless clayey materials such as landfill caps and liners; lacustrine or marine sediments, etc.	1
Soils which are both fine textured (clayey) and unstructured.	4
Most structured soils from clays through loams; also includes unstructured medium and fine sands. The first choice for most soils.	12
Coarse and gravelly sands; may also include some highly structured soils with large cracks and macropores.	36

to the capillarity of the soil (Reynolds and Elrick 1987). Since fine textured, structureless soils tend to have high capillarity, they consequently tend to also have low α^* values. Similarly, coarse textured and/or structured soils tend to have lower capillarity, and thereby higher α^* values. Elrick et al. (1989) used this relationship along with α^* values obtained from the literature to develop the porous medium categories in Table 1.

In order for the single-head approach to produce usable results, both the range and sensitivity of α^* in porous media should be small relative to those of K_{fs} and ϕ_m. This appears to be the case, although very little testing has been conducted so far. The few data available suggest that, for the most part, $1\ m^{-1} \leq \alpha^* \leq 100\ m^{-1}$ for ponded infiltration in the field (White and Sully 1987; Elrick et al. 1989). This range of 2 orders of magnitude is indeed small relative to the 6 or more orders of magnitude over which K_{fs} and ϕ_m can range from coarse sand soils to "tight" clay soils (Freeze and Cherry 1979; Warrick and Nielsen 1980). Additionally, the porous media categories in Table 1 are broad enough that the site estimates of α^* are not likely to be in error by more than one category; i.e. it is possible that an un~~saturated~~ structured clay ($\alpha^*=4\ m^{-1}$) could be categorized incorrectly as a structured clay ($\alpha^*=12\ m^{-1}$), but it is unlikely that it would be categorized as incorrectly as a coarse sand or as a clay with very large cracks and macropores ($\alpha^*=36\ m^{-1}$). Site estimates of α^* that are incorrect by one category usually introduce a maximum error of only a factor of 2 or 3 into the K_{fs} and ϕ_m calculations, which is generally acceptable for practical field application (Elrick et al. 1989).

Although the above preliminary indications are certainly encouraging, there is still a need for more extensive testing and analysis of the single-head procedure. Accordingly, the objectives of this study were: (i) to characterize the relationships between K_{fs}, ϕ_m, α^*, soil texture and soil structure by using multiple-head well permeameter measurements made on a range of soil types and structures; and (ii) to use these relationships to assess the accuracy of the single-head well permeameter analysis of Elrick et al. (1989) for natural soils. We will first describe the theoretical relationships used for testing the single-head technique, and then proceed with the analysis.

THEORY

The procedures used for testing the single-head well permeameter analysis are based on a technique proposed by Vieira et al. (1988) for analyzing multiple-head well permeameter measurements. In their approach, negative K_{fs} and ϕ_m values were avoided by employing a quasi-empirical technique based on the "successful" multiple-head well permeameter calculations (i.e. both K_{fs} and ϕ_m positive). They first combined the "Laplace" analysis of Reynolds and Elrick (1985, 1987),

$$K_L = CQ_s/(2\pi H_m^2 + C\pi a^2) \quad (5)$$

with Eq. 2 to obtain,

$$K_{fs} = \left[\frac{(2H_m^2 + Ca^2)}{(2H_m^2 + Ca^2)+(2H_m/\alpha^*)}\right] K_L \quad (6)$$

where $H_m(m)$ is the largest of the heads ponded in the well. Comparison of Eqs. 1, 2 and 5 shows that K_L (ms^{-1}) is an estimate of the field-saturated hydraulic conductivity obtained when soil capillarity (i.e. the ϕ_m term in Eq. 1 or the α^* term in Eq. 2) is disregarded. As a consequence, $K_L \geq K_{fs}$ for $\phi_m \geq 0$ in Eq. 1 and for $0 < \alpha^* \leq \infty$ in Eq. 2. Equation 6 shows the functional relationship between K_{fs}, soil capillarity and K_L. It is seen that the relationship between K_{fs} and K_L is direct, but the relationship between K_{fs} and capillarity is inverse, i.e. K_{fs} decreases as ϕ_m increases.

Vieira et al. (1988) "generalized" Eq. 6 using the empirical form,

$$K_{fs} = \beta K_L{}^{\gamma} \quad (7)$$

where β and γ are dimensionless empirical parameters (the rationale for this is discussed below). Also, they rearranged Eq. 6 to give,

$$\frac{1}{\alpha^*} = \frac{(2H_m^2 + Ca^2)}{2H_m}\left[\frac{K_L}{K_{fs}} - 1\right] \quad (8)$$

The values of β and γ were then determined by least squares fitting Eq. 7 (in its logarithmic form) to plots of $\ln K_{fs}$ vs. $\ln K_L$ data. The (K_L, K_{fs}) data pairs comprising the plots were obtained from wells where successful multiple-head well permeameter calculations were made (i.e., both K_{fs} and ϕ_m positive). Equations 5, 7 and 8 were then applied to all of the wells, regardless of whether or not the multiple-head calculations were successful, to produce estimates of K_{fs}, α^* and ϕ_m (via Eq. 4). This technique assumes that scatter in the successful multiple-head results is due to error or "noise" caused by random small-scale soil heterogeneity, ill-conditioning of the coefficient matrices, etc., and that the overall trend is "signal" resulting from the interaction between the field-saturated (K_{fs}) and capillarity (ϕ_m) components of flow. The $\ln K_{fs}$ vs. $\ln K_L$ regression therefore serves as a simple filter for separating the noise (data scatter) from the signal (data trend) (Gold 1977). Once the data trend is established by the regression, Eqs. 5, 7, 8 and 4 can be used to determine K_L, K_{fs}, α^* and ϕ_m, respectively, for the wells where the multiple-head calculations were not successful (i.e. K_{fs} or ϕ_m negative). The use of Eq. 7 in the regression provides a means of determining for any particular data set if α^* in Eqs. 6 and 8 is constant or variable. If the least squares fitting of Eq. 7 produces $\gamma = 1$, then α^* is a constant in Eqs. 6 and 8. If the fitting produces $\gamma \neq 1$, then α^* is not constant.

Vieira et al. (1988) considered Eqs. 7 and 8 sufficiently accurate for practical application, provided that there are enough (K_L, K_{fs}) data pairs from the multiple-head analysis to produce an accurate and stable regression line. They obtained good fits of Eq. 7 to the data ($R > 0.94$), and estimates for all the "failed" multiple-head measurements (i.e. K_{fs} or ϕ_m negative) were obtained with very little extrapolation of the regression beyond the limits of the (K_L, K_{fs}) data. They also found that the "successful" multiple-head measurements were distributed approximately uniformly throughout the field site, which suggests no bias towards any particular soil texture or structural conditions. Equations 5, 7 and 8 and the associated procedures were used in this study (discussed further in the Materials and Methods).

It is also possible to conduct the above quasi-empirical analysis in terms of ϕ_m, rather than K_{fs}. The ϕ_m-based relationships that correspond to Eqs. 5, 6, 7 and 8 have the forms,

$$\phi_G = CQ_s/(2\pi H_m) \quad (9)$$

$$\phi_m = \left[\frac{2H_m}{(2H_m^2 + Ca^2)\alpha^* + 2H_m}\right]\phi_G \quad (10)$$

$$\phi_m = b\phi_G{}^d \quad (11)$$

$$\alpha^* = \frac{2H_m}{(2H_m^2 + Ca^2)} \left[\frac{\phi_G}{\phi_m} - 1\right] \quad (12)$$

where ϕ_G ($m^2\ s^{-1}$) is the matric flux potential obtained using the "Gardner" analysis (Reynolds and Elrick 1985, 1987), and b and d are dimensionless empirical parameters obtained by least squares fitting a straight line through plots of lnϕ_m vs. lnϕ_G data obtained using the multiple-head well permeameter analysis. Equations 9–12 are derived in an analogous fashion to Eqs. 5–8. The α^* value in Eqs. 10 and 12 is constant when the least squares fit of Eq. 11 produces d = 1, and α^* is variable when the fit produces $d \neq 1$. Whether one uses the K_{fs}-based relationships or the ϕ_m-based relationships appears to depend on H_m. Preliminary testing by the authors suggests the Eqs. 5–8 produce the best results when H_m is large (say, $H_m \geq 0.09$ m), and Eqs. 9–12 are best when H_m is small (say, $H_m \leq$ 0.06 m).

MATERIALS AND METHODS

Four soils were tested which range widely in texture and structure. The soil series name, soil texture, soil type, land use and a description of the type and degree of the soil structure are given in Table 2. The Rideau soil was measured at two depth ranges (Rideau 1, Rideau 2 — see also Table 3) because of an abrupt change in soil texture and structure with depth. Similarly, the Carp soil was measured at four depth ranges (Carp 1–4, see also Table 3) because of a gradual change in soil structure with depth. The measurements for the Beverly and Fox soils were obtained from the literature (Bradshaw 1986; Richards 1987).

Table 2. Physical characteristics of the soils investigated

Soil series	Texture[z] Sand (%)	Clay (%)	Soil type	Land use	Soil structure[z]
Rideau 1	42	26	Loam	>5 year Legume/Grass Pasture	Moderate - strong; fine - medium subangular blocky; extensive roots and biopores.
Rideau 2	14	42	Silty Clay	>5 year Legume/Grass Pasture	Moderate, fine subangular blocky; numerous roots and biopores.
Carp 1	29	29	Clay Loam	Long-term Grass Pasture	Moderate - strong fine subangular blocky; extensive roots and biopores.
Carp 2	26	31	Clay Loam	Long-term Grass Pasture	Moderate - strong fine subangular blocky; extensive roots and biopores.
Carp 3	28	31	Clay Loam	Long-term Grass Pasture	Moderate medium subangular blocky; some roots and biopores.
Carp 4	26	30	Clay Loam	Long-term Grass Pasture	Weak - moderate medium - coarse subangular blocky; few roots and biopores.
Beverly	14	41	Silty Clay	22-year Lawn	Weak - moderate coarse columnar - angular blocky; few roots and biopores.
Fox	82	6	Loamy Sand	Long-term Grass	Single grain, loose and weak medium granular; few fine roots and biopores.

[z] Soil texture and structure data obtained from:
Rideau soil: measured during this study.
Carp soil: texture — C. Wang (pers. comm.); structure — McKeague and Wang (1982).
Beverly soil: texture — Bradshaw (1986); structure — Kingston and Presant (1989).
Fox soil: texture — Richards (1987); structure — Presant and Wicklund (1971).

Table 3. Details of the constant-head well permeameter measurements

Soil	Number of measurements	Well radius (m)	Well depth (m)	Depth range of measurements (m)	Heads ponded (m)
Rideau 1	126	0.03	0.15	0.06 -0.15	0.05, 0.07, 0.09
Rideau 2	176	0.03	0.50	0.35 -0.50	0.07, 0.09, 0.15
Carp 1	10	0.03	0.12	0.03 -0.12	0.05, 0.07, 0.09
Carp 2	10	0.03	0.27	0.18 -0.27	0.05, 0.07, 0.09
Carp 3	10	0.03	0.57	0.48 -0.57	0.05, 0.07, 0.09
Carp 4	10	0.03	0.92	0.83 -0.92	0.05, 0.07, 0.09
Beverly	17	0.05	0.60	0.35 -0.60	0.15, 0.20, 0.25
Fox	31	0.02	0.25	0.125-0.25	0.05, 0.075, 0.10, 0.125

The well permeameter measurements were made using the Guelph Permeameter (Soilmoisture Equipment Corporation, Santa Barbara, California). Steps were taken to minimize smearing, remolding and compaction of the well surfaces by the augering process; to minimize air entrapment in the soil during the initial filling of the well; and to minimize gradual siltation of the well during the course of the measurements (see Reynolds and Elrick (1986) for details). The measurements were taken on a square grid for the Rideau soil (10-m spacing, 1.2-ha total grid area); on two parallel transects for the Carp soil (20-m transect length, 5 m between transects, 5-m spacing of measurements); on a square grid for the Beverly soil (1-m spacing, 10-m^2 total grid area); and on a single transect for the Fox soil (30-m length, 5-m spacing of measurements). Details on the number of measurements analysed, well radius, well depth, the depth ranges of the measurements, and the heads ponded in the wells are given in Table 3. Equation 5 and the least squares procedure (Reynolds and Elrick 1986) were used to obtain the "successful" (K_L, K_{fs}) data pairs from the multiple-head well permeameter measurements. The criteria used to determine a successful multiple-head measurement were the same as those of Vieira et al. (1988) (i.e., K_{fs} and ϕ_m both positive), plus the additional requirement that α^* as determined by Eq. 4 must not be substantially less than 1 m^{-1} or substantially greater than 100 m^{-1}. The α^* criterion was added on the grounds that ponded infiltration tends to produce (as mentioned above) $1 \text{ m}^{-1} \leq \alpha^* \leq 100 \text{ m}^{-1}$, regardless of the method used (White and Sully 1987; Elrick et al. 1989). The α^* criterion also served as a means of excluding the multiple-head measurements that "almost failed" due to an unrealistically low (i.e. "almost negative") K_{fs} or ϕ_m value.

The specific steps taken in the data analysis included:

(i) Calculation of K_L (using Eq. 5) for each well in the data set (one K_L value per well).
(ii) Conduction of the multiple-head analysis (least squares procedure (Reynolds and Elrick 1986)) on all multiple-head well permeameter measurements and elimination of all results that produced a negative K_{fs} or ϕ_m value, or an α^* value (via Eq. 4) which did not fall within the range, $1 \text{ m}^{-1} \leq \alpha^* \leq 100 \text{ m}^{-1}$.
(iii) Least squares fitting of Eq. 7 to the remaining (K_L, K_{fs}) data plotted as $\ln K_{fs}$ vs. $\ln K_L$, and determination of the β and γ values.
(iv) Determination of K_{fs}, α^* and ϕ_m for every well in the data set using Eqs. 7, 8 and 4, respectively.
(v) Description of relationships between K_L, K_{fs}, ϕ_m, α^*, soil texture and soil structure.
(vi) Determination of the accuracy of the single-head well permeameter analysis for natural soils by analysis of the calculated α^* values (Table 6), and by comparison to the α^* categories in Table 1.

RESULTS AND DISCUSSION

1. Relationships Between K_{fs} and K_L

An example of a $\ln K_{fs}$ vs. $\ln K_L$ plot from the multiple-head analysis is given in Fig. 1. It is seen that the data are highly correlated and fit well with the linear regression line (i.e. Eq. 7 — see also Table 4). Note also that the data fall below the 1:1 line, which is consistent with the theoretical requirement that $K_L \geq K_{fs}$. The other data sets produced similar results, and Table 4 contains the respective correlation coefficients (R) and the β and γ values from the fitting of Eq. 7. Note also in Table 4 that the four measurement

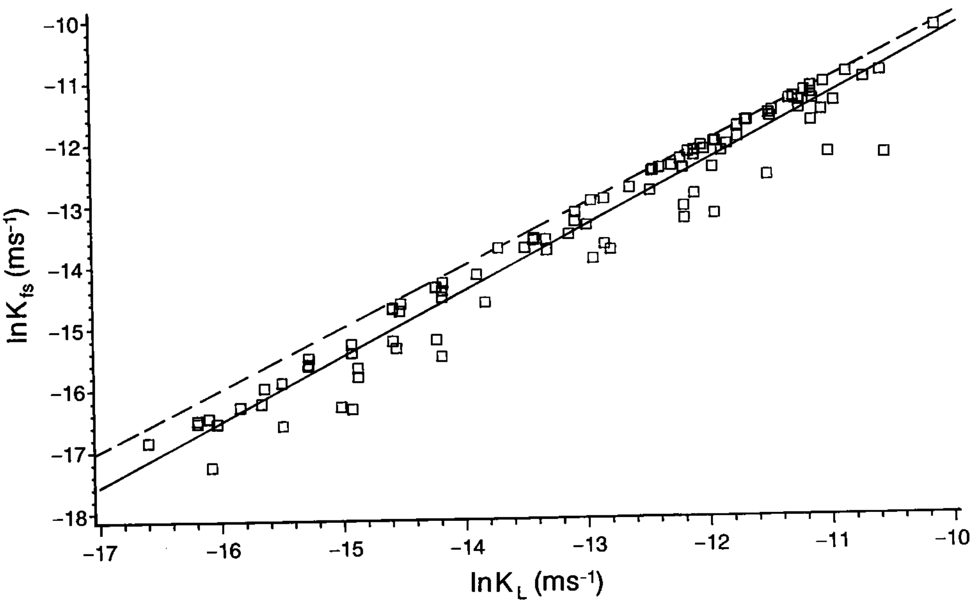

Fig. 1. Data point plot of $\ln K_{fs}$ versus $\ln K_L$ for the Rideau 2 soil. The solid line is Eq. 7 fitted to the data by least squares regression (correlation coefficient and fitting parameters given in Table 4). The dashed line is the 1:1 line.

depths for the Carp soil (i.e. Carp 1 to Carp 4, Table 3) were combined to produce one regression relationship (Carp 1–4). This was done because it was felt that there were too few (K_L, K_{fs}) data points at the individual depths (Table 3) to develop separate regression relationships, and because the combined data fell on a common trend line. As with Vieira et al. (1988), it was found that estimates for all of the failed multiple-head measurements could be obtained (via Eqs. 7, 8 and 4) with minimal extrapolation beyond the range of the (K_L, K_{fs}) data, and that the successful multiple-head measurements were distributed approximately uniformly throughout their respective measurement areas.

Table 4. Correlation coefficient (R) and the parameters of Eq. 7 (β, γ) obtained by least squares fitting a straight line through $\ln K_{fs}$ vs. $\ln K_L$ data

Soil	R	β	γ^x
Rideau 1	0.9248^z	9.0375^y	1.2422^z
Rideau 2	0.9770^z	1.1494 NS	1.0422^z
Carp 1-4	0.8589^z	1.1226 NS	1.0675^z
Beverly	0.9990^z	1.1973 NS	1.0256^z
Fox	0.9032^z	0.6779 NS	1.0085^z

^{z}Significantly different from zero at $P < 0.0001$.
^{y}Significantly different from unity at $P < 0.062$ (i.e. $\ln\beta$ significantly different from zero at $P < 0.062$).
NS, not significantly different from unity at $P < 0.648$.
^{x}The γ values are not significantly different at $P < 0.05$.

The R and γ values in Table 4 are seen to be highly significant ($P < 0.0001$), which indicates that the linear associations between $\ln K_L$ and $\ln K_{fs}$ are very strong and that the regression lines are highly plausible (Draper and Smith 1981). It is also seen that the regression slopes (γ values) are not statistically different from each other ($P < 0.05$), suggesting a common trend (i.e. $\Delta \ln K_{fs} / \Delta \ln K_L$) for all of the data sets. The regression intercepts (β) were not compared because they are dependent on the well radius (a) and maximum ponded head (H_m) (Eq. 6), which was not uniform across all of the data sets (Table 3).

2. Relationships between K_{fs}, ϕ_m, α^*, Soil Texture and Soil Structure

Table 5 gives geometric mean, standard deviation factor, and maximum and minimum values of the K_{fs}, α^* and ϕ_m values calculated using Eqs. 7, 8 and 4, respectively (log-normal distributions were assumed for K_{fs}, α^* and ϕ_m). Figure 2 presents a summary plot of α^* vs. $\log_{10}K_{fs}$ for the eight data sets.

It is clear from Table 5 that the K_{fs} and ϕ_m values reflect the structure of the soils more than the texture. The geometric mean K_{fs} and ϕ_m values of the moderately structured Rideau 2 are about 2.5 orders of magnitude higher than those of the weakly structured Beverly, despite both soils being silty clay in texture. The largest and second largest K_{fs} values are measured, respectively, in the highly structured Rideau 1 loam ($K_{fs} = 6.6 \times 10^{-5}$ ms^{-1}) and in the moderately structured Rideau 2 silty clay ($K_{fs} = 4.6 \times 10^{-5}$ ms^{-1}), rather than in the structureless Fox loamy sand. In addition, the geometric mean K_{fs} and ϕ_m values of the Carp soil decrease by nearly an order of magnitude from the moderately structured Carp 1 (0.03- to 0.12-m sampling depth) to the weakly structured Carp 4 (0.83- to 0.92-m sampling depth), despite a highly consistent clay loam texture throughout the entire profile (Table 2). The predominant influence of soil structure is illustrated in Fig. 2 as well, where it is seen that the ranges of K_{fs} covered by the four soils overlap considerably despite the significant differences in texture (e.g. the K_{fs} range of the Rideau 2 silty clay extends well beyond those of the Carp clay loam, and the Fox loamy sand). The overlapping K_{fs} ranges indicate that differing degrees of soil structure in the form of cracks, worm holes, root channels, etc. were being encountered by the individual K_{fs} measurements.

The α^* values, on the other hand, appear to be largely independent of soil structure, soil texture and K_{fs} for all but the Rideau 1 soil. It is seen in Fig. 2 that α^* is essentially constant for the virtually structureless Fox loamy sand, and that it varies only mildly with K_{fs} for the weak to strongly structured Beverly silty clay, Carp 1–4 clay loam and Rideau 2

Table 5. Field-saturated hydraulic conductivity (K_{fs}), matric flux potential (ϕ_m) and α^* obtained using the quasi-empirical analysis (Eqs. 5–8)

Soil	K_{fs} (ms^{-1})				ϕ_m (m^2 s^{-1})				α^* (m^{-1})			
	GM[z]	SDF[y]	MAX[x]	MIN[w]	GM	SDF	MAX	MIN	GM[v]	SDF	MAX	MIN
Rideau 1	5.9×10^{-6}	3.5	6.6×10^{-5}	1.2×10^{-7}	4.0×10^{-7}	1.9	8.6×10^{-7}	3.2×10^{-8}	14.8	1.9	93.5	3.7
Rideau 2	2.0×10^{-6}	5.1	4.6×10^{-5}	1.5×10^{-8}	1.5×10^{-7}	4.2	2.2×10^{-6}	1.9×10^{-9}	13.4	1.2	20.8	7.9
Carp 1	4.9×10^{-6}	1.9	1.1×10^{-5}	1.2×10^{-6}	4.4×10^{-7}	1.7	8.7×10^{-7}	1.3×10^{-7}	11.0	1.1	12.2	9.3
Carp 2	4.3×10^{-6}	2.1	1.5×10^{-5}	8.4×10^{-7}	4.0×10^{-7}	1.9	1.2×10^{-6}	9.5×10^{-8}	10.9	1.1	12.8	8.9
Carp 3	1.3×10^{-6}	2.4	2.9×10^{-6}	2.7×10^{-7}	1.4×10^{-7}	2.2	2.8×10^{-7}	3.5×10^{-8}	9.3	1.1	10.3	7.8
Carp 4	3.7×10^{-7}	3.4	4.3×10^{-6}	9.6×10^{-8}	4.6×10^{-8}	3.0	3.9×10^{-7}	1.4×10^{-8}	8.1	1.2	10.8	7.0
Beverly	4.7×10^{-9}	5.0	5.6×10^{-7}	5.2×10^{-10}	4.2×10^{-10}	4.2	2.9×10^{-8}	5.8×10^{-11}	11.0	1.2	19.2	9.0
Fox	1.3×10^{-5}	2.2	3.9×10^{-5}	2.2×10^{-6}	1.1×10^{-6}	2.2	3.0×10^{-6}	1.8×10^{-7}	12.7	1.02	13.0	12.1

[z] GM, Geometric mean.
[y] SDF, Standard deviation factor.
[x] MAX, Maximum value calculated.
[w] MIN, Minimum value calculated.
[v], Based on the Tukey HSD test ($P < 0.05$), Carp 4 is significantly different from Rideau 1, Rideau 2 and Fox; and Carp 3 is significantly different from Rideau 1.

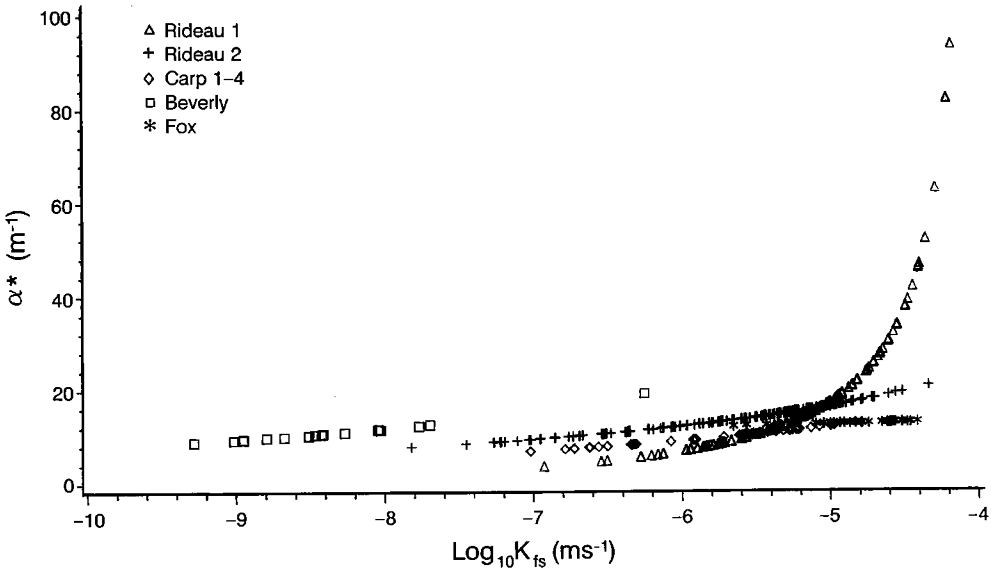

Fig. 2. Plot of α^* versus $\log_{10}K_{fs}$ for the four soils studied. A log scale was used for the X-axis because of the extreme range of K_{fs} values.

silty clay. It is also seen in Table 5 that the geometric mean α^* values differ by less than a factor of 2 (notwithstanding that some statistically significant differences exist), and that these means appear to be unrelated to soil texture, soil structure or the geometric mean K_{fs} or ϕ_m values. In addition, the standard deviation factors for α^* tend to be small relative to those for K_{fs} and ϕ_m. It appears, therefore, that α^* is relatively constant for ponded infiltration from wells augered into undisturbed, unsaturated soils.

The moderately to strongly structured Rideau 1 soil is an obvious exception to the above, with α^* increasing substantially with $\log_{10}K_{fs}$ (Fig. 2). It is not clear why this occurs since the soil is not greatly different in structure from the Rideau 2 or the Carp 1, 2 and 3 soils. Perhaps the trend is related to an interaction between the soil structure and the extensive legume rooting in that soil (Table 2). In any case, the geometric mean α^* value of 14.8 m^{-1} (Table 5) is still not greatly different from the other mean values.

The geometric mean α^* for all eight data sets from these soils is 11.2 m^{-1} (SDF = 1.2). This compares very well with the value of 10 m^{-1} estimated by White and Sully (1987) from measurements taken by several researchers using a variety of methods in a range of tilled and untilled soils. It also supports the value of 12 m^{-1} proposed by Elrick et al. (1989) for structured soils and unstructured medium and fine sands (Table 1), since all of the soils tested here fall more or less within that category. A representative α^* value of 10–12 m^{-1} therefore appears to be appropriate for most field soils, notwithstanding, of course, exceptions such as the Rideau 1 loam. The effect of using $\alpha^* = 11\ m^{-1}$ on the accuracy of the single-head well permeameter analysis is discussed below.

3. Accuracy of the Single-head Well Permeameter Analysis

The accuracy of the single-head well permeameter analysis is assessed in Table 6. The values, K_1 and ϕ_1, are, respectively, the field-saturated hydraulic conductivity (K_{fs}) and matric flux potential (ϕ_m) obtained by substituting the mean α^* for all eight data sets (i.e., $\alpha^* = 11\ m^{-1}$) into the single-head well permeameter equations (i.e. Eqs. 2 and 3). The K_2 and ϕ_2 values are similarly

Table 6. Accuracy of the single-head well permeameter analysis when using $\alpha^* = 11\ m^{-1}$

Soil	Well radius (m)	Head ponded (m)	K_2^z/K_1	K_3^z/K_1	K_4^z/K_1	ϕ_2^y/ϕ_1	ϕ_3^y/ϕ_1	ϕ_4^y/ϕ_1
Rideau 1	0.03	0.03	2.61	0.42	1.22	0.31	1.25	0.91
		0.10	1.69	0.52	1.13	0.20	1.56	0.84
		0.25	1.30	0.66	1.07	0.15	1.96	0.80
	0.05	0.03	2.38	0.44	1.20	0.28	1.29	0.89
		0.10	1.65	0.53	1.13	0.19	1.58	0.84
		0.25	1.30	0.66	1.07	0.15	1.96	0.80
Rideau 2	0.03	0.03	1.49	0.78	1.14	0.79	1.09	0.94
		0.10	1.28	0.85	1.09	0.68	1.18	0.89
		0.25	1.14	0.91	1.05	0.60	1.26	0.86
	0.05	0.03	1.45	0.80	1.13	0.77	1.11	0.93
		0.10	1.27	0.85	1.09	0.67	1.18	0.89
		0.25	1.14	0.91	1.05	0.60	1.26	0.86
Carp 1	0.03	0.03	1.07	0.89	1.00	0.97	1.05	1.00
		0.10	1.05	0.92	1.00	0.94	1.09	1.00
		0.25	1.03	0.95	1.00	0.93	1.13	1.00
	0.05	0.03	1.07	0.89	1.00	0.96	1.06	1.00
		0.10	1.05	0.92	1.00	0.94	1.09	1.00
		0.25	1.03	0.95	1.00	0.93	1.13	1.00
Carp 2	0.03	0.03	1.11	0.86	0.99	0.95	1.06	1.00
		0.10	1.07	0.90	1.00	0.92	1.11	1.00
		0.25	1.04	0.94	1.00	0.89	1.16	1.01
	0.05	0.03	1.10	0.87	0.99	0.95	1.07	1.00
		0.10	1.07	0.90	1.00	0.92	1.12	1.01
		0.25	1.04	0.94	1.00	0.89	1.16	1.01
Carp 3	0.03	0.03	0.95	0.78	0.89	1.02	1.10	1.05
		0.10	0.97	0.84	0.92	1.04	1.19	1.09
		0.25	0.98	0.90	0.95	1.05	1.27	1.13
	0.05	0.03	0.96	0.79	0.89	1.02	1.11	1.06
		0.10	0.97	0.84	0.92	1.04	1.19	1.09
		0.25	0.98	0.90	0.95	1.05	1.27	1.13
Carp 4	0.03	0.03	0.99	0.71	0.80	1.01	1.12	1.09
		0.10	0.99	0.79	0.86	1.01	1.24	1.17
		0.25	1.00	0.87	0.91	1.01	1.37	1.24
	0.05	0.03	0.99	0.73	0.81	1.01	1.14	1.10
		0.10	0.99	0.80	0.86	1.01	1.25	1.17
		0.25	1.00	0.87	0.91	1.01	1.37	1.24
Beverly	0.03	0.03	1.43	0.87	1.00	0.82	1.06	1.00
		0.10	1.24	0.91	1.00	0.71	1.11	1.00
		0.25	1.13	0.94	1.00	0.65	1.15	1.00
	0.05	0.03	1.39	0.87	1.00	0.80	1.07	1.00
		0.10	1.24	0.91	1.00	0.71	1.11	1.00
		0.25	1.13	0.95	1.00	0.64	1.16	1.00
Fox	0.03	0.03	1.12	1.07	1.10	0.95	0.97	0.96
		0.10	1.08	1.04	1.07	0.91	0.95	0.92
		0.25	1.04	1.02	1.04	0.88	0.93	0.90
	0.05	0.03	1.11	1.06	1.10	0.94	0.97	0.95
		0.10	1.07	1.04	1.06	0.91	0.95	0.92
		0.25	1.04	1.02	1.04	0.88	0.93	0.90

[z] K_1, K_2, K_3, K_4 are K_{fs} obtained using, respectively, $\alpha^* = 11\ m^{-1}$, the maximum α^* for the soil, the minimum α^* for the soil, and the geometric mean α^* for the soil.
[y] ϕ_1, ϕ_2, ϕ_3, ϕ_4 are ϕ_m obtained using, respectively, $\alpha^* = 11\ m^{-1}$, the maximum α^* for the soil, the minimum α^* for the soil, and the geometric mean α^* for the soil.

obtained by substituting in the maximum α^* for each soil (i.e., the "MAX" column for α^* in Table 5); K_3 and ϕ_3 by substituting in the minimum α^* for each soil ("MIN" α^* column in Table 5); and K_4 and ϕ_4 by substituting in the geometric mean α^* for each soil ("GM" α^* column in Table 5). The ratios, K_2/K_1, K_3/K_1, ϕ_2/ϕ_1 and ϕ_3/ϕ_1, therefore indicate for each soil the maximum "error" (i.e., maximum overestimate or underestimate) in K_{fs} and ϕ_m that can be expected from the single-head analysis when $\alpha^* = 11\ m^{-1}$ is used. Similarly, the ratios, K_4/K_1 and ϕ_4/ϕ_1, indicate the average error that can be expected. The calculations are made for a range of well radii (a) and ponded heads (H) that are commonly used in the field.

It is seen from the K_2/K_1 and K_3/K_1 columns in Table 6 that the error in K_{fs} can be as high as a factor of 2.6 ($K_2/K_1 = 2.61$) for the Rideau 1 soil. Similarly, the ϕ_2/ϕ_1 and ϕ_3/ϕ_1 columns indicate that the error in ϕ_m for Rideau 1 can be as high as a factor of 6.7 ($\phi_2/\phi_1 = 0.15$). These relatively large errors reflect the wide range of α^* values obtained for the Rideau 1 soil (Table 5, Fig. 2). The maximum errors for the other soils (i.e. Rideau 2, Carp 1-4, Beverly, Fox) which have much narrower ranges of α^* are seen to be much smaller, however, at $\pm$ 50% or less for K_{fs} (i.e. $0.95 \leq K_2/K_1 \leq 1.49$; $0.71 \leq K_3/K_1 \leq 1.07$) and $\pm$ 67% or less for ϕ_m (i.e. $0.60 \leq \phi_2/\phi_1 \leq 1.05$; $0.93 \leq \phi_3/\phi_1 \leq 1.37$). In addition, the K_4/K_1 and ϕ_4/ϕ_1 colums indicate that the average error for all of the soils (including the Rideau 1) ranges from only $\pm$ 25% (Rideau 1, Carp 4) to effectively zero (Carp 1, Carp 2, Beverly) for both K_{fs} and ϕ_m.

It should also be noted from Table 6 that the error in K_{fs} and ϕ_m changes as H changes. For example, the maximum error in K_{fs} for the Rideau 1 soil decreases from a factor of 2.6 for H = 0.03 m, to a factor of about 2 for H = 0.10 m, to within $\pm$ 52% for H = 0.25 m. For the rest of the soils, the maximum error in K_{fs} decreases from $\pm$ 50%, to $\pm$ 28%, to $\pm$ 15% for the same increase in H. The error in ϕ_m, on the other hand, changes in the opposite direction. For the Rideau 1 soil, the maximum error in ϕ_m decreases from a factor of 6.7 for H = 0.25 m, to a factor of 5.3 for H = 0.10 m, and to a factor of 3.6 for H = 0.03 m. For the other soils, the decrease is from $\pm$ 67%, to $\pm$ 50%, to $\pm$ 30% as H decreases. The average errors in K_{fs} and ϕ_m (i.e. the K_4/K_1 and ϕ_4/ϕ_1 columns) are also seen to respond to changing H when the mean α^* for the soil differs from the overall mean of 11 m^{-1}.

These trends occur because the relative importance of the α^* term in Eqs. 2 and 3 changes with the magnitude of H. In Eq. 2 the relative contribution of the α^* term (i.e., the third term in the denominator) decreases as H increases because of the H^2 term (i.e. the first term in the denominator). Consequently, K_{fs} is less sensitive to the value of α^* when H is large. In Eq. 3 the opposite occurs. Here the relative contribution of the α^* terms (i.e. the first and second terms in the denominator) decreases as H decreases, again, because of the H^2 term. ϕ_m is consequently less sensitive to the value of α^* when H is small. The accuracy of the single-head analysis is therefore increased by using large H values when determining K_{fs} via Eq. 2, and small H values when determining ϕ_m via Eq. 3. An important consequence of this general behaviour is that the above described errors in K_{fs} and ϕ_m can often be reduced even further by increasing H beyond 0.25 m when measuring K_{fs}, and decreasing H below 0.03 m when measuring ϕ_m.

Equations 2 and 3 also indicate that the sensitivities of K_{fs} and ϕ_m to α^* will change with well radius (a) in a fashion similar to the way they change with H. It is seen in Table 6, however, that the effect is negligible over the range of a values tested (i.e. $0.03\ m \leq a \leq 0.05\ m$). A wider range of "$a$" values would obviously produce a greater effect; however use of $a < 0.03$ m in the field may be questionable because of small sample size, and use of $a > 0.05$ m may be impractical because of greater water use and increased time to reach steady state flow.

It would appear from the above, then, that the use of $\alpha^* = 11\ m^{-1}$ to represent undisturbed field soils in the single-head well permeameter analysis introduces an overall error in K_{fs} and ϕ_m which is usually less than a factor of 2 and often less than ± 25%. This is particularly so if, as mentioned above, the magnitude of H is chosen to minimize sensitivity to α^*. Such levels of error are considered to be within acceptable limits for a field method, considering the many other potential sources of error and the extreme range and variability of K_{fs} and ϕ_m normally encountered in the field. In the well permeameter method, for example, smearing, remolding and/or compaction of the well surfaces during augering, gradual siltation of the well during the course of the measurement, and air entrapment by the infiltrating water can all reduce K_{fs} and ϕ_m by up to a factor of 2 or more if preventative measures are not taken (Reynolds and Elrick 1986; Stephens et al. 1987; Talsma 1987; Elrick et al. 1989). Also, the range of K_{fs} and ϕ_m for field soils is up to 6 orders of magnitude (as mentioned above), and their coefficients of variation range from about 65% for structureless sands to 600% or more for structured clays (Topp et al. 1980; Warrick and Nielsen 1980; Lee et al. 1985). Indeed, the soils in this study (Table 5) yield individual ranges as high as 3.5 and 3.1 orders of magnitude, and coefficients of variation as high as 360% (SDF = 5.1) and 260% (SDF = 4.2), for K_{fs} and ϕ_m, respectively (Rideau 2 soil). Even the structureless Fox sand is seen to have a range of 1.2 orders of magnitude and a coefficient of variation of 93% (SDF = 2.2) for both K_{fs} and ϕ_m. Additionally, the soils in this study yield a collective range of 5.1 orders of magnitude for K_{fs}, and 4.7 orders of magnitude for ϕ_m (Table 5). A common result of such large ranges and variability is that differences between mean K_{fs} and ϕ_m values of a factor of 2 or more are often not significantly different statistically (Lee et al. 1985; Reynolds and Elrick 1985). Consequently, the use of $\alpha^* = 11\ m^{-1}$ to represent most undisturbed field soils in the single-head well permeameter analysis seems justified.

CONCLUDING REMARKS

The mean, range and variability of the K_{fs} and ϕ_m values obtained using the constant head well permeameter method seem to be controlled primarily by soil structure, rather than by soil texture, vegetation or other factors. This is perhaps not surprising, considering that the method is a ponded infiltration technique and water would therefore flow preferentially through the soil macrostructure. A fortunate consequence of this is that the K_{fs} and ϕ_m values obtained using the constant head well permeameter method should be particularly useful for quantifying changes in soil structure due to land management practices, etc.

From a practical point of view, the α^* values seem to be largely independent of soil structure, soil texture, vegetation and K_{fs} (exceptions, such as the Rideau 1 soil, are presumed to be a relatively small minority). The mean α^* values for eight data sets from four soils fall within a factor of 2 of each other, and these mean values are not related to the other soil properties that were measured. In addition, the variability of α^* is small relative to that of K_{fs} and ϕ_m. These results suggest that α^* is relatively constant for ponded infiltration; and that for many soils α^* may be represented adequately by one "global" mean value. This work suggests a global mean value of $\alpha^* = 11\ m^{-1}$, which agrees well with the mean values of $10\ m^{-1}$ and $12\ m^{-1}$ proposed by White and Sully (1987) and Elrick et al. (1989), respectively.

Use of $\alpha^* = 11\ m^{-1}$ in the single-head well permeameter analysis introduces errors into the K_{fs} and ϕ_m calculations which are usually less than a factor of 2 and often within ± 25%, particularly if the magnitude of H is chosen to minimize sensitivity to α^*. These levels of error are considered to be well within acceptable limits for a field method, considering the many other potential sources of error (e.g. smearing, remolding, siltation, etc.), and considering the extreme range of variability of K_{fs} and ϕ_m normally encountered in the field. The use of $\alpha^* = 11\ m^{-1}$ in the single-head well permeameter analysis should therefore yield K_{fs} and ϕ_m determinations which are sufficiently accurate for most practical applications. Of course if greater accuracy or an independent measure of α^* is required then the quasi-empirical technique given by Eqs. 5–8 (or Eqs. 9–12) can be applied directly, providing sufficient K_L vs. K_{fs} data (or ϕ_G vs. ϕ_m data) are available to produce accurate and stable regression lines.

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