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Unsaturated Hydraulic Conductivity Determined by the Hot Air Method for Some Danish Till Soils

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Unsaturated hydraulic conductivity relations for topsoil and subsoil in 12 Danish till soils were obtained from measurements by the hot air method. In the range of pressure potentials (pF-values from 1.7 to 3.0) within which the method is most suitable the hydraulic conductivities were found to be within the range of 10^{-10}-10^{-7} m s^{-1} for topsoils and 10^{-11}-10^{-8} m s^{-1} for subsoils. The hydraulic conductivity relations obtained were briefly discussed in relation to the corresponding pF-curves. At any pF-value the subsoils differed more than the topsoils in hydraulic conductivity.

Introduction

Many soil water transport processes such as infiltration, soil water redistribution, uptake of water by plants, and evapotranspiration involve flow in unsaturated soil. In order to describe such water flow quantitatively in the context of the soil-plant-atmosphere continuum a precise assessment of the parameters entering the flow equations is necessary. In addition to the soil water retention characteristics the hydraulic conductivity as a function of soil water content is one of the most important relations for successful simulation of unsaturated flow. However, the experimental evidence is limited regarding hydraulic conductivity for soils over a wide range of soil water contents. In the present study unsaturated hydraulic conductivity relations for topsoil as well as subsoil in 12 Danish till soils are provided using the hot air method.

Theory

By combining the Darcy flow Eq (1) and the continuity Eq. (2), Richards Eq. (3) for one dimensional horizontal transient flow is obtained

$$v = -K(\psi)\frac{\partial\psi}{\partial x} \tag{1}$$

$$\frac{\partial\theta}{\partial t} = -\frac{\partial v}{\partial x} \tag{2}$$

$$\frac{\partial\theta}{\partial t} \equiv \frac{\partial}{\partial x}\left[K(\psi)\frac{\partial\psi}{\partial x}\right] \tag{3}$$

where

v – flux, m s^{-1}
θ – volumentric water content, m^3 m^{-3}
ψ – pressure potential, m
x – horizontal distance, m
$K(\psi)$ – unsaturated hydraulic conductivity, m s^{-1}
t – time, s

By introducing soil water diffusivity ($D(\theta)$), Eq. (4), Richards equation takes the form of Eq. (5)

$$D(\theta) \equiv \frac{K(\psi)}{d\theta/d\psi} \tag{4}$$

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial\theta}{\partial x}\right] \tag{5}$$

By applying a Bolzmanns transformation using the parameter $\lambda = x/\sqrt{t}$ Eq. (5) can be transformed to Eq. (6) for a semi-infinite system

$$-\frac{\lambda}{2}\frac{d\theta}{d\lambda} = \frac{d}{d\lambda}\left[D(\theta)\frac{d\theta}{d\lambda}\right] \tag{6}$$

The so-called hot air method proposed by Arya *et al.* (1975) is based on Eq. (6) applied to a short soil column subjected to the following boundary conditions in which θ_i is initial water content, θ_0 is water content of the air-dry soil, x is the distance for the evaporating surface, and t is evaporating time

$$\theta \equiv \theta_i \quad \text{for} \quad \lambda \Rightarrow \infty \, (t=0, x\geq 0)$$
$$\theta = \theta_o \quad \text{for} \quad \lambda \equiv 0 \, (t>0, x\equiv 0)$$

$$D(\theta_x) = \frac{1}{2t}\left[\frac{dx}{d\theta}\right]_{\theta_x}\int_{\theta_x}^{\theta_i} x \, d\theta \tag{7}$$

For the boundary conditions indicated a solution (Bruce and Klute 1956) to Eq. (6) is given as Eq. (7) from which soil water diffusivities can be calculated after which hydraulic conductivities can be calculated from Eq. (4)

$$K(\psi) = a|\psi|^{-b} \tag{8}$$

For application in simulation models it is an advantage to express hydraulic conductivity explicitly as a function of either soil water content or pressure potential and several forms of such relationships have been suggested in the literature. However, in the present study we only consider a relationship suggested by Wind (1955) expressed as Eq. (8) in which ψ is pressure potential expressed in cm and *a* and *b* are parameters which are to be determined.

Experimental Methods

All the 12 soils investigated are developed from moraine deposits. Geological descriptions of some of the soils are given by Nielsen and Møberg (1984, 1985). For each soil *in situ* soil samples were taken in 10 and 70 cm depth using steel cylinders. Furthermore loose soil samples were taken for determination of textural composition by the hydrometer method (Day 1965). For determination of pF-curves as described by Schjønning (1985) 100 cm^3 soil samples were used whereas for hydraulic conductivity determination 250 cm^3 soil samples, 85.5 mm in length and with a diameter of 61.0 mm were used. For each soil investigated 18 and 9 *in situ* soil samples were used for hydraulic conductivity determination for topsoil and subsoil, respectively.

The soil samples for hydraulic conductivity determination were brought to water saturation and then drained to a selected pressure potential (-25 to -100 hPa) by using a sand box equipment. After drainage the samples were sealed and placed horizontally for several days to unify the water content. Afterwards one end of the soil column was exposed to a stream of hot air, 120-150 °C, in 16 minutes to induce evaporation. To prevent or minimize the effect of temperature on the soil water movement the soil column was embraced by a water cooled shield.

During the exposure to hot air the sample was placed on a sensitive balance for continuously registration of the accumulated evaporation. The accumulated evaporation was plotted against square root of time to control fulfillment of the boundary conditions. If a straight line was not obtained the results were dismissed. Immediately after stopping the air stream the soil column was cut into 2-5 mm slices and the soil water profile determined gravimetrically. The experimental procedure is described in details elsewhere (Jacobsen 1989).

From the obtained soil water profile, an example of which is shown in Fig. 1, the soil water diffusivity can be determined by Eq. (7) after which the hydraulic conductivity is obtained from Eq. (4) in which $d\theta/d\psi$ is derived from the corresponding pF-curve. In the present study an iterative calculation procedure described by Van Grinsven *et al.* (1985) was used to obtain the values of the coefficients *a* and *b* in Eq. (8), which was then subsequently used to construct the hydraulic conductity relationships.

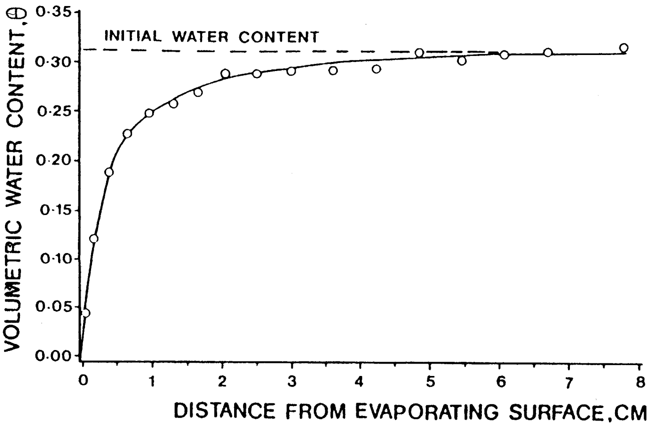

Fig. 1. Soil water profile for Kalø sandy loam soil sample after exposure to hot air stream for 16 minutes.

Results and Discussion

From Table 1 it appears that clay content in the topsoil vary from 5.6 % in soil 1 to 17.5 % in soil 12 whereas in the subsoil the clay content vary from 7.7 % in soil 2 to 36.7 % in soil 12. Thus except soil 10 the clay content increases significantly with depth.

In Fig. 2 the pF-curves are shown for both sampling depths. For the topsoil total porosity vary from 36 % in soil 11 and 12 to 50 % in soil 3. The porosities of the other soils are within the range of 40-46 %. The form of the pF-curves reflects the soil water retention properties of the pore system of the soils.

For the subsoil it appears that the range of total porosity is less and that the pF-curves are more smooth than for the topsoil. It also appears that the pF-curves for the subsoil fell more apart than the pF-curves for the topsoil which has been exposed to homogenizing actions resulting *e.g.* from soil tillage operations.

The obtained values of a and b are shown in Table 1. For topsoil log a and b were found to vary from -3.7 to -5.4, and from 1.43 to 1.85, respectively, whereas for subsoil log a and b were found to vary from -5.3 to -7.4 and from 0.98 to 1.53, respectively.

The relationships between hydraulic conductivity and pressure potential calculated by using Eq. (8) and the obtained values of a and b are shown in Fig. 3 for the topsoil as well as for the subsoil. In the range of pressure potentials considered (pF $\equiv$ 1.7-3.0) it appears that the hydraulic conductivities are within the range of 10^{-10}-10^{-7} m s^{-1} for the topsoils and within the range of 10^{-11}-10^{-8} m s^{-1} for the subsoil. Thus in general the hydraulic conductivity for the topsoil is greater than that of the subsoil by an order of magnitude. This may be explained partly by differences in

Table 1 – Textural composition (%), and hydraulic conductivity function parameters *a* and *b* obtained for 12 Danish till soils.

Soil No.	Location	Depth, cm	Clay	Silt	Fine Sand	Coarse Sand	Organic Matter	-log *a*	*b*
1	Borris	10	5.6	7.6	59.7	24.8	2.2	4.1	1.83
		70	12.8	8.7	55.1	23.0	0.3	6.8	1.17
2	Hornum	10	5.6	8.1	50.0	33.2	3.1	4.7	1.67
		70	7.7	7.3	47.5	37.3	0.3	5.3	1.53
3	Travsted	10	7.3	6.4	44.9	35.9	5.5	4.8	1.62
		70	17.3	6.8	41.7	34.1	0.3	5.7	1.38
4	Foulum	10	7.7	9.9	46.1	33.9	2.5	3.7	1.85
		70	10.3	9.7	45.2	34.6	0.2	6.1	1.29
5	Ødum	10	9.8	15.1	52.8	19.8	2.5	3.8	1.83
		70	16.5	12.6	50.7	20.2	0.2	6.5	1.20
6	Aarslev	10	10.4	14.6	57.1	15.7	2.3	4.5	1.68
		70	19.5	13.5	58.0	8.8	0.2	6.4	1.27
7	Roskilde	10	10.5	16.9	54.3	15.9	2.4	4.3	1.77
		70	26.6	14.3	50.8	7.8	0.5	7.4	1.02
8	Askov	10	10.7	12.3	51.0	23.4	2.6	4.3	1.78
		70	22.6	12.4	47.2	17.3	0.5	6.2	1.29
9	Rønhave	10	14.2	15.3	60.0	8.4	2.1	4.8	1.64
		70	17.5	15.5	59.7	7.0	0.3	6.7	1.22
10	Tystofte	10	14.4	16.1	57.5	10.0	2.0	4.9	1.51
		70[1]	13.7	11.3	53.9	3.4	0.1	6.1	1.28
11	Ø. Ulslev	10	15.3	15.0	45.2	21.1	2.3	4.9	1.58
		70	13.4	12.0	47.4	16.7	0.4	5.4	1.46
12	Kalø	10	17.5	14.2	44.9	22.1	1.4	5.4	1.43
		70[2]	36.7	13.3	32.3	15.6	0.4	7.5	0.98

1) 17.6 % $CaCO_3$

2) 1.8 % $CaCO_3$

texture and partly by differences in pore geometry. At any pF-value the ratio of highest and lowest value of the hydraulic conductivity is greater for the subsoil than for the topsoil which is in accordance with the course of the pF-curves for topsoil and subsoil, respectively. At pF = 4.2 the hydraulic conductivity approaches 10^{-12} m s^{-1} with small differences only between topsoil and subsoil.

The hydraulic conductivity relationships may be related to the corresponding pF-curves. Considering for example soil 4 and soil 11 the pF-curves of which for 10 cm depth almost coincide at pF = 2.0. The hydraulic conductivity in the pF-range considered (pF = 1,7-3,0) appears to be significantly greater for soil 4 as compared to soil 11. This may be explained in terms of the pore size distributions derived from the pF-curves indicating a greater proportion of pores with larger equivalent pore diameters in soil 4 than in soil 11. Similar considerations apply to other soils.

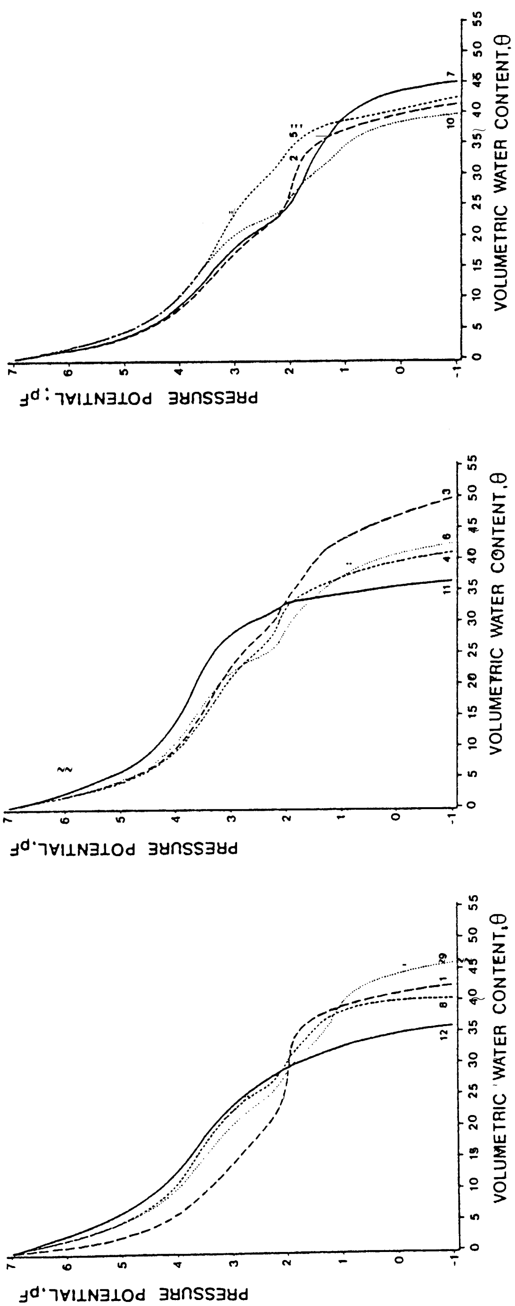

Fig. 2a. Soil water retention characteristics (pF-curves) for 12 Danish till soils, 10 cm depth.

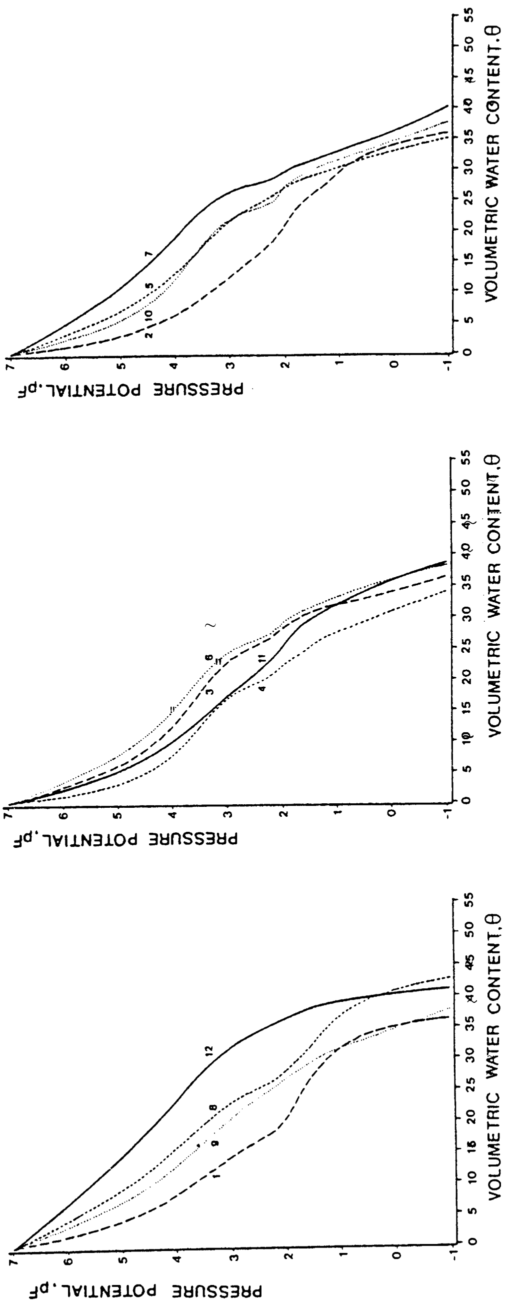

Fig. 2b. Soil water retention characteristics (pF-curves) for 12 Danish till soils, 70 cm depth.

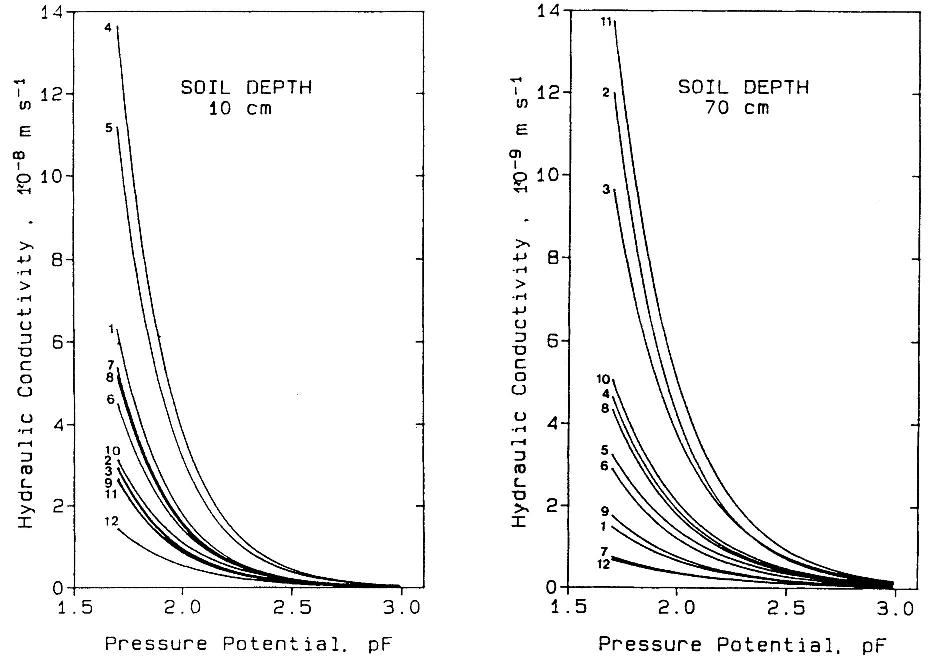

Fig. 3. Unsaturated hydralic conductivity relationships for 12 Danish till soils obtained by the hot air method.

However, an unambiguous interpretation of the hydraulic conductivity relationships in terms of the corresponding pF-curves is made difficult by the fact that differences in microstructure, turtousity, immobile water *etc.* between the soils most probably occur.

The hot air method is simple, quick and inexpensive to carry out and it is applicable to a wider range of soil water contents than most other experimental methods. In a comparative study Ragab *et al.* (1980) found that the hot air method among several experimental methods provided intermediate values of the hydraulic conductivity. The hot air method is most suitable for loamy soils in the intermediate soil water content range outside of which it is difficult to fulfill the boundary conditions (Van Grinsven *et al.* 1985). Thus for the present soils the results obtained are considered reliable for simulation of unsaturated water flow in the respective soils in the pressure potential range form pF = 1.7 and at least to pF = 3.0. In very dry soil the hydraulic conductivity may be overestimated by the hot air method (Jacobsen 1989).

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