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COMPARISON OF METHODS FOR ASSESSING SOIL HYDRAULIC PROPERTIES

A Thesis Presented

by

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ABSTRACT

COMPARISON OF METHODS FOR ASSESSING SOIL HYDRAULIC PROPERTIES

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Three methods for assessing soil hydraulic properties were conducted and their results compared for two soils in Western Massachusetts. The methods compared are: the Instantaneous Profile Method, the Guelph Permeameter, and laboratory determination using intact soil cores. The saturated hydraulic conductivity and unsaturated conductivity function, as well as the moisture retention relationship when possible, were determined and the results compared with respect to their ranges of applicability and the respective limitations of each method. Close agreement was found between the moisture retention relationships determined by the instantaneous profile method and the soil cores for the ranges of pressures and moisture contents they have in common. In addition, there was also close agreement between the $K(\Psi)$ relationship measured using the instantaneous profile method and that predicted using the van Genuchten and Mualem models. The field saturated conductivity results determined using the Guelph Permeameter were one to three orders of magnitude less than the saturated conductivity results determined from soil cores and those determined by the instantaneous profile method. The unsaturated $K(\Psi)$ relationship

using Gardner's definition of matric potential and the results from the Guelph permeameter predicted hydraulic conductivity values three to four orders of magnitude less then the other two methods at 200 cm of pressure.

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CHAPTER 1

INTRODUCTION

The movement of water and solutes into and through the soil is an often overlooked aspect of watershed dynamics. The ability of the soil in the unsaturated zone to retain and conduct water is a function of its hydraulic properties. These hydraulic properties depend on the pore size distribution, which is in turn affected by the texture and the structure of each soil.

Considerable work has been done in the field of soil physics to develop an understanding of the parameters governing fluid flow in the vadose zone. The most important parameters are the saturated conductivity and the unsaturated conductivity function (Clothier and Smettem 1990) as well as the moisture retention characteristic (Boels et al. 1978; Ahuja et al.1980). The most obvious way to obtain these parameters is by experimental methods; however, these tend to be difficult, laborious, and time consuming (Libardi et al. 1980; Ragab et al. 1981). Due to the physical and theoretical limitations of measuring soil hydraulic properties in the field, many investigators have sought to derive soil hydraulic properties from moisture retention curves of soil samples removed from the field and measured in the laboratory (Millington and Quirk 1959; Brooks and Corey 1964; Green and Corey 1971; Campbell 1974; Mualem 1976; van Genuchten 1980). Calculations of the hydraulic properties from soil cores, however, are only an estimate of the actual field conditions. They indicate a great deal about the particular sample, but not necessarily about the soil as it occurs in the field (Gardner 1974).

The development of a standard method or set of procedures which can be readily used to measure the hydraulic properties of a soil in situ is therefore desirable. The effectiveness of a field method depends upon the limitations of the particular theory purporting to describe water movement in the vadose zone. The selection of the proper measurement technique for a particular site and soil is crucial (Bouma 1983). The parameter estimates used as well as the accuracy, time, repeatability, spatial resolution, and non-destructiveness are important factors for assessing the relative merits of a method.

Recently, new or modified methods have been developed to measure the hydraulic properties in situ (Reynolds et al. 1985; Stephens et al. 1987; White 1988; Amoozegar 1989). The Guelph permeameter method (Reynolds et al. 1985), a variation of the borehole method, measures the steady state flux of water out of an augered hole at a constant head to estimate the field saturated conductivity and matric flux potential of a soil. The Guelph permeameter is portable, uses little water, and is relatively fast and easy to use. However, the method is theoretically complex even if the ideal of homogeneity is met (Philip 1985). It does not directly measure the soil moisture or the matric potential of the soil. Rather, it relies on theoretical assumptions about the shape of the "saturated bulb" around the well and the slope of the lnK vs Ψ curve. The instantaneous profile method (Watson 1966; Hillel et al. 1972) is a more cumbersome, time consuming field method. It employs a neutron probe and tensiometers to directly measure the soil moisture and matric potential in a draining soil profile to determine the hydraulic conductivity function. The method assumes non-hysteretic, one-dimensional downward flow.

This study compares the effectiveness and the accuracy of the two field methods and of a standard laboratory method using intact soil cores in determining soil hydraulic properties. The hydraulic properties determined by the three methods are compared for a fine sandy loam and a silt loam soil, taking into consideration the inherent limitations and assumptions of each method.

CHAPTER 2

THEORY

Guelph Permeameter

In 1980, Talsma and Hallam reduced the time and water requirements of the Borehole permeameter method by decreasing the well radius and ponded depth of water in the well. Reynolds et al. (1983) developed the Guelph permeameter, a constant-head well permeameter which regulates the ponded head level, while measuring the flux of water into the soil from a cylindrical auger hole. The theory of the method was then expanded (Reynolds and Elrick 1985) to account for the effects of unsaturated flow.

Reynolds and Elrick (1985) described the steady flow of water out of a well into the soil in terms of three fluxes. The water flows out of the well by radial pressure-induced flux, and through the base of the well by both vertical pressure and gravity. The total flux is described by the solution of Richard's analysis for steady flow out of a cylindrical well:

$$Q = 2\pi H^2 \left\{ \frac{K_{fs}}{C} + \frac{K_{fs}}{2} \left(\frac{a}{H}\right)^2 C + \frac{\phi_m}{H} \right\} \qquad (1)$$

where K_{fs} is the field saturated hydraulic conductivity, Q the steady flow rate out of the well, a the radius of the well, H the ponded depth, and C an index characterizing the shape of the saturated bulb around the well. C is a function of the matric potential as well as the H/a ratio.

The matric flux potential ϕ_m was defined by Gardner (1958) as

$$\phi_m = \int_{\Psi}^{0} K(\Psi)\, d\Psi \tag{2}$$

The Guelph permeameter method uses the exponential $K(\Psi)$ relationship of Gardner (1958)

$$K = K_{fs}\, e^{(\alpha\Psi)};\quad \Psi_i < \Psi < 0 \tag{3}$$

where α is the slope of the ln (K) versus Ψ, and Ψ_i is the initial matric pressure head of the soil. By substituting equation 3 into the definition of the matric flux potential and integrating, Reynolds and Elrick (1985) obtained the following relationship

$$\phi_m = (K_{fs}/\alpha)\ (1-e^{(\alpha\Psi_i)}) \tag{4}$$

which they employed in their analysis of three dimensional flow from a well. That relationship can be simplified to

$$\alpha = K_{fs} / \phi_m \tag{5}$$

for most soils that are not saturated, i.e. at "field capacity" or less (Scotter et al. 1982; Rockhold et al. 1988). This derived relationship permits a simultaneous equations approach to solve for K_{fs} and ϕ_m using the Richards' analysis (GP-R) of Reynolds et al. (1985). The GP-R requires two or more measurements using different hydraulic head values in the same well.

The Guelph Permeameter method is limited by the assumptions inherent in the theory. The field saturated conductivity is measured indirectly, by making theoretical assumptions about the size of the saturated bulb, the effects of capillarity and the slope of the ln K (Ψ) curve. The field saturated conductivity is then estimated based on those assumptions and the measured flux out of the borehole. It does not take into account the possible effects of antecedent moisture, macropores, or air entrapment on the flow rate out of the well (Stephens et al. 1987; White 1988; Bouwer 1966; Mohanty et al. 1991).

Though there have been theoretical and therefore practical changes to the Guelph permeameter method since 1985 (Elrick and Reynolds 1990), the method as employed in this study uses the commercially available Guelph Permeameter (Soil Moisture Inc., Golleta, CA) and the simultaneous equations solution appropriate to it.

Instantaneous Profile Method

The instantaneous profile method for determining the unsaturated hydraulic conductivity and diffusivity is based on Darcian analysis of transient soil water content and hydraulic head profiles during vertical drainage following a thorough wetting by irrigation or rain. Richards et al. (1956) were the first to use the drainage-flux method in the field. K.K. Watson (1966) improved upon the method by replacing the computation of differences in time and depth by the presumably more accurate "instantaneous profile method" in laboratory studies (Klute and Dirksen 1986). The instantaneous profile method was then adapted to the field (Rose et al. 1965; van Bavel et al. 1968; Hillel et al. 1972).

The method requires monitoring the transient state internal drainage of a soil profile. Uniform, one-dimensional flow, non-hysteretic and isothermal conditions are assumed, enabling the use of a Darcian analysis of vertical drainage described by:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \{ K(\theta) \frac{\partial H(z,t)}{\partial z} \} \tag{6}$$

where $K(\theta)$ is the hydraulic conductivity as a function of volumetric moisture content; H (the hydraulic head) = $\Psi + z$; and z the depth positive downward (Hillel et al. 1972). Frequent and concurrent measurements of both the soil wetness and matric suction over time are required during vertical drainage following heavy irrigation or rain. From these measurements, the unsaturated hydraulic conductivity and diffusivity, as well as the water content and hydraulic head profiles can be determined following the procedure outlined by Hillel (1980).

The method can be limited by the properties of the soil being tested, as well as the assumptions inherent in the theory. The method works well when applied to field situations where a water table may be absent or too deep to affect soil moisture flow and where the soil profile is either homogeneous or heterogeneous (e.g. layered). However, it will not work well in sloping or slowly permeable soils where lateral flow would no longer be negligible (Baker et al. 1974).

Though used in the field and presumed to be representative of an area, it only measures the hydraulic properties of the soil in one direction, downward. The method is also limited in its range of application: it can only measure properties between saturated and field capacity conditions (Bouma 1983), after which water movement may be too slow to detect.

Core Method (Laboratory)

The complexity of obtaining reliable estimates of the unsaturated hydraulic conductivity in the field, due to extensive variability of the soil properties as well as time and expertise requirements, has lead some investigators to develop indirect methods for calculating the unsaturated hydraulic conductivity from the more easily measured soil moisture characteristic curve in the laboratory (van Genuchten 1980; Ragab et al. 1981; White 1988).

Several methods have been proposed for determining the unsaturated conductivity of soils from soil cores (Childs and Collis-George 1950; Millington and Quirk 1959; Brooks and Corey 1964; Campbell 1974). Some of the numerical methods, such as the Millington-Quirk method, produced tabular results which appear to be fairly accurate, but not easy to apply to non-homogeneous soils. The analytical solutions, such as those presented by Brooks and Corey, tend to predict discontinuous curves and may be less accurate than some forms of the Millington-Quirk method (van Genuchten 1980).

Mualem (1976) derived a simplified model for predicting the hydraulic conductivity from the soil water retention curve ($\Psi[\theta]$) and saturated conductivity of a soil sample

$$K = \Theta^{0.5} \left[\int_0^{\Theta} \frac{1}{\Psi(x)\,dx} \Big/ \int_0^{1} \frac{1}{\Psi(x)\,dx} \right]^2 \qquad (7)$$

where Ψ is the pressure head, x is a dummy variable, and $\Theta = \dfrac{\theta-\theta_r}{\theta_s-\theta_r}$ (s and r indicate saturated and residual values of the volumetric moisture content). The following closed form solution was developed by van Genuchten (1980)

$$\Theta = \left[\frac{1}{1+(\alpha\Psi)^n} \right]^m \qquad (8)$$

where α, n and m are characteristic parameters for each soil. The advantages of this solution are that it is both continuous and has a continuous slope. The independent parameters are determined by matching the proposed soil-water retention curve to experimental data. This equation can be used to calculate the relative unsaturated hydraulic conductivity, when substituted into the predictive conductivity model developed by Mualem (1976).

The soil core method can be used to estimate the unsaturated hydraulic conductivity of a soil when field determination is not possible, or as a laboratory basis to compare other methods or theories (Hillel 1980; van Genuchten 1980; Reynolds and Elrick 1985; White 1988). As stated earlier, it is only an estimate of actual field conditions. In this study, the core method, employing the closed form solutions equation of van Genuchten (1980) and the prediction model of Mualem (1976) for moisture retention data, is used as a standard of comparison with the instantaneous profile and the Guelph permeameter methods.

CHAPTER 3

METHODS

Experimental Procedure

Experiments were conducted in 5-by 5-meter plots in the soil physics experiment field located north of the University of Massachusetts Amherst campus. The methods were conducted in six experimental sites arranged in two transects in a toposequence, three sites in each, with 25 to 30 meters between sites.

Three replicates of each method were run at each site. The instantaneous profile method was conducted in a 1.2-m by 1.2-m area. Measurements of the soil moisture and matric potential were made with a depth moisture gauge (Troxler Electronic Laboratories, Inc., Research Triangle Park, N.C.) and tensiometers and a tensimeter (Soil Measurement Systems, Tucson, AZ) respectively, at 20 cm increments to a depth of 160 cm.

Guelph permeameter measurements were made at 15, 30, 50, 60, 70, and 90 cm depths using the Guelph Permeameter distributed by Soil Moisture Corp. Inc. (Golleta, CA). At least three different hydraulic heads were used at each test.

Soil cores were collected in 3 cm high brass cylinders using a soil corer (Soil Moisture Corp. Inc., Golleta, CA). Three cores were taken at 15, 30, 60, and 90 cm depths in both soils, plus 50 and 70 cm depths in the Enfield silt loam site (see Fig.1b). The soil cores were transported to the laboratory and saturated in a vacuum chamber. Moisture characteristic curves were determined according to the method outlined by Klute (1986) using a pressure outflow system (Soil Moisture Corp. Inc., Golleta, CA). The saturated conductivity values were measured using the model K-605 constant head permeameter (Soiltest Inc., Lake Bluff, Ill). Results from two of the six sites will be presented herein.

Site Description

The soil at the first site discussed is classified as an Aquic Dystrochrept taxadjunct (Coarse-loamy, mixed, mesic) of the Ninigret series. It is a fine sandy loam soil overlaying a uniform stratified, loamy very fine sand (see Fig. 1a) and is a moderately well drained soil. The field is underlain by a layer of compact basal till from 1.4 to 2.4 meters below the soil surface (Fayer 1981). The water table at this site fluctuates between a depth of 1 to 2 meters below the soil surface for most of the year. The second site is located 30 m east and upslope from the first site. It is a silt loam soil classified as a Typic Dystrochrept taxadjunct (Coarse silty/coarse loamy, mixed, mesic) of the Enfield series (see Fig. 1b). It is a well-drained soil with a depth to water table greater than 2.4 meters.

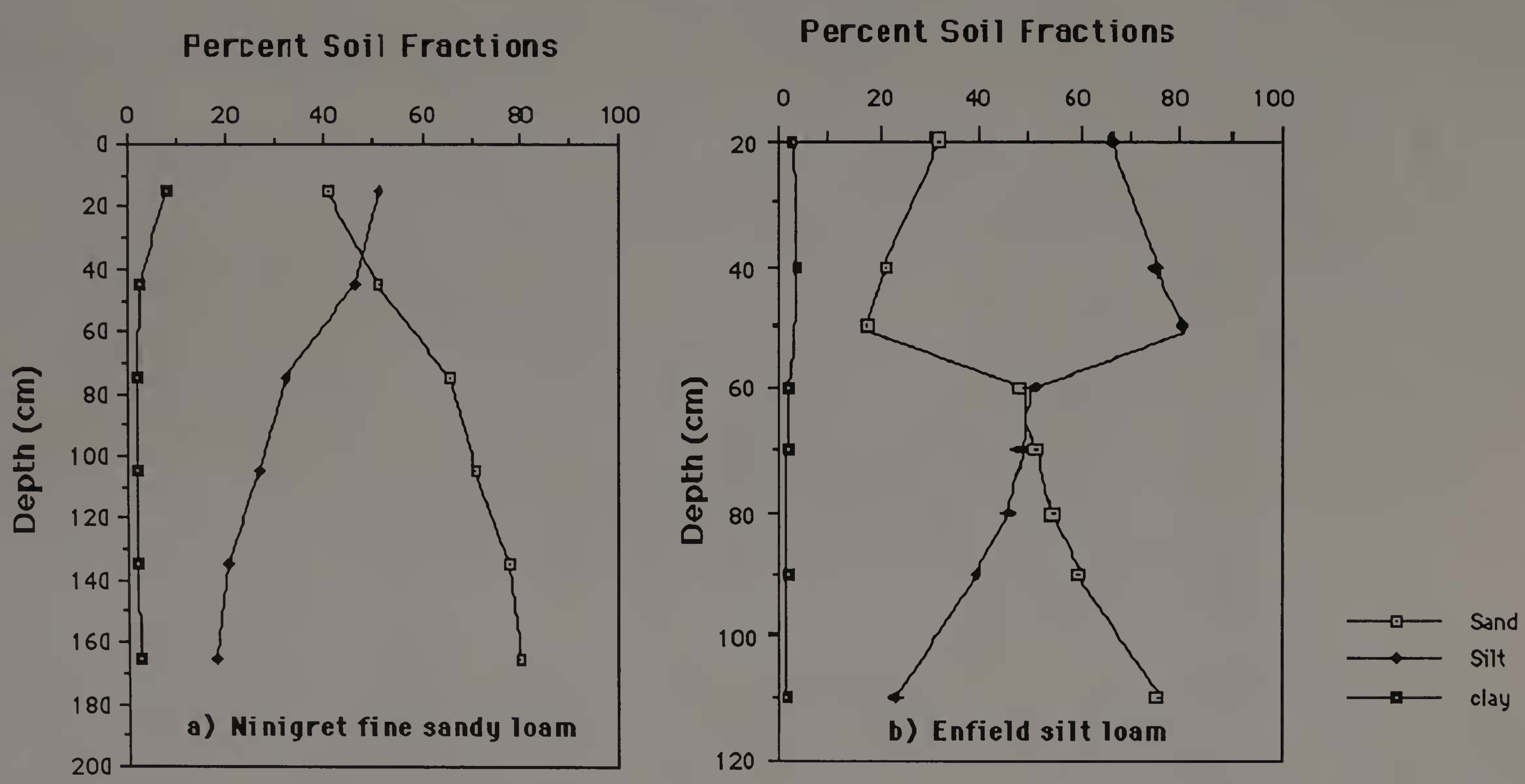


Fig. 1 Particle size distribution with depth.

CHAPTER 4

RESULTS AND DISCUSSION

Instantaneous Profile Method

Figure 2 illustrates the differences in soil texture and layering as well as the depth of the water table of the two soils. The total head gradient in the Ninigret soil shown in Figure 2a reached equilibrium quickly due to the wet soil conditions and the high water table. The anomaly at the 60 cm depth in Figure 2b is evidently due to the abrupt change in texture and bulk density in the soil profile. The negative gradient rendered it impossible to determine the hydraulic conductivity function for that depth.

Figure 3 shows the ranges of moisture contents measured in the field during the drainage process. The drier conditions in the Enfield soil are indicated by the greater range of measurable moisture contents. The distinct layering of the soil is also apparent.

The ranges of hydraulic conductivities which could be calculated for the two soils are shown in Figure 4. The regression plot for the Enfield displays little scatter around the regression line ($R^2 = 0.89$) while the Ninigret displays much more scatter ($R^2 = 0.71$) due to the wetter soil. The $K(\Psi)$ relationships in both soils range from 10^{-1} to 10^{-4} cm/s.

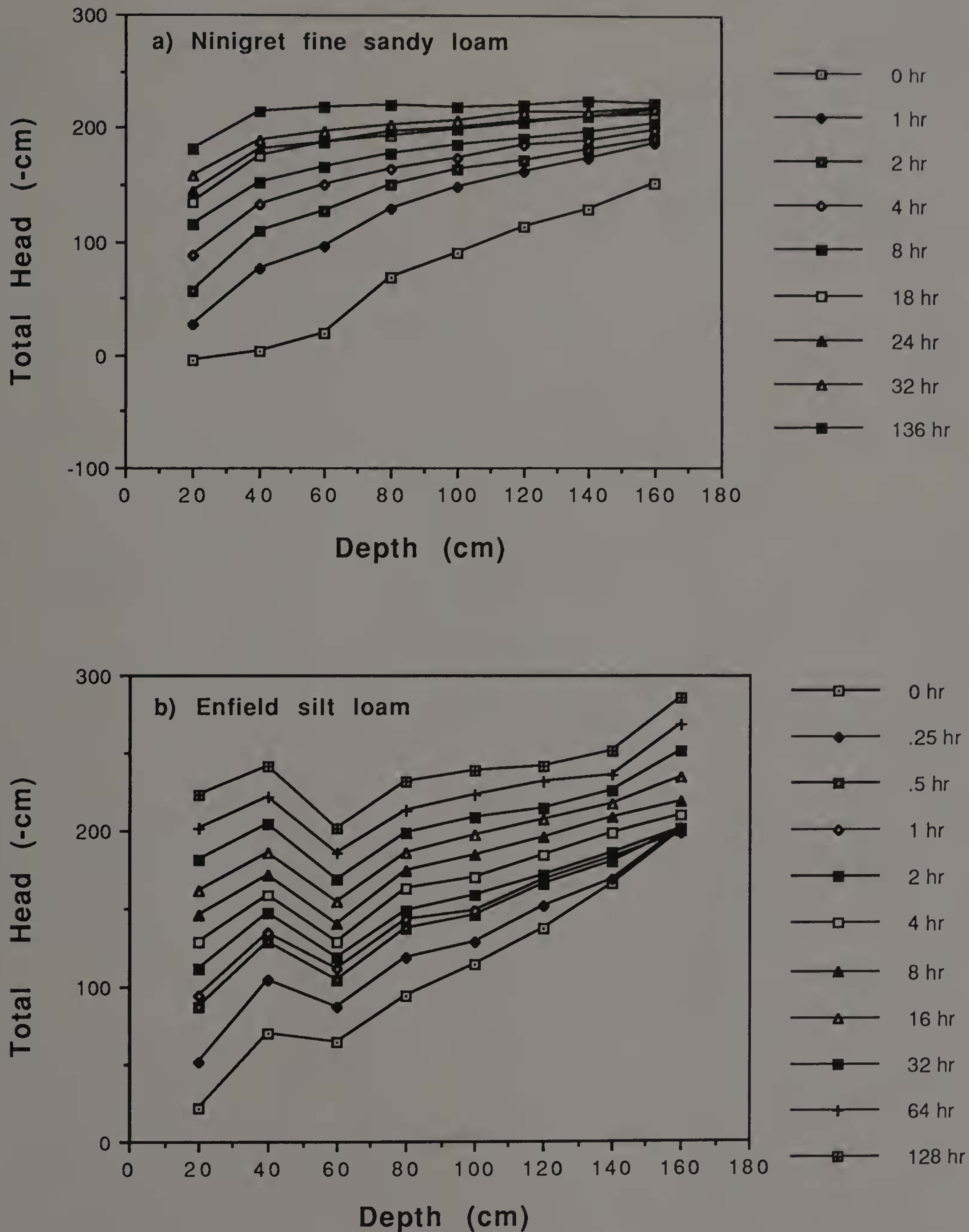


Fig. 2 Total hydraulic head vs. depth relationship during drainage from the Instantaneous profile method.

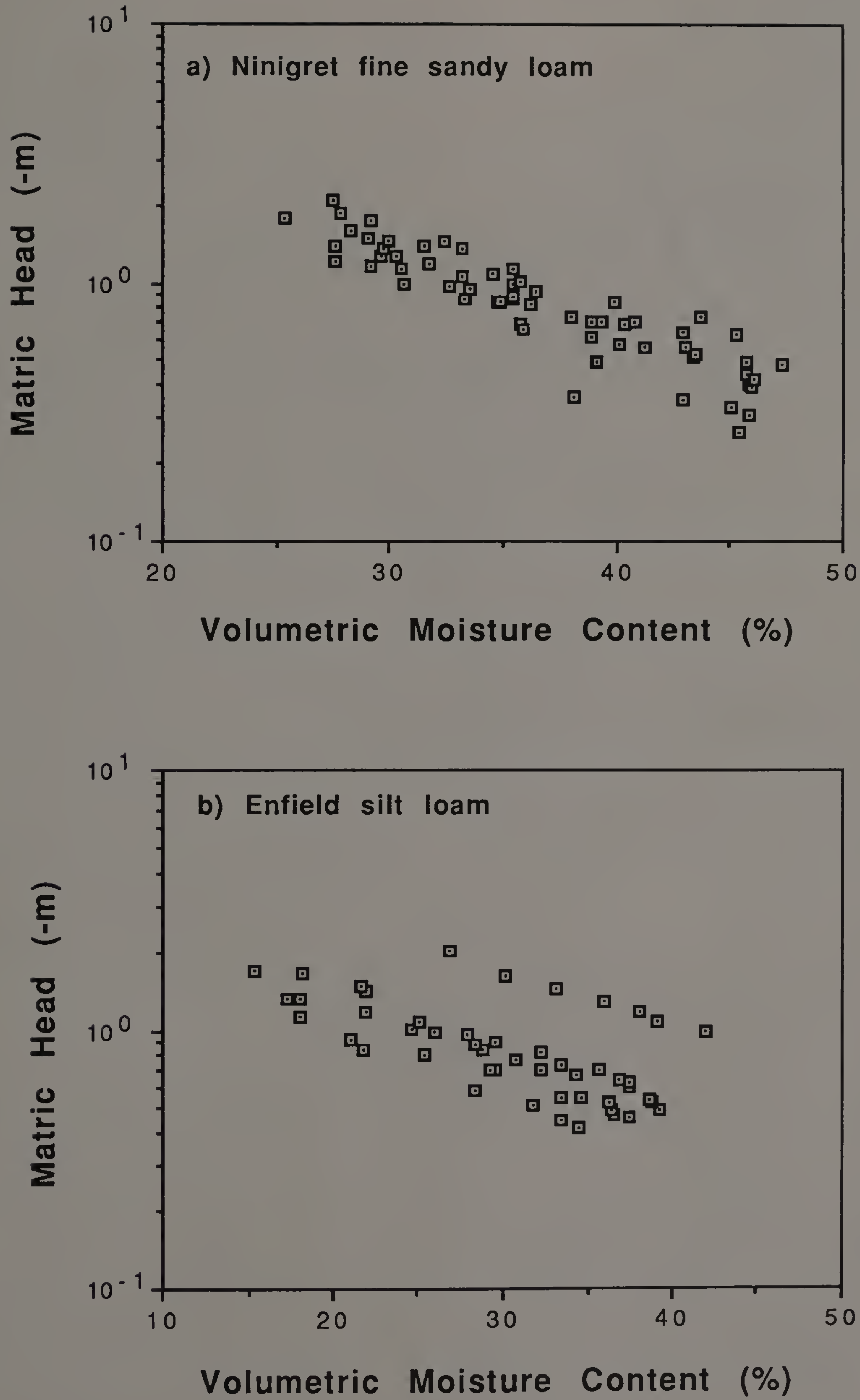


Fig. 3 Moisture desorption curve from the Instantaneous profile method.

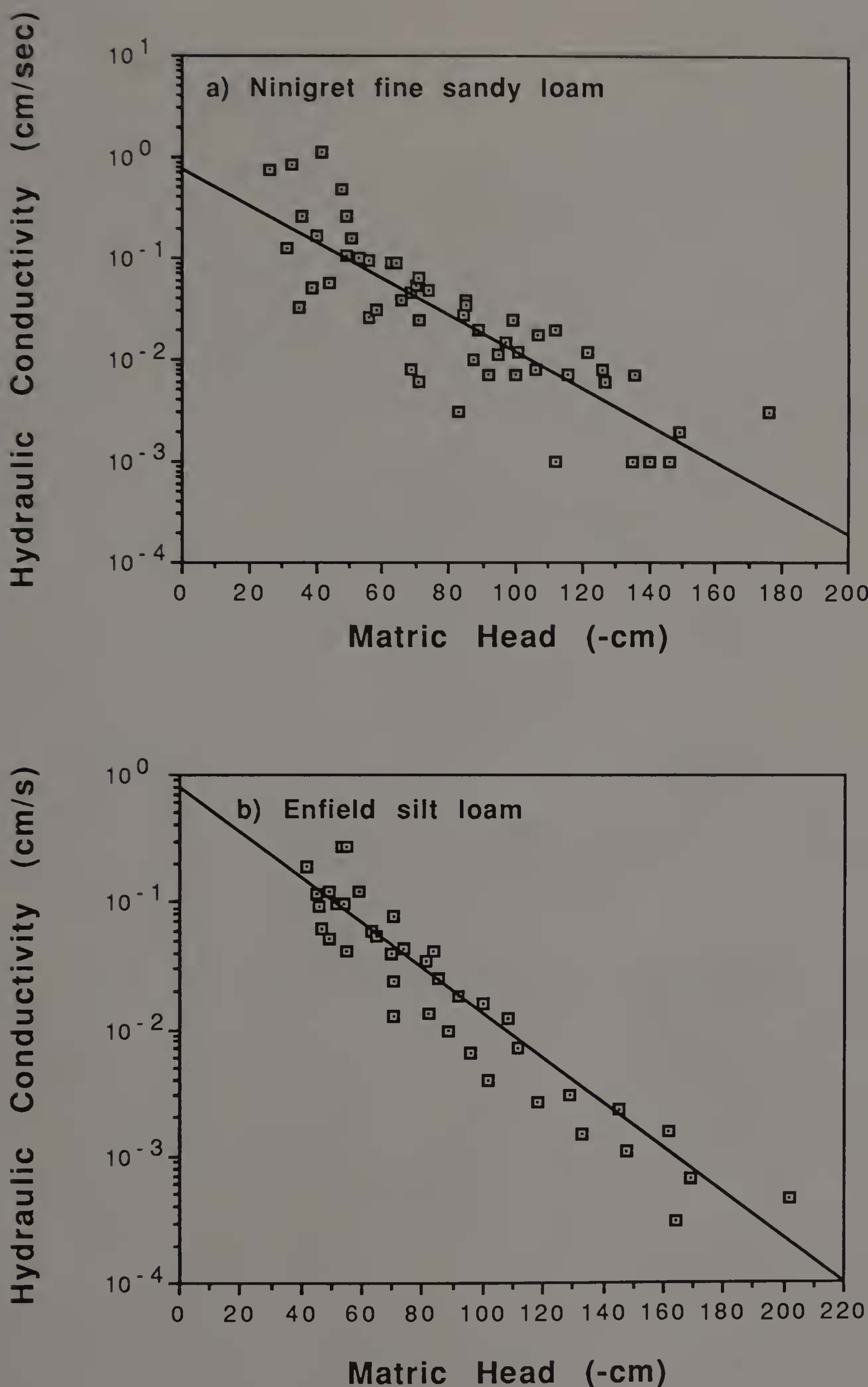


Fig. 4 Hydraulic conductivity as a function of matric head from the Instantaneous profile method.

Guelph Permeameter

The field saturated conductivity values determined for the different soils using the simultaneous solutions approach are presented in Figure 5. There was very little variation between replicates for each depth. The values determined in the Ninigret soil vary from 10^{-3} to 10^{-4} cm/s and the alpha values (Table 1) range from 0.11 to 0.12 cm^{-1} which are appropriate for a sandy loam soil. In the Enfield soil, the Guelph yielded values all in the 10^{-3} cm/s range; the alpha values varied from 0.11 to 0.20 (Table 2). The alpha values are appropriate for the soil texture.

The predicted $K(\Psi)$ relationships were calculated using the definition of matric flux (Equation 2) and the exponential relationship (Equation 3) as defined by Gardner (1958). For both soils the predictions were of very low hydraulic conductivity values of 10^{-9} cm/s to 10^{-12} cm/s at 200 cm suction (Fig. 6).

Core Method

The saturated hydraulic conductivity values determined from intact soil cores using a constant head permeameter ranged from 10^{-3} cm/s in the top layers of both soils to 10^{-2} cm/s in the Enfield soil and 10^{-1} cm/s in the Ninigret (Fig. 7) The variation between replicates can be attributed to (1) the macroporosity of the soil (discontinuous macropores in the field may be continuous in a particular soil core sample) (Smettem 1986); and (2) natural soil variability (Nielsen et al. 1973; Lee et al. 1985; Mohanty et al., 1991).

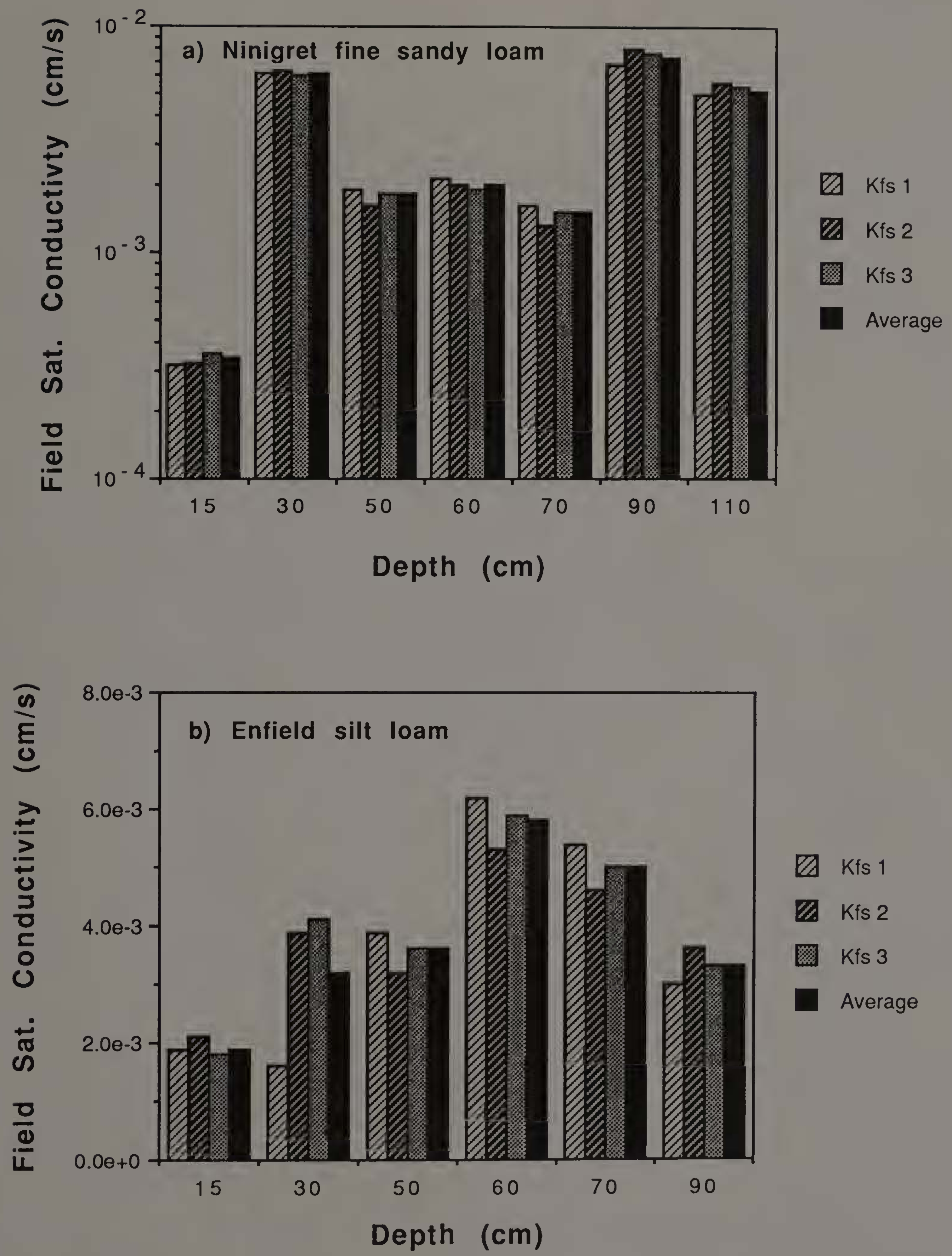


Fig. 5 Field saturated hydraulic conductivity from the Guelph permeameter method.

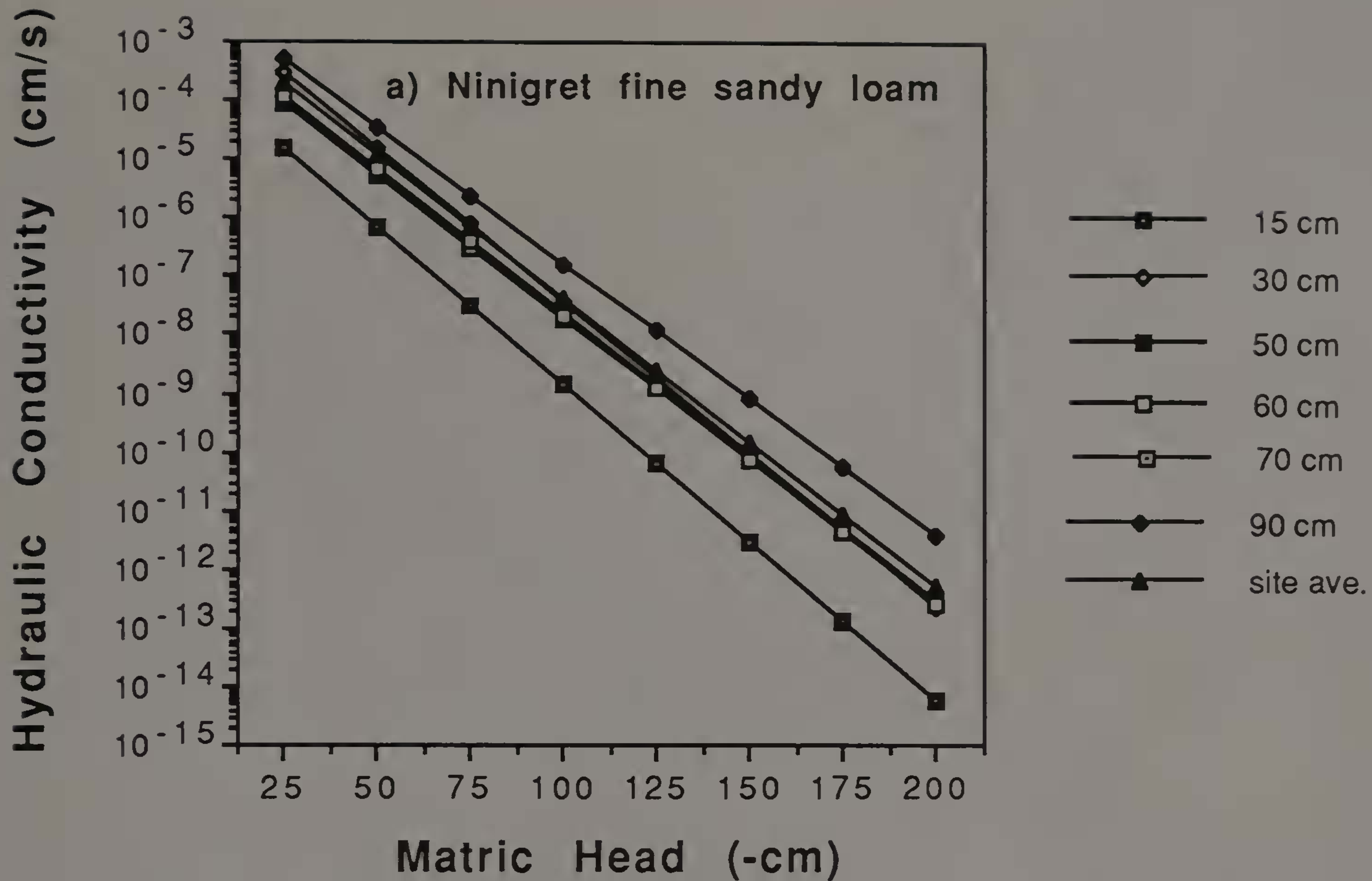
Table 1. Guelph permeameter results averaged by depth for the Ninigret fine sandy loam.

Depth (cm)	K_{fs} (cm/s)	Φ_m (cm^2/s)	α (cm^{-1})
15	0.0003	0.0027	0.1111
30	0.0062	0.0515	0.1204
50	0.0018	0.0157	0.1146
60	0.0020	0.0175	0.1143
70	0.0015	0.0130	0.1154
90	0.0072	0.0677	0.1064
site ave:	0.0032	0.0280	0.1143

Table 2. Guelph permeameter results averaged by depth for the Enfield silt loam.

Depth (cm)	K_{fs} (cm/s)	Φ_m (cm^2/s)	α (cm^{-1})
15	0.0019	0.0135	0.1333
30	0.0040	0.0200	0.2000
50	0.0036	0.0317	0.1136
60	0.0058	0.0513	0.1131
70	0.0050	0.0450	0.1111
90	0.0033	0.0273	0.1209
site ave:	0.0032	0.0280	0.1143

Φ_m (cm^2/s) = matric flux potential α (cm^{-1}) = slope of lnK(h) line



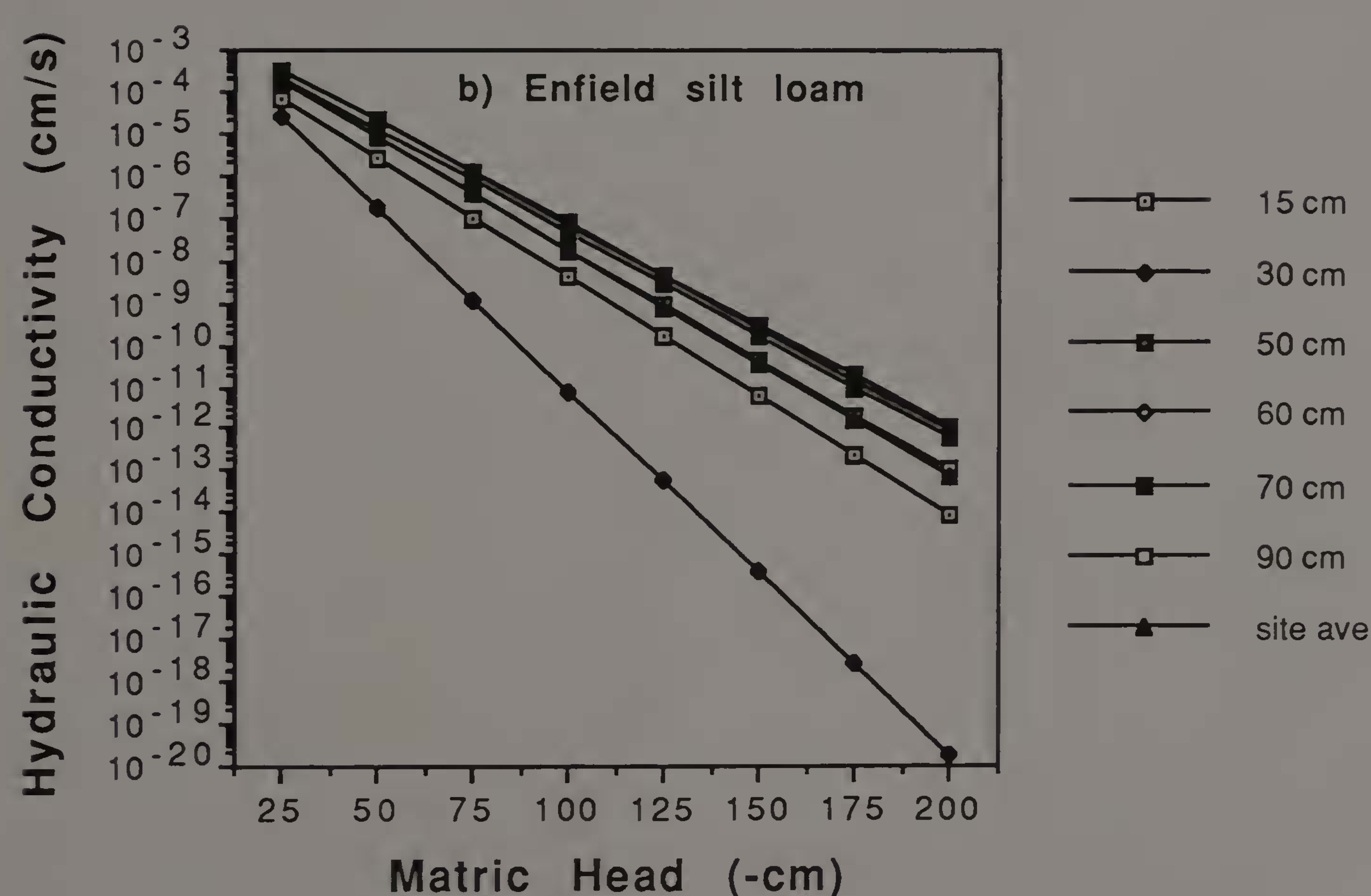


Fig. 6 Unsaturated hydraulic conductivity as a function of matric potential predicted from the Guelph permeameter method.

Moisture retention curves were determined for each core. Figure 8 shows the depth averaged moisture retention curves for each of the soils. The textural differences between the two soils are evident when comparing the shapes of the moisture retention curves.

Figure 9 presents the $K(\Psi)$ relationships calculated using the closed form solution of van Genuchten (1980) and Mualem's model (1978). The model calculated hydraulic conductivity values of 10^{-9} to 10^{-7} cm/sec at 50 m of pressure even though both soils have different saturation values. The measured effective saturation values were used to determine the hydraulic conductivity function. There was an average variance of 18% between the measured and predicted effective saturation values using the van Genuchten equation (see Appendix B). This is primarily due to the low number of pressure points used, as well as the effect of the macropores.

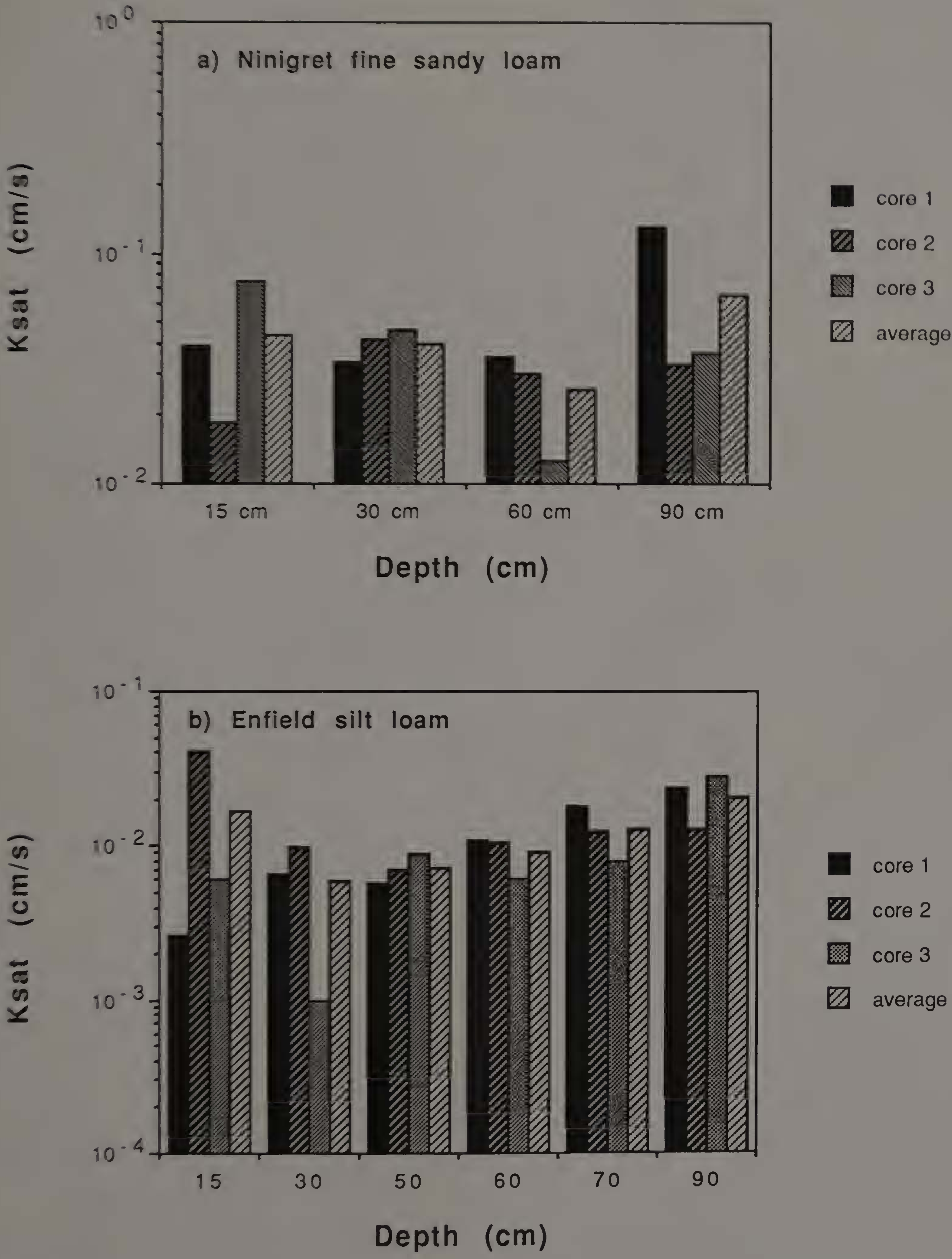


Fig. 7 Saturated hydraulic conductivity from the Core method.

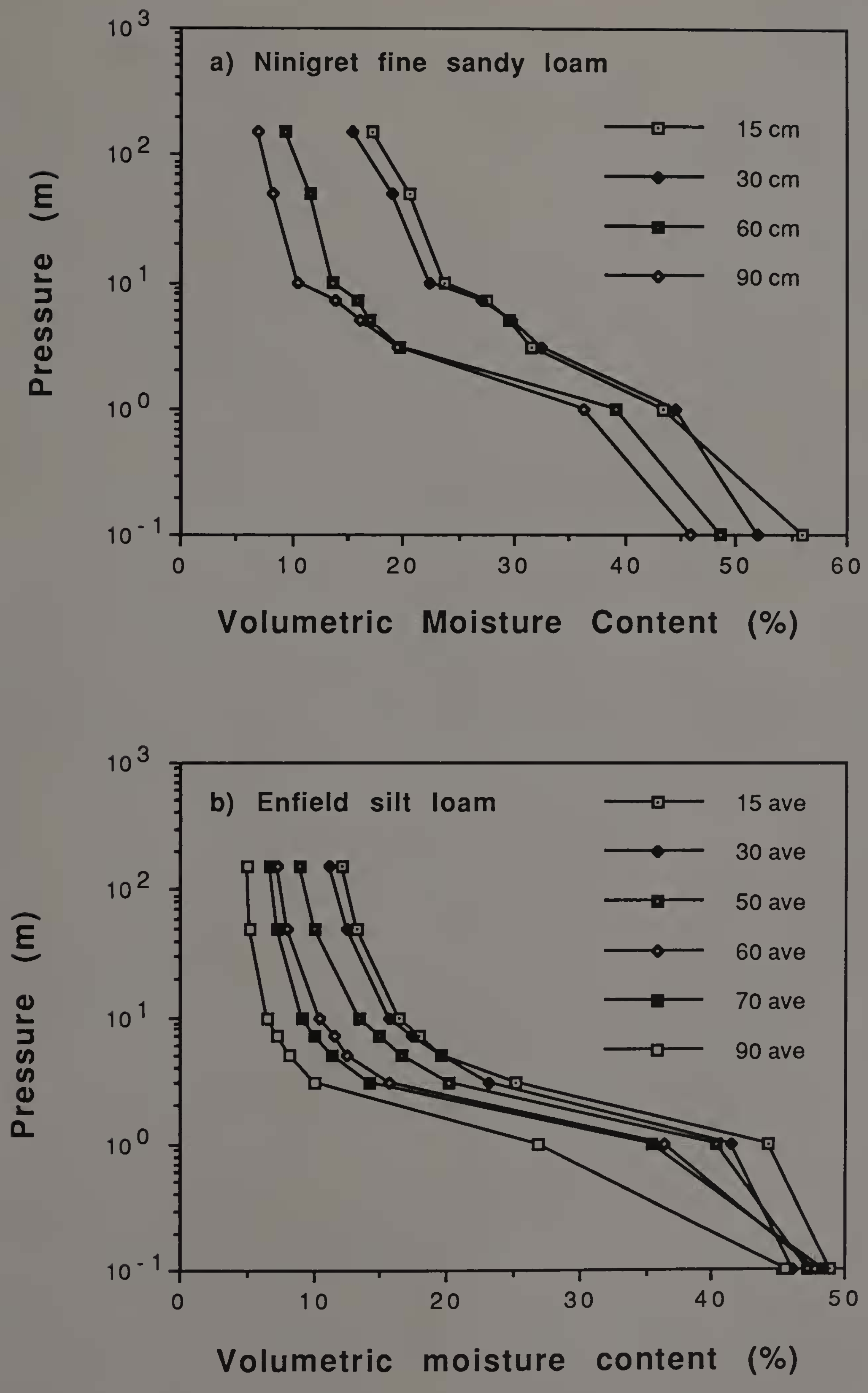


Fig. 8 Desorption curves averaged by depth from the Core method.

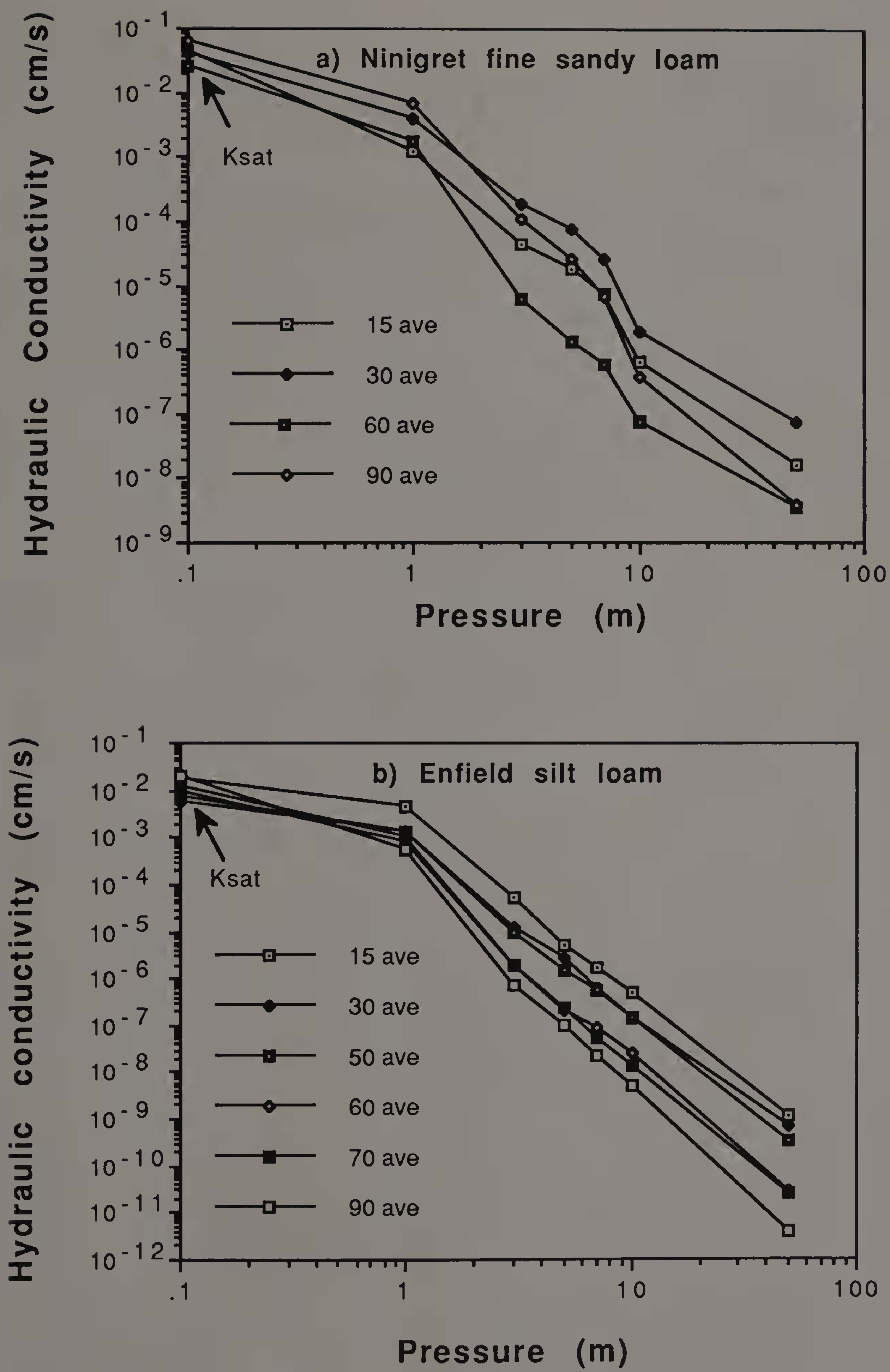


Fig. 9 Hydraulic conductivity function predicted by the van Genuchten and Mualem models from the Core method.

Comparison of Methods

The Guelph Permeameter yielded conductivity results much lower than those determined by the instantaneous profile and core methods. Tables 3 and 4 present a comparison of the saturated conductivity values from the soil cores with the field saturated values (K_{fs}). There is greater discrepancy between the results of the two methods for the Ninigret than between the results for the Enfield soil. However there is still a significant difference between the methods in both soils. The K_{fs} values are at least an order of magnitude less than the K_{sat} values determined from soil cores. The Guelph permeameter method often yields conductivity values smaller than those determined by soil cores and other methods (Lee et al. 1985; Reynolds and Elrick 1985; Talsma 1987; Stephens et al. 1987).

At least two factors can account for some of the discrepancies in the results. Entrapped air in the soil can lead to K_{fs} results which are less than the saturated values (Bouwer 1966; Talsma and Hallam 1980; Lee et al. 1985; Stephens et al. 1987). Smearing of the well walls can contribute to low K_{fs} results, especially in clay-rich soils (Reynolds et al. 1985; Koppi and Geering 1986; Talsma 1987; Amoozegar 1989; Mohanty et al. 1991). However, there is very low clay content in both of our tested soils. In addition, a wire brush was used to score the sides of the well after augering in order to obviate any smearing that might have taken place.

Table 3. Average hydraulic conductivities from the Guelph permeameter and Core methods for the Ninigret fine sandy loam.

Depth (cm)	Guelph Perm. K_{fs} (cm/s)	Core Method K_{sat} (cm/s)
15	0.0003	0.0445
30	0.0062	0.0406
60	0.0020	0.0259
90	0.0072	0.0662

Table 4. Average hydraulic conductivities from the Guelph permeameter and Core methods for the Enfield silt loam.

Depth (cm)	Guelph Perm. K_{fs} (cm/s)	Core Method K_{sat} (cm/s)
15	0.0019	0.0170
30	0.0032	0.0060
50	0.0036	0.0073
60	0.0058	0.0092
70	0.0050	0.0127
90	0.0033	0.0202

In addition to air entrapment, the results of the Guelph Permeameter were most likely affected by (1) the antecedent wetness conditions of the soil and (2) the macroporosity of the soil. The Ninigret soil, a wetter soil with a higher percentage of macropores, showed a greater discrepancy in the results determined by the three methods than did the Enfield soil. Although initial soil moisture conditions do not affect the results of the instantaneous profile and core methods, they affect the infiltration rate of water into soil (Philip 1956) and therefore can affect the results of the Guelph permeameter method. Talsma and Hallam (1980) found higher cumulative infiltration rates in a dry soil compared with an initially moist soil when using the borehole permeameter method. The Guelph permeameter theory is predicated on the $K(\Psi)$ relationship, which is very sensitive to hysteresis. The initial moisture content as well as the matric potential of the soil and their histories are not defined when using the Guelph method. Consequently, it is impossible to know where to locate the field saturated conductivity value on the scanning curve of the $K(\Psi)$ relationship of the soil.

The macroporosity of a soil can lead to high Ksat readings in soil cores (pipe flow) as discussed earlier; however, it can also cause anisotropic conditions in the soil and therefore affect the flow of water out of the well. A possible consequence of discontinuous macropores in the soil could be lower conductivity values for the Guelph permeameter than for the core method (Smettem 1986).

The hydraulic functions determined by the instantaneous profile and core methods are in close agreement for the soil moisture ranges they have in common. A comparison of moisture retention characteristics from the two methods (Fig. 10) indicates that there is no substantial difference between the pressure values measured for the ranges of moisture contents common to the two methods. This result is expected, since both methods measure the moisture content and pressure in draining soils starting from saturation.

Superposing Figures 4 , 6 and 9 plus the K_{sat} and K_{fs} values from each site, allows us to compare the $K(\Psi)$ relationships determined by all three methods simultaneously (Fig. 11). Both the Guelph permeameter and the core method predict lower values than the instantaneous profile method. The $K(\Psi)$ relationships calculated from the moisture characteristics of the soil cores compare closely with those determined by the instantaneous profile method, for the moisture content ranges which they have in common. The higher range of hydraulic conductivity values determined by the instantaneous profile method can be explained by the characteristics of the soil as well as the inherent differences in the methods. The instantaneous profile method was conducted to a depth of 160 cm, whereas soil cores were only taken down to a depth of 90 cm. The soil is much sandier at 160 cm, and has a higher conductivity. In addition, the methods have different volume scales of measurement which can change the effect that soil structure and macropores have on the hydraulic conductivity. The volumetric moisture content, especially when the soil is saturated, is most likely to be affected by the macropores in the soil. The presence of macropores apparently results in higher conductivity values in the instantaneous profile

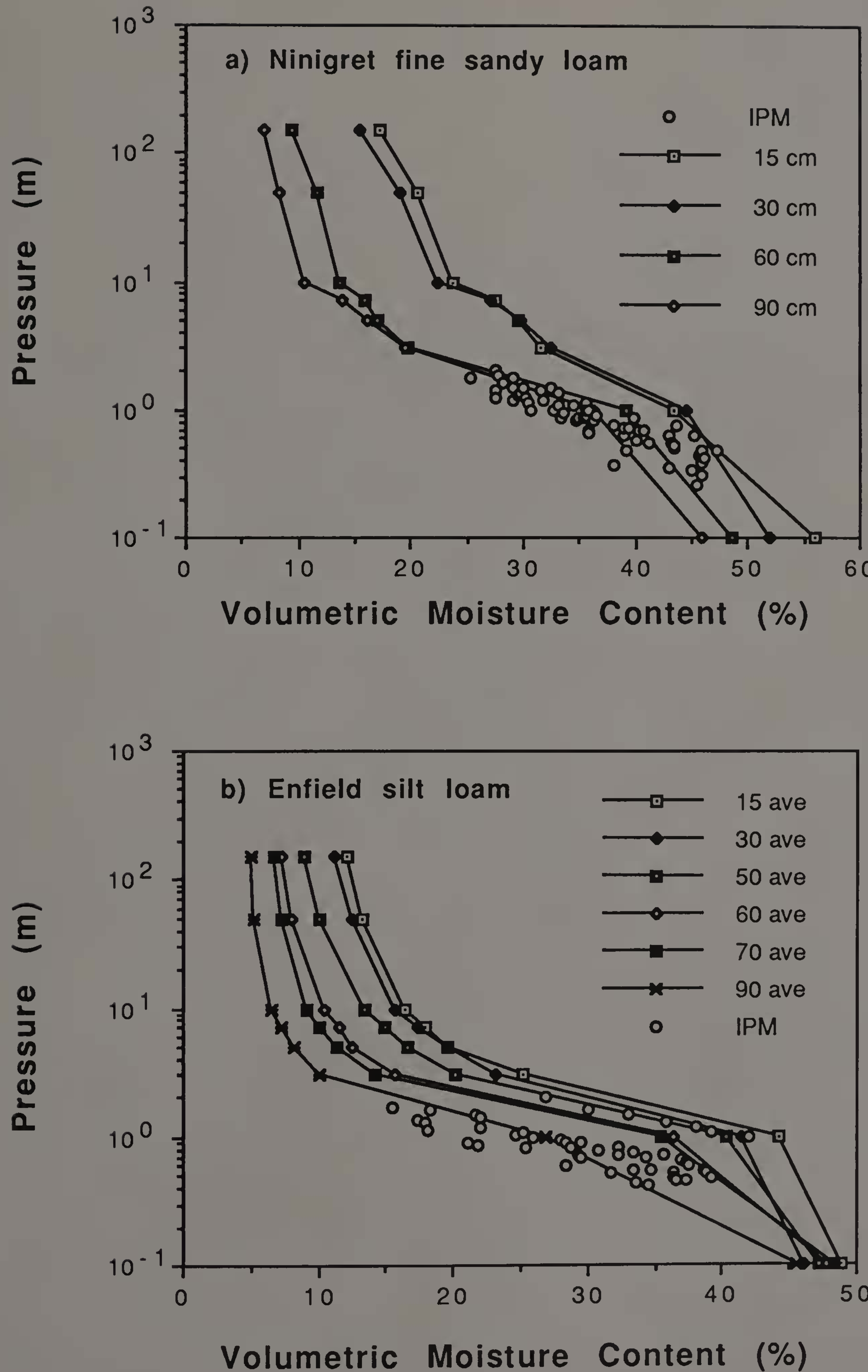


Fig. 10 Comparison of desorption curves from the Instantaneous profile and Core methods.

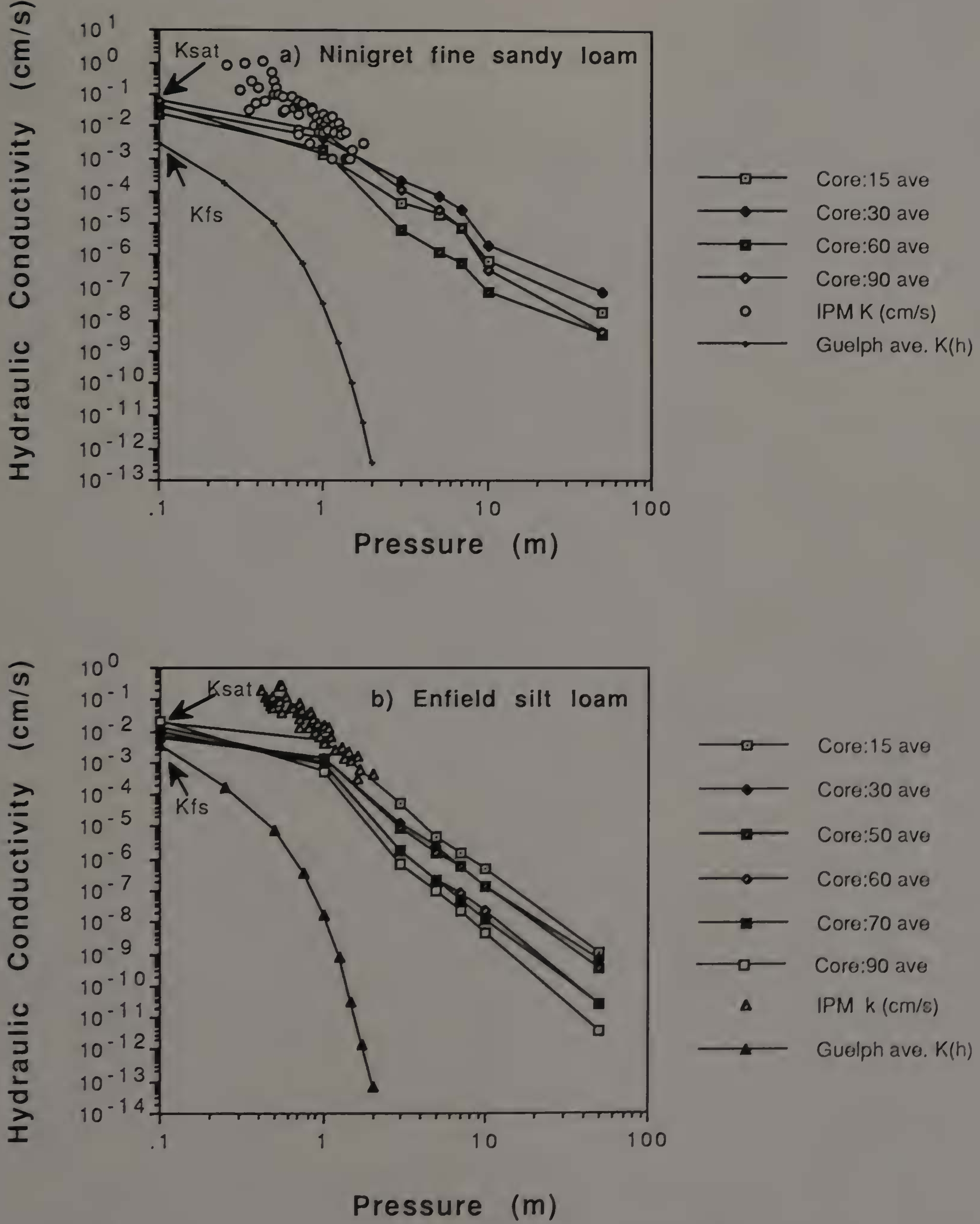


Fig. 11 Comparison of the hydraulic conductivity function from all three methods.

method due to the high volumetric moisture contents when the soil is saturated (Smettem and Kirby 1990).

The Guelph permeameter $K(\Psi)$ function is an exponential relationship based on the equation of Gardner (1958): $K=K_{fs}\, e^{(\Psi\alpha)}$. However, the $K(\Psi)$ relationships determined by the Instantaneous Profile and Core methods appear to be log-log distributed. The low K_{fs} values plus the effect of the exponential model used to predict the $K(\Psi)$ relationship from the Guelph permeameter, resulted in values which deviated from the corresponding conductivities (determined by the other methods) by several orders of magnitude at 200 cm suction.

The problem of which experimental and/or prediction method is the most valid is of primary concern to soil physicists. The Guelph permeameter is fast and simple to use. However, in this study it yielded conductivity values much lower than the other two methods, even when considering the effects of air entrapment. The flow rate of water out of an augered well can be influenced by any or all of the following, which are specific to each soil: (1) macropore content and distribution; (2) soil compaction; and (3) initial soil moisture conditions. Without actually measuring either the soil moisture content or the matric potential of a soil in the course of conducting the Guelph permeameter test, it is difficult to determine the field saturated conductivity accurately, or even assess how closely the so-called "field saturation" approximates total saturation.

The core method, though directly measuring the saturated hydraulic conductivity and moisture characteristic, we found was limited by (1) its scale of measurement and the spatial variability of the soil, which either exaggerated or neglected the effects of macropores, and (2) its difficulty in directly measuring the unsaturated hydraulic conductivity function. The method is easy to conduct and has well defined boundary conditions, which eases computational difficulties. However, it requires much time to measure all of the points of the moisture characteristic necessary to "accurately" determine the unsaturated conductivity function.

The instantaneous profile method seemed to be the most effective of the three methods for directly measuring the hydraulic properties of the soils for the ranges which occur in the field. However, it is a labor and time consuming method, and limited by the fact that it measures flow only in one direction. A relatively high water table in one soil and an abrupt change in texture in the other affected the results. Nevertheless, the results reflected what had actually occurred during the drainage process in the field.

Experimental methods are often difficult, tedious, or theoretically complex. The appropriateness of any of the above methods for determining the hydraulic properties of a soil depends upon: (1) the scale of measurement desired; (2) the site and soil conditions being characterized; (3) the time and resources available; and (4) the accuracy of the measurement required. It may be necessary to use more than one method to ensure an understanding of the flow dynamics occurring in the soil.

CHAPTER 5
SUMMARY

1) The results were consistent within methods: there was little variation between replicates at the same site. Differences in soil texture and structure were evident, however, when comparing same-method results from different sites.

2) The moisture retention characteristic and the hydraulic conductivity function calculated from the soil core data agreed closely with the measured values obtained by the instantaneous profile method for the corresponding ranges of pressures and moisture contents.

3) The Guelph permeameter yielded field saturated hydraulic conductivity results one to three orders of magnitude less than those determined by the instantaneous profile and core methods.

4) The instantaneous profile method was found to be the most effective method for determining soil hydraulic properties *in situ.*

APPENDIX A

SUPPLEMENTAL INFORMATION

Site descriptions

a) Ninigret fine sandy loam, taxadjunct

Classification: Aquic Dystrochrept, coarse-loamy, mixed, mesic

Location: Amherst, MA

Horizon	**Depth**	**(cm)**
Of	3-0	clear smooth boundary
Ap	0-20	dark brown (10YR3/3) very fine sandy loam; weak medium granular structure; friable; many fine roots; common medium distinct very dark gray (10YR3/1) blotches of material richer in organic matter; abrupt smooth boundary.
Bw1	20-36	olive brown (2.5Y4/4) fine sandy loam, with common fine to medium faint (10YR3/2) mottles; massive; friable; common medium and fine roots; many krotovinas; clear wavy boundary.
Bw2	36-48	light olive brown (2.5Y5/4) very fine sandy loam, with common fine to medium faint 5Y5/3 mottles; massive; friable; common fine roots; many krotovinas; clear wavy smooth boundary.

Bw3	48-58	olive brown (2.5Y 4/4) very fine sandy loam, with many fine to medium 5Y5/3 mottles; common fine distinct (10YR 5/8) channel ferrans and neoferrans; massive; friable; common krotovinas; few fine roots; clear wavy boundary.
BC	58-85	olive (5Y 4/3) loamy very fine sand matrix, with diffuse mottles and pore associated concretions; pockets of light olive brown (2.5Y 5/4) C material; many medium blotchy (5Y 7/3) mottles; massive; friable; few krotovinas; few fine roots; clear wavy boundary.
C	85-160+	alternating bands of olive gray (5Y 5/2) fine silt 1-2 mm and light brown (2.5Y 6/4) sand 2-3 mm in thickness; silt bands are massive and firm sand bands are single grained and loose; many medium concretions associated with pores; distinct mottles approximately 3 mm in diameter 10YR 2/1 in the silt layer and 7.5YR 5/8 in the sand layer; diffuse high and low chroma mottling across strata; no roots; bands dip slightly to the southeast.

b) Enfield silt loam, taxadjucnt

Classification: Typic Dystrochrept, coarse-silty/coarse-loamy, mixed, mesic

Location: Amherst, MA

Horizon	**Depth (cm)**	
Of	3-0	abrupt smooth boundary
Ap	0-24	dark brown (10YR3/3) silt loam; weak medium granular structure; friable; friable; many fine roots; few coarse fragments; abrupt irregular boundary.
Bw1	24-45	dark yellowish brown (10YR4/6) silt loam becoming yellowish brown (10YR 5/6) at bottom of horizon; fine krotivinas to depth of 32 cm filled with Ap material; common fine roots; some charcoal and ant larvae; gradual smooth boundary.
Bw2	45-87	light olive brown (2.5Y 5/4) very fine sandy loam; massive; friable; few fine roots; few macropores (1 mm.); common fine channel ferrans; common quasialban neoferrans in pockets; some charcoal; clear smooth boundary.

BC	87-113	60% light olive brown (2.5Y 5/4) and 40% light yellowish brown (2.5Y 6/3) loamy fine sand with common fine channel ferrans; few low chroma mottles in (2.5Y 5/4) matrix; fine channel and pore ferrans associated with fine roots; few fine roots; clear wavy boundary.
C	113-150+	olive gray (5Y 5/2) fine sandy matrix with common high chroma channel ferrans; weak platy; alternating bands of olive gray (5Y 5/2) fine silt 1-2 mm and light brown (2.5Y 6/4) sand 2-3 mm in thickness; silt bands are massive and firm sand bands are single grained and loose; diffuse high and low chroma mottling across strata; no roots; bands dip slightly to the southeast.

Infiltration Rates

Infiltration rates under positive pressure were measured at each site using a 50 cm diameter infiltrometer and a 750-ml beaker. Infiltration sites were located within each experiment site (see Chapter 3). The sod was removed and the infiltrometer was inserted 5 cm into the soil. Water was applied, using a board and screen to minimize soil surface disturbance, to obtain a ponded head of 5 cm. A constant head was maintained and the volume of water infiltrating per unit time was recorded until a steady state flux was achieved, usually within the first 10 minutes. Two replicates were conducted at each site. The steady state flux of water infiltrating the soil was then divided by the area to determine the average infiltration rate. The steady state infiltration rates determined for the Ninigret fine sandy loam were 9.5×10^{-3} and 1.1×10^{-2} cm/s, and 6.28×10^{-3} and 5.83×10^{-3} cm/s for the finer textured Enfield silt loam. The infiltration rates and cumulative infiltration rates from the first replicates for the two soils are shown in figure A.1.

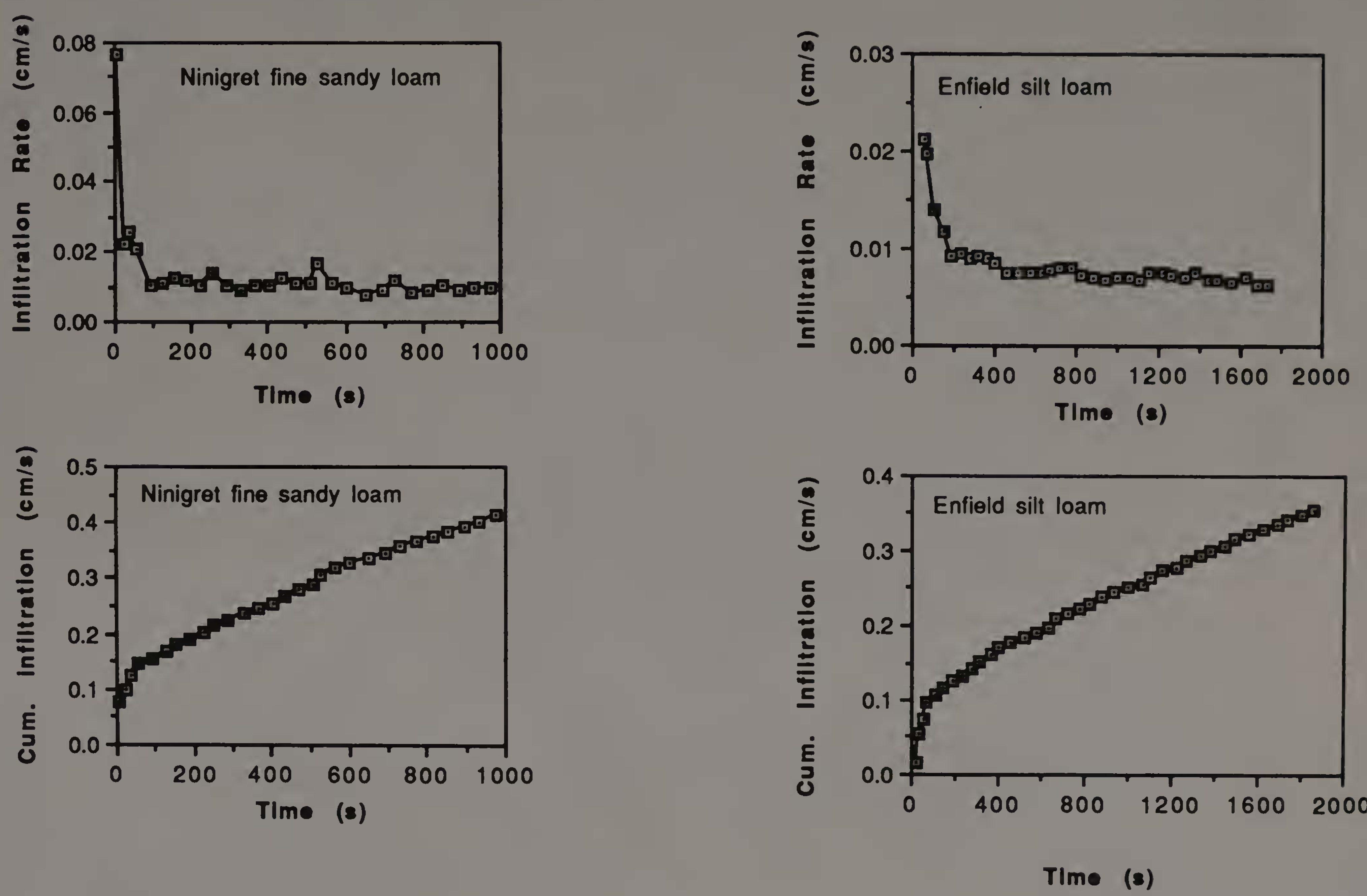


Fig. A.1 Infiltration and cumulative infiltration rates.

APPENDIX B

PARAMETER ESTIMATES

<u>Parameter Estimates for calculating the hydraulic conductivity function from $\theta(\Psi)$ data.</u>

To calculate the hydraulic conductivity function $K(\Psi)$ from the measured $\theta(\Psi)$ data the closed form equation ($\Theta = [\frac{1}{1+(\alpha\Psi)^n}]^m$) of van Genuchten (1980) was used. The optimum values of the two parameters α and n were determined using a nested Fibonacci (Golden Section) search (Beveridge and Schechter, 1970) optimization method (Ranjitkar, 1989). The program (Appendix C) seeks to minimize the relative estimation error, δ_j, defined as

$$\delta_j = \frac{\Theta_j(\text{measured}) - \Theta_j(\text{predicted})}{\Theta_j(\text{predicted})}$$

A search is specified for the unknown parameter n for which it is assumed that the mean relative error

$$\delta_m = \frac{1}{j} \sum_{j=1}^{j} \delta_j$$

is unimodally distributed with respect to n, when the optimum value for n = $n(\delta_{min})$. An outer search for α is conducted in a similar procedure to determine the optimum value of a which corresponds to the minimum standard deviation σ_{min} of δ, defined as

$$\sigma = \sqrt{\frac{1}{j} \sum_{j=1}^{j} (\delta j)^2 - (\delta_m)^2}$$

The results and the goodness-of-fit statistics for the parameter estimation of the two soils are presented in tables 5 and 6. The large values of σ are attributed to the low number of points used to determine a over a large range of pressures.

Table B.5 Parameter estimation using the van Genuchten closed-form equation for the Ninigret fine sandy loam

Depth	$\Theta_a \leq \Theta$ (m)	$\leq \Theta_b$*	α m^{-1}	n	δ	σ
15_1	0.6445	0.0903	3.75	1.64	3.86×10^{-4}	0.166
15_2	0.7028	0.0911	1.61	1.74	1.00×10^{-6}	0.115
15_3	0.6715	0.0721	2.42	1.77	7.09×10^{-6}	0.107
ave.	0.6738	0.0843	2.25	1.72	1.57×10^{-4}	0.113
30_1	0.7983	0.1088	0.93	1.77	1.41×10^{-6}	0.126
30_2	0.7805	0.1011	1.08	1.77	4.06×10^{-6}	0.134
30_3	0.8092	0.0944	1.16	1.80	4.25×10^{-5}	0.142
ave	0.7963	0.1014	1.05	1.78	4.10×10^{-4}	0.134
60_1	0.6839	0.0503	12.3	1.76	1.08×10^{-5}	0.379
60_2	0.7640	0.0859	3.14	1.71	3.82×10^{-6}	0.228
60_3	0.8311	0.0512	3.58	1.89	1.08×10^{-6}	0.242
ave	0.7586	0.0614	5.10	1.78	1.42×10^{-4}	0.267
90_1	0.8520	0.0736	1.76	2.10	4.69×10^{-5}	0.140
90_2	0.8168	0.0358	4.24	1.99	3.31×10^{-7}	0.222
90_3	0.5862	0.0280	12.5	1.90	4.32×10^{-8}	0.201
ave	0.7521	0.0344	4.15	1.99	2.94×10^{-5}	0.168

* for pressures ranging from 1 to 50 meters

Table B.6 Parameter estimation using the van Genuchten closed-form equation for the Enfield silt loam

Depth	$\Theta_a \leq \Theta$ (m)	$\leq \Theta_b$*	α m^{-1}	n	δ	σ
15_1	0.8355	0.0299	3.74	1.85	3.50×10^{-7}	0.233
15_2	0.9006	0.0358	2.15	1.83	3.89×10^{-6}	0.228
15_3	0.8984	0.0305	1.96	1.89	1.03×10^{-6}	0.187
ave.	0.8775	0.0321	2.50	1.86	3.63×10^{-6}	0.212
30_1	0.8236	0.0500	3.25	1.72	4.12×10^{-6}	0.253
30_2	0.8540	0.0373	2.52	1.81	2.94×10^{-5}	0.220
30_3	0.9366	0.0487	1.06	1.81	5.14×10^{-6}	0.179
ave	0.8710	0.0452	2.02	1.78	2.13×10^{-7}	0.206
50_1	0.8436	0.0300	4.07	1.86	2.75×10^{-6}	0.259
50_2	0.8115	0.0144	5.07	1.96	6.06×10^{-7}	0.231
50_3	0.8209	0.0302	2.03	1.82	1.93×10^{-6}	0.199
ave	0.8256	0.0249	3.36	1.88	3.11×10^{-7}	0.198
60_1	0.7441	0.0231	6.79	1.88	3.53×10^{-7}	0.236
60_2	0.7256	0.0094	11.4	1.96	5.66×10^{-8}	0.314
60_3	0.6992	0.0282	7.28	1.75	9.57×10^{-8}	0.258
ave	0.7229	0.0203	7.87	1.86	9.02×10^{-7}	0.244
70_1	0.7338	0.0136	11.7	1.95	2.00×10^{-7}	0.290
70_2	0.6622	0.0111	13.5	1.96	7.43×10^{-8}	0.246
70_3	0.6873	0.0120	11.8	1.90	5.38×10^{-6}	0.303
ave	0.6943	0.0122	12.1	1.94	4.65×10^{-9}	0.270

Table B.6 continued

Depth	$\Theta_a \leq \Theta$ (m) $\leq \Theta_b$*		α m^{-1}	n	δ	σ
90_1	0.5170	0.0080	48.6	1.96	1.13×10^{-6}	0.384
90_2	0.7487	0.0082	10.8	2.02	5.46×10^{-6}	0.287
90_3	0.3739	0.0050	59.1	1.96	3.08×10^{-6}	0.169
ave	0.5436	0.0071	28.3	1.99	4.91×10^{-7}	0.249

* for pressures ranging from 1 to 100 meters.

APPENDIX C

TWO PARAMETER SEARCH PROGRAM

```
******************************************************************
This program will carry out a two parameter search to determine
optimum values of van Genuchten's parameters, alpha and exponent
'n' using fortran.
*******************************************************************
PROGRAM THESIS
IMPLICIT REAL*8(A-H, O-Z)
COMMON/DATAM/NPOINT,THETM(100). H(100), DEL(100)
COMMON/DATAW/ALMIN,ALMAX,ENMIN,ENMAX

OPEN (UNIT=4, STATUS='OLD', FILE='BRK3.DAT', DISPOSE='KEEP')
OPEN (UNIT=7, STATUS='UNKNOWN', FILE='BRK3.OBJ',
DISPOSE='DELETE')
OPEN (UNIT=8, STATUS='NEW', FILE='BRK3.OUT', DISPOSE='SAVE')

READ (4,*) ALMIN, ALMAX, ENMIN, ENMAX, NPOINT

DO 10 I=1, NPOINT
READ (4,*) H(I), THETM (I)
CONTINUE
WRITE (8,'(///4E10.3,1I8//)') ALMIN, ALMAX, ENMIN, ENMAX,
NPOINT

AL1=ALMIN + 0.382*(ALMAX-ALMIN)
CALL OPTEN (EN,AL1,DELT,SIG)
SIG1 = SIG
```

```
AL2=ALMIN + 0.618*(ALMAX-ALMIN)
CALL OPTEN (EN,AL2,DELT,SIG)
SIG2 = SIG
DO 20 ITER=1,50
IF (SIG2 .GT. SIG1) THEN

Set upper search boundary.

ALMAX = AL2
AL2 = AL1
SIG2 = SIG1
AL1=ALMIN + 0.382*(ALMAX-ALMIN)
CALL OPTEN (EN,AL1,DELT,SIG)
SIG1 = SIG

ELSE

Set lower search boundary.

ALMIN = AL1
AL1 = AL2
SIG1 = SIG2
AL2 = ALMIN + 0.618*(ALMAX-ALMIN)
CALL OPTEN (EN,AL2,DELT,SIG)
SIG2 = SIG

ENDIF
CONTINUE

AL = (AL1 + AL2)/2.
```

```
WRITE (8,'(4(//8X,A5,E12.3//))') 'AL=',AL,'EN=',EN,
:'DELT=',DELT,'SIG=',SIG

WRITE (8,'(//1X,I8,2X,3F10.4,2X,E12.6)')
:(J,H(J), THETM(J), DEL(J), J=1,NPOINT
STOP
END

*****************************************************************
This subroutine optimizes the exponent 'n'
*****************************************************************
SUBROUTINE OPTEN (EN,AL,DELT,SIG)
IMPLICIT REAL*8(A-H, O-Z)
COMMON/DATAM/NPOINT,THETM(100). THETP(100), DEL(100)
COMMON/DATAW/ALMIN,ALMAX,ENMIN,ENMAX

ENMX = ENMAX
EN1=ENMIN + 0.382*(ENMAX-ENMIN)
CALL EQUATION (EN1,AL,DELT,SIG)
DELT1 = DELT
ENMN = ENMIN
EN2 = ENMIN + 0.618*(ENMAX-ENMIN)
CALL EQUATION (EN2,AL,DELT,SIG)
DELT2 = DELT

DO 100 I=1,50
IF(DELT2 .GT. DELT1) THEN

Set upper search boundary
```

```
ENMIN = EN1
EN1 = EN2
DELT2 = DELT1
EN1 = ENMN + 0.382*(ENMX-ENMN)
CALL EQUATION (EN1,AL,DELT,SIG)
DELT1 = DELT

ELSE

Set lower search boundary.

ENMN = EN1
EN1 = EN2
DELT1 = DELT2

EN2 = ENMN + 0.618*(ENMX-ENMN)
CALL EQUATION (EN2,AL,DELT,SIG)
DELT2 = DELT
ENDIF
CONTINUE

EN = (EN1 + EN2)/2
CALL EQUATION (EN,AL,DELT,SIG)

WRITE (8,'(5X,A5,F8.2,5X,A5,E12.4)')
:'EN=',EN,'DELT=',DELT

RETURN
END
```

```
******************************************************************
This subroutine computes the predicted Theta values.
******************************************************************
SUBROUTINE EQUATION (EN,AL,DELT,SIG)
IMPLICIT REAL*8(A-H, O-Z)
COMMON/DATAM/NPOINT,THETM(100). THETP(100), H(100)
DEL(100)

DELT = 0
SIG = 0

DO 1000 J = 1,NPOINT

THETP (J) = 1/((1 +(AL*H(J)88EN)88(1-1/EN)))

DEL(J) = (THETM (J) - THETP (J))/THETP (J)
DELT = DELT + DEL (J)
SIG = SIG + DEL (J)*DEL(J)
CONTINUE

DELT = ABS (DELT)/NPOINT
SIG = SQRT(SIG/NPOINT-DELT*DELT)
RETURN
END
```

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