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SMR/147-4

COLLEGE ON SOIL PHYSICS

15 April - 3 May 1985

COLLOQUIUM ON ENERGY FLUX AT THE SOIL ATMOSPHERE INTERFACE

6 - 10 May 1985

METHODS FOR MEASURING HYDRAULIC CONDUCTIVITY OF SATURATED AND UNSATURATED SOIL

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1 Introduction

Many methods are available to measure the Hydraulic Conductivity of both saturated and unsaturated soil. A summary of methods, with literature references, will be presented here. Emphasis is not on a highly detailed description of theory or procedure -the reader is referred to specific publications for that- but on operational aspects, such as cost, accuracy, complexity, advantages, disadvantages etc. These aspects are often neglected in purely technical descriptions, even though they are of paramount importance for practical applications.

Flow of water: measurement of hydraulic conductivity. J. Bouma

Saturated soil

Permeability of saturated soil is defined in terms of the hydraulic conductivity (K_{sat}) which follows from the law of Darcy:

$$K_{sat} = \frac{q}{\Delta H}$$

In which K_{sat} (ms^{-1}) is found as a ratio between a flux q (ms^{-1}) and a gradient of the hydraulic head ΔH (mm^{-1}). Saturation is defined as a state in which the soil-water has a zero or positive pressure. Some entrapped air may occur. At saturation, all pores are therefore not necessarily filled with water.

Reference methods for measurement of K_{sat} can be classified in four major types, which use:

1 Calculations based on soil texture, moisture retention data or soil morphology data

None of these methods qualify as reference methods

2 Undisturbed samples
2.1 Sampling cylinders
2.2 Gypsum-encased large columns

3 Auger holes
3.1 Auger holes
3.2 Piezometers
3.3 Inverse auger-hole method

4 Specific techniques
4.1 Air entry permeameter
4.2 Double ring infiltration
4.3 Drainflow

The Bouwer double-tube method is not included as a reference method.

Unsaturated soil

Permeability of unsaturated soil is also defined in terms of the hydraulic conductivity (K) which follows from the law of Darcy. Unlike K for saturated soil, which has one characteristic value, K for unsaturated soil (K_{unsat}) is different for different moisture contents (and corresponding pressure heads). K_{unsat} is therefore not represented by one value but by an infinite number of values which are usually shown by curves relating K_{unsat} to either the moisture content (θ) or to the negative pressure head (h). K_{unsat} is defined as a ratio between a flux q (ms^{-1}) and a gradient of the hydraulic head ΔH (mm^{-1}), at defined θ or h-values.

Next to hydraulic conductivity, the diffusity (D) is also being used to describe flow in unsaturated soil:

$$D = -K.\frac{dh}{d\theta}$$

where $dh/_{d\theta}$ = shape of the moisture rentention curve. Many methods determine D (m^2s^{-1}), which has to be transformed into K values.

A special category of flow is the so-called: "bypass-flow" which describes downward flow of free water along macropores through an unsaturated soil matrix. This type of flow occurs frequently under field conditions, but is not covered in classical soil physics theory. A method to measure bypass flow is included in this chapter, even though it does not represent unsaturated flow in the usual sense.

Reference methods for K_{unsat} and D can be classified in four major types, which use:

1 Calculations

1.1 Based on soil texture

1.2 Based on moisture retention data

Calculations based on soil morphology are not included

2 Steady flow systems

2.1 Crust test

2.2 Two-plate method

2.3 Infiltration in columns

3 Unsteady flow systems

3.1 One-step method

3.2 Instantaneous-profile method

4 Specific techniques

4.1 Sorptivity measurement

4.2 Hot-air method

A fifth category is added which contains a method for measuring bypass-flow.

5.1 Column-outflow method (bypass-flow)

Method 2.1 K_{sat}-Use of sampling cylinders

Principle: An undisturbed soil sample is collected in a rigid metal or plastic cylinder. The sample is slowly saturated and a water flux is induced through the sample, usually by shallow, constant ponding on top and by allowing free outflow at the bottom. The measured flux is used to calculate K_{sat} by the law of Darcy.

Equipment needed: Rigid metal or plastic cylinders with an internal volume of often 100 cm³ or sometimes 300 cm³; sampling equipment such as spades and devices to push cylinders into soil; laboratory set-up for measurements.

Procedure: Two possibilities exist: (1) Shallow, constant ponding and monitoring of outflow, and (2) Measurement of the rate of decline of the ponded water at a certain height in a collar on top of the sample, after stopping the addition of water.

Calculations: For the first procedure K is calculated as follows:

$$K = \frac{Q}{A} \cdot \frac{L}{\Delta H} \qquad (1)$$

For the second procedure:

$$K = \frac{A_1 L}{A\ (t_2-t_1)} \cdot \ln\ \Delta H_1/\ \Delta H_2 \qquad (2)$$

where: Q = volume of water per unit time (m³ s^{-1})

A_1 = surface area of soil sample (m²)

A_1 = surface area of collar on top of sample (m²)

L = length of soil sample

H = Hydraulic Head (= h + z) (m) (h = pressure head)

z = height above the bottom of the soil (m)

Time required: Sampling, and measurement take little time. Batch treatment well possible. Saturation of samples may take several days when they are initially dry, but sampling in clayey soils should occur only when the soil is wet or moist. Then, saturation takes little time.

Cost: Limited. Cylinders and the laboratory set-up are simple and cheap.

Accuracy: Good, assuming that undisturbed samples are obtained that do not swell upon wetting. Measurement under controlled laboratory conditions in terms of temperature is favorable, but transportation may induce disturbance and dessication of samples.

Advantages: Simple method which allows many multiple measurements in a short time. By changing sampling direction, both vertical and horizontal samples may be obtained.

Disadvantages: Disturbance of the soil may occur when sampling. Sample sizes that are often used may be too small to be representative for the soil structure to be characterized. Sampling in stony soils is impossible. Sampling only in soil above the water-table, unless the water table is being lowered before sampling.

Remarks: Use of small, standard cylinder sizes of 100 cm³ should be avoided as they do not produce representative samples for many soils, particularly those containing silt and clay. Sample size should be a function of the size of the structural elements ("peds") and of the pattern of occurrence of large pores. Maximum cylinder sizes are appr. 6 liters. Samples should be taken in soils that are very moist or wet at the time of sampling. The salt concentration and the temperature of the percolating water should correspond with natural soil conditions.

Reference:

Klute, A. (1965): Laboratory measurement of hydraulic conductivity of saturated soil in: Methods of soil analysis 1. ed. C.A. Black, ASA monograph 9.

Method 2.2 K_{sat}-Use of gypsum-encased large columns

Principle: An undisturbed cylindrical column with a diameter and height of 30 cm or more is carefully carved out in situ in very moist or wet soil. An infiltrometer is placed on top. The column is encased in gypsum around the column. The column of soil is saturated and the steady flux of water, is monitored during constant, shallow ponding, induced by a mariotte device, and free outflow at the bottom. This flux is equal to K_{sat} because the gradient of the hydraulic head $H = 1\ mm^{-1}$.

Equipment needed: Cylinder infiltrometer with mariotte device; field equipment such as spades and knifes to carve out the column; gypsum or other materials that allow formation of a rigid, well-fitting encasement.

Procedure: Steady inflow into the column can be measured with a mariotte device, or steady outflow can be collected.

Calculations: K_{sat} is equal to the measured flux.

Time required: At least three columns can be carved out per day in surface soil. Sampling in subsoil takes more time. Measurements itself take little time because fluxes become steady very rapidly in initially very moist or wet soil. All measurements take place in the field; most time required is needed for excavation and sample preparation.

Cost: Limited. Cylinder infiltrometers are most expensive.

Accuracy: Very good, considering presence of a large volume of undisturbed soil which is not transported. The measured flux is equal to K_{sat}, which is therefore obtained in a very accurate manner.

Advantages: Attractive method to obtain large, undisturbed sample. Method can be used in stony soil.

Disadvantages: Carving of a column of soil in very loose structures is difficult. Can only be used in soil above the water-table unless the water-table is lowered before sampling. Only K_{sat}-vertical can be determined (see remarks).

Remarks: Columns should be carved out in soils that are very moist or wet at the time of sampling. The salt concentration and the temperature of the percolating water should correspond with natural soil conditions.

Two variants of the method have been developed:

(1) The cube method, which not only measures $K_{sat-vert.}$ but also $K_{sat-hor.}$ This is accomplished by turning a gypsum covered cube of soil and by making measurements twice. For further information the reader is referred to Bouma and Dekker (1981).

(2) The drain-cube method, which measures K_{sat} in soil directly above and below tile drains. This is done by carving out a cube of soil around the tile drain and by cutting the tile. For further details the reader is referred to Bouma et.al (1981).

Columns and cubes can be strenghtened by adding a thin layer of quick-setting cement before application of the gypsum.

References:

Bouma, J. 1977: Soil survey and the study of water in unsaturated soil. Soil Survey Paper 13. Soil Survey Institute, Wageningen, 107 p.

Bouma, J. and L.W. Dekker (1981): A method for measuring the vertical and horizontal K_{sat} of clay soils with macropores. Soil Sci. Soc. Amer. Journ. 3: 66.

Bouma, J., J.H. van Hoorn and G.H. Stoffelsen. 1981. The hydraulic conductivity of soil adjacent to tile drains in some heavy clay soils in the Netherlands. J. of Hydrology 50: 371-381.

Method 3.1 K_{sat}-Use of auger holes

Principle: An auger hole is made to a level well below the water-table. The hole is pumped out and the velocity with which the water moves back into the hole is measured. This velocity is related to K_{sat} with a calculation procedure. A variant of the method removes water to a constant level and maintains it there. The necessary pumping rate is monitored and is used to calculate K_{sat}.

Equipment needed: Auger, stopwatch, measuring equipment for water levels, pump.

Procedure: Two procedures can be followed: (1) The rate is measured by which the water-level moves back to its original level before pumping, and (2) The pumping rate is measured which is necessary to maintain the water level at a specified level which is lower than the level in surrounding soil.

Calculations: For the first procedure, K_{sat} is calculated as follows (Van Beers, 1970):

$$K_{sat} = C \cdot \frac{\Delta Y}{\Delta t} \quad (1)$$

where: y = distance between the water-table level and the level in the augerhole (m), t = time after emptying of the augerhole and C = geometry factor (from tables).

For the second procedure (Ranger, 1958):

$$K_{sat} = \frac{Q}{C.r} \cdot \frac{G}{(G^2-y^2)} \quad (2)$$

where: Q = flow rate (m^3 s^{-1})

r = radius augerhole (m)

G = depth augerhole below watertable (m)

y = height water table in the augerhole (m)

C = geometry factor, as a function of y, r and the distance to an impermeable level, if present.

Time required: Boring of hole and pumping takes little time. Consistancy between replicate measurements can usually be obtained after several hours in slowly permeable soils. A shorter period is usually needed in more permeable soils. Calculations take very little time due to the use of nomograms.

Cost: Very limited. However, use of electric pumps is expensive and complicated in the field. Procedure 1 can be executed with simple manual pumping. This is more difficult with procedure 2.

Accuracy: Good in reasonably homogeneous sandy soils, without layering. In layered, clayey soils conditions are quite different from those that are assumed in the models that are used to calculate the geometry factor C. Accuracy may be low under those conditions.

Advantages: Simple field methods which allow many measurements in a relatively short period of time, if applied in sandy, homogeneous soils.

Disadvantages: Methods can only be used in soil below the water-table. Augerholes in clayey soils will often have puddled walls which do not allow flow of water into the augerholes. Thus, unrepresentative (low) K_{sat} values are obtained. The method is not suitable for unstable soil structures in which boreholes will collaps. The method yields a K_{sat} that is an undefined mixture of vertical and horizontal flow lines, although the horizontal component dominates.

Remarks: Augerholes can be made in a dry period of the year to be used later when the water-table has higher levels. Thus, puddling of sidewalls is avoided. Puddling is difficult to remove by mechanical means once it has occurred.

References:

Beers, W.J.F. van (1958): The auger-hole method. Int. Institute for Land Reclamation and Improvement. bull. no. 1. Wageningen.

Black, C.A. (ed.) (1965): Methods of Soil Analysis. Agronomy no. 9, American Society of Agronomy Monographs. Madison Wisconsin.

Zanger, C.N. (1953): Theory and problems of water percolation. U.S. bur. of Reclamation Eng. Monogr. 8.

Method 3.2 K_{sat}-use of piezometers

Principle: A closed, open-ended pipe is installed in the soil to well below the water-table and a cylindrical hole is bored beyond the end of the pipe by inserting a small auger into the pipe. Water is pumped out and the velocity with which the water moves back into the hole is measured. This velocity is related to K_{sat} with a calculation procedure. The four-holes method also uses piezometers and can be described as follows:

Two auger holes are made to a level well below the water-table. Water is pumped from one hole into the other until a stationary condition obtains. At least two piezometers are used to measure the head-gradients between the two holes. The pumping rate is related to K_{sat} with a calculation procedure.

Equipment needed: Piezometers, small augers, pump, stopwatch, measuring equipment for water levels.

Procedure: The rise of the water-level in a piezometer is measured after removal of water that was present at hydraulic equilibrium. The piezometers in the four-hole method indicate steady pressures that correspond with the steady flow regime between the two auger-holes.

Calculations: K_{sat} is calculated as follows (Luthin and Kirkham, 1949):

$$K_{sat} = \frac{\pi r^2}{C\,(t_2 - t_1)} \ln \frac{Y_1}{Y_2} \qquad (1)$$

where: r = radius of piezometer (m)

t_1, t_2 = time (s)

Y_1, Y_2 = distance between water-level in piezometer and groundwater level at times t_1 and t_2.

C = geometry factor (m)

The four-holes method uses the following calculation (Snell and Van Schilfgaarde, 1964):

$$K_{sat} = 0{,}221\ \frac{C.Q}{G.Y} \quad \text{for } d = \frac{1}{3} D \qquad (2)$$

where: Q = pumping speed ($m^3\ s^{-1}$)

G = distance between water-table and lower boundary augerholes (m)

D = distance between the two boreholes (m)

d = distance between the two piezometers which are placed at regular distances between the two boreholes (m)

C = geometry factor, which depends on G, d, D and the distacne to an impermeable layer, if present. Tables of C values are presented by Snell and Van Schilfgaarde, 1964).

Time required: Precise placement of the piezometers takes more time than boring a hole, but time required is still limited. The four-holes test is more laborious as it requires installation and monitoring of a set of holes and piezometers. Calculations take little time due to the use of nomograms and standard tables.

Cost: Limited. However, use of an electric pump is expensive and complicated in the field. The piezometer method can be executed with a simple handpump. The four-holes method requires use of a pump.

Accuracy: Good in soils that are reasonably homogeneous with well-defined layers. In layered, clayey soils conditions are quite different from those that are assumed in the models that are used to calculate geometry factors C. Accuracy may be low under those conditions.

Advantages: Relatively simple method that allows many measurements in a short period of time. The piezometer allows characterization of specific layers in the soil because water can enter the piezometer only at the bottom. This makes the measurement more specific than the one with the augerhole-method (3.1). The four-holes method characterizes a large volume of soil.

Disadvantages: Methods can only be used in soil below the water-table. Piezometer holes in clayey soils will often have puddled sidewalls which do not allow flow of water. This is the more serious since the cavity below the piezometer is very small. Thus, unrepresentative (low) K_{sat} values are obtained. The method cannot be used in unstable soil materials. The measured K_{sat} reflects only properties in the horizontal direction.

Remarks: Installation of piezometers in a dry period with low watertables may avoid the puddling problem.

Installation of the piezometers should occur with care to avoid flow of water along their shafts. This mechanism is a potential source of error.

References:

Luthin, J.N., and Don Kirkham (1949): A piezometer method for measuring permeability of soil in situ below a water table. Soil Sci. 68: 349-358.

Snell, A.W. and J. van Schilfgaarde (1964): Four well method of measuring hydraulic conductivity in saturated soils. Trans. Am. Soc. Agr. Eng. 7: 83-87, 91.

Method 3.3 The inverse auger-hole method

Principle: An augerhole is made to the required depth in soil above the watertable. The hole is filled with water and, after a certain period, the infiltration rate is measured. This rate is "translated" into a K_{sat} value.

Equipment needed: auger, stopwatch, measuring tape.

Procedure: Two procedures can be followed: (1) The rate is measured by which the water level in the borehole moves downwards, or (2) The rate is measured by which water has to be added to the borehole to maintain the water at a constant level.

Calculations: The following equation is used for the second procedure; which assumes hydraulic gradients of 1 m per m.

$$K_{sat} = \frac{1.15r}{t_2 - t_1} \cdot \log \frac{y_1 + \frac{1}{2}r}{y_2 + \frac{1}{2}r}$$

where: r = radius borehole (m)

$y_{1,2}$ = height of waterlevel in the borehole above its bottom at times t_1 and t_2 (m)

$t_{1,2}$ = time (s)

Time required: Soaking of soil is necessary when initial conditions are moist or dry. This may take at least a day. The measurement itself, to be executed several consecutive times to establish constancy, takes several hours.

Cost: Limited. Equipment is simple.

Accuracy: Good in reasonably homogeneous sandy soils without layering. In cracked clays, the method is unreliable because natural swelling effects cannot be achieved by a relatively short soaking period. The measured K is an undefined mixture of vertical and horizontal components. Accuracy is reduced by the fact that the hydraulic gradient is often not 1 mm^{-1}.

Advantages: Simple method which allows many replicate measurements.

Disadvantages: Cannot be used in soils with very high K_{sat} values and in clay soils.

Remarks: This method is widely used in the USA as the so-called "percolation test" which is used to estimate soil permeability for septic tank disposal fields.

References:

Boersma, L. (1965): Field measurement of hydraulic conductivity above a water table. In: C.A. Black (Ed.): Methods of soils analysis. I. Agronomy 9. Am.Soc. of Agronomy. Madison Wis. USA: 234-252.

Int. Inst. for Land Reclam. and Impr. (ILRI) (1974): Drainage principles and applications. III: 292-294. Wageningen, The Netherlands.

Method 4.1 K_{sat} - Air entry permeameter

Principle: Water infiltrates into dry soil from an infiltrometer, using a high head of water. Once the water has infiltrated to a depth of about 10 cm, water application is stopped. Continued infiltration into the soil causes the development of a negative pressure in the (closed) infiltrometer. This pressure is measured with a manometer, and decreases to a critical value when the air-entry pressure of the wetted soil is exceeded and air bubbles through the wetted soil into the infiltrometer. Then, the pressure being registrated by the manometer drops to zero. The critical pressure, the depth of wetting and the infiltration rate are used to calculate K_{sat}.

Equipment needed: A specially built air-entry permeameter must be available (diameter 20 or 30 cm). No futher special equipment needed.

Procedure: A horizontal plane is prepared in the soil at the required depth on top of which the air-entry-permeameter is placed. The experimental procedure was described above.

Calculation: K_{sat} is calculated with the following equation:

$$K_{sat} = \frac{Q}{A} \cdot \frac{z}{(Y - \frac{1}{2} h_a) + z} \qquad (1)$$

where: Q/A = flux, just before water application is stopped (ms^{-1})

z = depth of water front (m)

Y = height of water in standpipe above the soil surface at the moment when water application is stopped (m)

The term h_a is measured as follows:

$$h_a = h_{min} + G + z \qquad (2)$$

where: h_a = air entry value (m)

G = height manometer above soil surface (m)

Time required: One measurement can be made in about one hour, including placement of the permeameter. At one location, water can only be applied once.

Cost: Restricted to the air-permeameter.

Accuracy: Good in dry soils with well defined air entry values. Poor under other conditions.

Advantages: Relatively rapid method which uses a large sample.

Disadvantages: The method can only be used in soil with well defined air-entry values. Occurrence of continuous macropores results in instant air breakthrough, making the test useless. Application can only be considered in sandy, nonswelling and non-stony soil. K_{sat} of clayey soils can only be measured when the soil is wet and swollen, not in dry condition.

Remarks: None.

References:

Bouwer, H. (1966): Rapid field measurement of air entry value and hydraulic conductivity of soil as significant parameters in flow system analysis. Water Res. Res. 2, 4: 729-738.

Topp, G.C. and M.R. Binns (1976): Field measurement of hydraulic conductivity with a modified air-entry permeameter. Can. J. Soil Sci. 56: 139-147.

Method 4.3 K_{sat}-Double ring infiltration

Principle: Two concentric cylinders are placed on top of the soil and they are filled with water. The water levels in the two rings are maintained at a constant level, while the downward rate of movement of the water-level in the inner-ring is observed. This rate is representative for K_{sat} when wetting has progressed beyond a certain depth for an extended period of time. Higher initial infiltration rates can be measured as well.

Equipment needed: An inner- and outer metal cylinder, to be used as infiltrometer. Measuring equipment to observe the downward rate of movement of water in the inner cylinder.

Procedure: The infiltration rate is observed until constant. A bottle with mariotte device can be used to measure the infiltration rate.

Calculation: Vertical infiltration in a deep, homogeneous soil is characterized by:

$$K_{sat} = \frac{Q}{A} \cdot \frac{z}{(h-h_f) + z} \qquad (1)$$

where: Q/A = flux (ms^{-1}). (Q = flow rate in m^3s^{-1} and A = surface area infiltrometer in m^2)

h = pressure head at soil surface (m)

h_f = pressure head at the infiltration front (m)

z = depth infiltration front below surface (m)

As the infiltration front moves deeper, $(h-h_f)$ will become much smaller than (z). Thus, equation (1) changes to:

$$K = \frac{Q}{A} \qquad (2)$$

Time required: Varies in different soils, but usually several hours per measurement. Steady infiltration rates are directly equal to K_{sat}. No additional calculations needed.

Cost: Limited, only infiltrometers needed and measuring equipment.

Accuracy: High, when fluxes are accurately measured. Inner infiltrometers often have a diameter of 30 cm, yielding relatively large samples.

Advantages: Simple, direct method. Steady infiltration rates are equal to K_{sat} in homogeneous soils.

Disadvantages: The method does not work in soils with slowly or very highly permeable horizons that occur relatively close to the soil surface. Then, the pressure head gradient is most likely not equal to 1 mm^{-1} with the result that the infiltration rate is lower than K_{sat}. Also, lateral flow of water may occur away from the outer ring in soils with macropores. This disrupts the required one-dimensional system.

Remarks: K_{sat} in swelling clayey soils can only be measured in initially wet soil. The method being described here can be used then. However, continuous downward flow in the soil should be assured.

References:

FAO (1979). Soil Survey Investigations for irrigation. Rome.

Winger, R.J. (1960). In place permeability tests and their use in subsurface drainage. Int. Congr. Comm. Irrig. and Drainage. Madrid.

Method 4.4 K_{sat} - drainflow

Principle: Water-table levels and drain discharges are measured during a certain period. K_{sat} is calculated with an equation which expresses relationships between drain discharge, water-table level and soil profile characteristics.

Equipment needed: Bucket, stopwatch, piezometers, and measuring tape.

Calculation: The calculation is based on the drainage equation by Hooghoudt, as follows:

$$q = \frac{8\ K_o d.h.}{L^2} + \frac{4\ K_b\ h^2}{L^2}$$

where:
- q = drain discharge per m^2 of surface area (ms^{-1})
- h = height of water-level between the drains, measured halfway between the drains (m)
- d = equivalent thickness of the layer through which flow occurs, to be determined from tables (m)
- L = distance between the drains (m)
- K_o = K_{sat} of soil below the drains (ms^{-1})
- K_b = K_{sat} of soil above the drains (ms^{-1})

The equivalent thickness d is smaller than the real thickness of the layer through which flow occurs, as it expresses the effect of the resistance of the soil surrounding the drains. For specific calculation details, the reader is referred to the reference below.

Time required: The method is laborious, because repeated measurements are needed. Drain discharge depends, of course, on weather conditions.

Cost: Low, except for time requirements.

Accuracy: Limited. Flow above the drains is vertical; the direction below the drains is variable. The volume of soil being characterized is very large. The equation being used is valid for "ideal" soil with a uniform profile, constant thickness and permeability and stationary flow. This is often not true, and the value of d may therefore vary considerably.

Advantages: Very large sample consisting of undisturbed soil, except for possible compaction around the drains.

Disadvantages: Method can only be used when drains discharge water and when the water level in the ditches is below drainlevel.

Remarks: None.

Reference:

Institute of Land Reclamation and Improvement (ILRI) (1974). Drainage principles and applications vol. 3: 337-431.

Method 1.1 K_{unsat} - Calculations based on soil texture

Principle: The grain-size distribution of a soil (soil texture) is related to soil permeability by means of regression analysis, using measured K(h) curves and soil texture data.
Equipment needed: none if K(h) and soil texture data are available. Only statistical calculations are needed.
Procedure: see below.
Calculations: The procedure used by Bloemen (1980) will be described as a specific example of this approach. His calculations are based on the equation of Brooks and Corey (1964):

$$K(h) = K_s \left(\frac{h_a}{h}\right)^n \qquad (1)$$

where: $K_s = K_{sat}$
h_a = air entry value of the soil sample
n = measure for the pore size distribution.

These three variables are transformed into terms that relate to soil texture. To this purpose regression analyses are made using existing data. The following results were obtained for a wide range of soils:

$$K_s = 0.02\ M_d^{1.93} \cdot p^{-0.74} \quad (s = 167\ \text{cm d}^{-1})$$

$$h_a = 2914\ M_d^{-0.96} \cdot p^{0.79} \quad (s = 12.7\ \text{cm})$$

$$n = 1.4 + 4.536\ (f^{0.3p} - 1) - 0.75\ p^{1.6} \cdot \log h$$

where: M_d = median grain-size;
p = grain-size distribution index as defined by Bloemen (1980)
f = porosity

Time required: Very little time required when calculation programs are available.
Cost: Very limited.
Accuracy: Poor. Estimates for K_s, h_a and n have each a relatively high standard deviation (s value). The n value can also be calculated from corresponding moisture retention data. Correlation of such values, with the calculated ones according to the equations listed above, yields low coefficients of 0.77 (Bloemen, 1980).
Advantages: Simple, rapid method that yields many data in a short time.
Disadvantages: Only suitable for sands with little clay, for which n values are defined. Not suitable for soils with poorly defined h_a values.
Remarks: Due to the limited applicability and the relatively high error involved, this method is not recommended, with the exception for sands.
Reference:

Bloemen, G.W. 1980. Calculation of hydraulic conductivities of soils from texture and organic matter content. Zeitsch. für Pflanzenern. und Bodenkunde. 143: 581-615.

Method 1.2 K_{unsat} - Calculations based on moisture retention data

Principle: The method is based on a model-concept in which soil pores are represented as bundles of cylindrical pores. Their (equivalent) size distribution is derived from moisture retention data. When saturated, all pores are filled with water. As the pressure head decreases, increasingly smaller pores are emptied. K decreases accordingly in a pattern that is related to the pore-size distribution.
Equipment needed: none, if moisture retention data are available. Only computer calculations are needed.
Procedure: Two procedures are being followed. One procedure was initially published by Marshall, Millington and Quirk and was later summarized by Green and Corey (1971). The second procedure was derived by Brooks and Corey (1964).
Calculations: The first procedure is based on Poiseuill's law and starts with an equation defining the pressure head (h) at which pores with radius r are still filled with water:

$$h = \frac{-2\sigma}{\rho . g . r} \qquad (1)$$

where: σ = surface tension of water ($kg\ s^{-2}$)
ρ = density of water ($kg\ m^{-3}$)
g = acceleration of gravity ($m s^{-2}$)
r = radius cylindrical pore (m)

Poiseuille's law relates the flow rate of water to the size of a (cylindrical) pore, as follows:

$$K = \frac{r^2 \rho g}{8\eta} \qquad (2)$$

in which: η = viscosity of the water ( )

Equations (1) and (2) are combined and the moisture-content range of the soil is divided in n-intervals (i = 1, 2, ... n). The pore volume in an interval i is occupied by cylindrical pores that are still filled with water at the pressure head h_i. h values are read from the moisture retention curve. The following equation results after introduction of a pore-interaction model:

$$K(\theta)_i = K_s/K_{sc} \cdot \frac{\sigma^2}{\rho g \eta} \cdot \frac{f^p}{n^2} \cdot \sum_{j=i}^{m} (2j+1-2i)\ h_j^{-2} \qquad (3)$$

where $K(\theta)_i$ = K for θ_i (i = 1 is saturated soil). i = m = pore-class with lowest water content for which calculations are made. p = constant f = porosity ($m^3 m^{-3}$). The term K_s/K_{sc} is the matching factor which defines the ratio of the measured versus the calculated K_{sat}.
The second procedure is based on the following equation (4):

$$K(h) = K_s \left(\frac{h_a}{h}\right)^n \qquad (4)$$

where: h_a = air-entry value, n = measure for pore-size distribution as defined by Brooks and Corey (1964). K_s and h_a must be measured. n is derived from the moisture retention curve. They use the factor S_e which is defined as "effective saturation":

$$S_e = \frac{S - S_r}{1 - S_r}$$

where: S = ratio of water-filled pores to total porosity and
S_r = residual saturation. They prove that:

$$n = 2 + 3\lambda$$

where: λ = d (log S_e) / d (log h)

Time required: Quite limited if moisture retention data are available. Measurements of K_{sat} (for matching purposes) and h_a may take considerable time.
Cost: Very limited if activities can be restricted to calculations.
Accuracy: Higher for the first procedure than for the second, because of the often poorly defined h_a values. Particular h_a values can only be well determined in well-sorted sands. Clayey soils with macropores have undefined h_a values. The first procedure works rather well in sandy soils for which the equivalent pore-size model is suitable. Problems arise in clayey soils as is evident by often very small matching factors, as cited by Green and Corey. The matching factor has no physical significance.
Advantages: Both procedures are relatively simple and cheap, allowing multiple applications in a short period of time.
Disadvantages: Both methods have severe theoretical limitations for soils with poorly defined h_a values and with a pore size distribution that cannot be represented by a static capillary-bundle model. Unfortunately, most soils belong to both of these problem categories.
Remarks: These methods should be applied with utmost care to avoid generation of irrelevant data.
References:

Procedure 1: Green, R.E., and J.C. Corey (1971). Calculation of hydraulic conductivity: A further evaluation of some predictive methods. Soil Sci. Soc. Amer. Proc. 35: 3-8.
Procedure 2: Brooks, R.H. and T. Corey (1964). Hydraulic properties of porous media. Colorado STate Univ. Hydr. Papers 3. 27 p.

Method 1.3 K_{unsat} Use of soil morphology

Measurements of pore sizes in thin sections can be used to calculate K_{unsat} as discussed in method 1.3: K_{sat}.
The method can be used to calculate K_{unsat} for thin layers of sandy soil that cannot be sampled for traditional physical methods.

Method 2.1. - K_{unsat} - Crust test

Principle: The infiltration rate through a crust is measured which is present on top of a soil column. A steady flow system develops and the measured flux is then equal to K_{unsat} at the subcrust pressure head which is also measured.

Equipment needed: A cylinder infiltrometer and tensiometer equipment.

Procedure: An undisturbed, large soil sample is carved out in situ and is encased in gypsum after placement of an infiltrometer on top. (see column method for K_{sat}: method 2.2.). A crust is placed on top of the soil. It is made by mixing quick setting cement and sand in particular mixtures (usually 10%, 20% and 50% cement). Sand and cement are mixed when dry and a paste is formed by adding water. This paste is put on top of the soil and hardens in a few minutes. The infiltration rate through the crust is measured and the subcrust pressure head. The latter should preferably be measured at two points to allow an estimate of the vertical hydraulic gradient which is usually 1 mm^{-1} in a deep column of soil. The measurement is repeated with several crusts.

Calculations: The flux is equal to K_{unsat} at the measured subcrust pressure head. No calculations are needed.

Time required: Limited. Preparation of samples will take some time; but measurements can be made quite rapidly since the method is restricted to pressure heads close to saturation, when fluxes are relatively high.

Cost: Limited, when a cylinder infiltrometer is available.

Accuracy: Excellent, because flux and associated pressure head are obtained directly, while the sample is large.

Advantage: Simple, very accurate method which yields K values in a pressure head range for which K values are difficult to obtain with other methods. The method of crust application ensures perfect contact between soil and crust.

Disadvantages: The range of the method is restricted to pressure heads of approximately 0 to -50 cm or so, which are associated with fluxes of at least several mm's per day.

Remarks: Earlier versions of the method used gypsum-sand crusts. These may dissolve slowly during the measurements. Use of quick setting cement overcomes these problems. The method, as described here, measures inflow into the soil. Outflow from a soil column can also be measured, buth then the column should be sufficiently long.

Reference: (Only the latest paper is mentioned, see other references in the following paper).

Bouma, J., C. Belmans, L.W. Dekker and W.J.M. Jeurissen. 1983. Assessing the suitability of soils with macropores for subsurface liquid waste disposal. Journal of Environmental Quality 12 (3): 305-311

Method 2.2. K_{unsat} -Two-plate method

Principle: A soil sample is placed between two porous-plates which are subjected to different (negative) pressure heads. A steady flow is established and K_{unsat} is obtained by also measuring the two pressure heads in soil adjacent to the two plates.

Equipment needed: Porous plates, tensiometers, flux measuring equipment.

Procedure: The two plates can be subjected to negative pressure heads (Laliberte and Corey, 1967) or to positive gas pressure (Elrick and Bowman, 1964). A small difference in pressure is induced between the two plates, so as to allow calculation of the K at the average pressure head.

Calculations: K_{unsat} is considered constant for the pressure head range being considered. K_{unsat} for the average pressure head follows from:

$$K_{unsat} = \frac{Q}{A} \cdot \frac{1}{1 - \Delta h / \Delta z}$$

where Q = volume of water that leaves the sample during time t ($m^3 s^{-1}$)

A = cross sectional surface (m^2)

h = pressure head (m)

z = depth below the soil surface in the sample (m)

Time required: At lower pressure heads, equilibrium steady-state flow systems are only reached after several days or more, which makes the method very timeconsuming. At higher pressure heads, measurements take less time, although frequent observations of fluxes and pressure heads are needed.

Cost: Material costs are low, but labour cost may be high.

Accuracy: Good, when the gradient of the pressure head is low. However, fluxes can only be measured if the gradient has some value. At certain moisture contents, K may change strongly upon small changes in moisture content. Then, the method is rather inaccurate.

Advantages: Relatively simple method requiring only simple, direct calculations.

Disadvantages: Labour intensive method. Results are approximate due to the averaging procedure involved. Contact of soil and plates is critical to allow flow, and this may offer problems in swelling or unstable soils because plates should not be pressed too hard onto the soil sample. The closed system does not allow air to escape, nor does it allow air-entry.

Remarks: A variant of the method has been published by Henseler and Renger (1968) who used a decreasing pressure head difference in a "falling-head" method. Nielsen et al (1960, 1961) used one porous plate at the bottom of the sample to induce a constant flux there, while allowing free evaporation at the top of the sample.

References:

Henseler, K.L. und M.Renger, 1968: Die Bestimmung der Wasserdurchlässigkeit in Wasserungesättigden Boden mit der Doppeltmembran-Druckapparatur. Z. Pflanzenern. Bodenk. 122: 220-228.

Nielsen, D.R., D.Kirkham and E.R. Perrier, 1960: Soil capillary conductivity: Comparison of measured and calculated values. Soil Sci. Soc. Amer. Proc. 24: 157-160.

Nielsen, D.R. and J.W. Biggar, 1961: Measuring capillary conductivity Soil Sci. 92: 192-193.

Elrick, D.E. and Bowman, D.H., 1964: Improved apparatus for soil moisture flow measurements. Soil Sci .Soc. Amer. Proc. 28: 450-453.

Method 2.3 K_{unsat} - Infiltration in columns

Principle: A long column, filled with dry soil, is subjected to a constant flux of water at its upper surface. After some time a constant moisture content and pressure head is observed below the surface of infiltration. The measured flux is equal to K_{unsat} at the measured water content and pressure head.
Equipment needed: Column filled with soil, equipment to apply water. Tensiometer and equipment to measure water contents. Required equipment is simple and not expensive.
Procedure: Three methods are being followed to apply water at a constant rate: (1) Water can be sprinkled on the column at a series of rates that are lower than K_{sat}. (2) Water is applied through a porous plate to which a negative pressure is applied (Youngs, 1963), or (3) Water is applied through a crust with a higher resistance which allows a small positive head on top of the crust (see method K_{unsat}: 2.1 the crust test).
Calculations: Very simple and direct: Flux is equal to K_{unsat} at the observed moisture content and pressure head.
Time required: Data are rapidly obtained at high fluxes. Low fluxes require long times of infiltration.
Cost: Limited.
Accuracy: Good. The procedure is quite direct, K_{unsat} h and θ are measured directly.
Advantages: Simple method with good accuracy.
Disadvantages: Long measurement times at low fluxes. Method, using procedure 1, cannot be applied in soils with macropores because of short-circuiting.
Remarks: None.
References:

Youngs, E.G. 1963. An infiltration method of measuring the hydraulic conductivity of unsaturated porous materials. Soil Sci. 97: 307-311.

Hillel, D. and W.R. Gardner. 1970. Measurement of unsaturated conductivity and diffusivity by infiltration through an impeding layer. Soil Sci. 109: 149-153.

Method 3.1. K_{unsat} One-step method, yielding D

Principle: A soil sample is placed on a porous plate in a pressure chamber or in a Büchner funnel. The sample is in contact through the plate with water of a known pressure. Suddenly the pressure in the chamber is increased to a known value (or the negative pressure below the porous plate is reduced to a known value). Outflow from the sample is measured as a function of time. Once a new hydraulic equilibrium has been reached, the moisture content in the sample is determined. Data are used to calculate the diffusity (D) which can be transformed into K.

Equipment needed: Pressure chamber or Büchner funnel with associated equipment.

Procedure: see principle.

Calculations: The equation used to calculate D is as follows: (Gardner, 1962)

$$D(\theta) \frac{4L^2}{\pi^2 (\theta_t - \theta_f)} : d\theta_t/dt$$

Where: $D(\theta)$ = diffusity ($m^2 s^{-1}$)
θ_t = moisture content at time t ($m^3 m^{-3}$)
θ_f = final moisture content ($m^3 m^{-3}$)
t = time after application of pressure (s)
L = height soil sample (m)

Time required: depending on the pressure range being considered. Equilibrium takes more time to reach at lower pressure heads.

Cost: limited; equipment is relatively simple and inexpensive.

Accuracy: limited, because of relatively small sample sizes. Outflow volumes can be measured accurately with a graduated burette. Transformation of D into K involves introduction of some error.

Advantages: Relatively simple method that yields good data for a limited range of pressure heads and moisture contents.

Disadvantages: rather time consuming at low fluxes. Unsuitable in swelling soils. Cannot be used to obtain K near saturation, because of rapidly changing outflow rates.

Remarks: This method is suitable to be applied simultaneously in a series of samples.

References:

Gardner, W.R. (1962): Note on the separation and solution of diffusion type equations. SSSAP 26:404-405.
Jaynes, D.B. and E.J. Tyler (1980): Comparison of one-step outflow method to an in situ method for measuring hydraulic conductivity SSAJ44: 903-907.
Gupta, S.C., D.A. Farrell and W.E. Larson (1974): Determining effective soil water diffusivities from one-step outflow experiments. SSSAP 38: 710-716.

Method 3.2 K_{unsat} - Instantaneous-profile method

Principle: A soil profile is wetted in situ and covered with a plastic sheet to stop evaporation. Moisture contents and pressure heads are measured at different times during natural drainage of the soil. These data are used to calculate K.

Equipment needed: tensiometers, equipment to measure moisture contents (e.g. neutron probe), other miscalleneous equipment.

Procedure: see principle.

Calculations: Fluxes are calculated as follows:

$$q(z,t) = -\int_0^z \left(\frac{d\theta}{dt}\right)_z dz \qquad (1)$$

where:
q(z,t) = flux at depth z and time t (ms^{-1})
θ = moisture content ($m^3 m^{-3}$)
z = depth below surface (m)
t = time (s)

K is calculated as follows:

$$K = \frac{q(z,t)}{\left(-\frac{dh(z,t)}{dz}\right)} \qquad (2)$$

Time required: The measurement may take several weeks, particularly in clayey soils with low internal drainage rates. Field observations take much time.

Cost: relatively high, due to equipment needs and labour intensive procedures.

Accuracy: Good. Method is directly derived from field drainage experiments and posseses thus a built-in validation.

Advantages: Method yields representative data for field soils in a pressure head range that is relevant for internal drainage problems.

Disadvantages: The assumption of one-dimensional flow does not allow occurrence of subsurface horizons with different properties. Application in sloping soils is not possible. Method is not suitable to obtain values near saturation because of very rapid drainage. Very time consuming when low fluxes occur.

Remarks: The method can also be used allowing evaporation at the soil surface. The observed pressure heads allow a determination of the depth of the "zero-flux-plane" from where upward flow occurs towards the soil surface and downward flow towards the water-table or subsurface horizons. (see Richards et.al., 1956). A similar method for soil samples in the laboratory has been proposed by Wind (1969) and Boels et.al. (1978).

References:

Hillel, D.I., V.D. Krentos and Y. Stylianou. 1972. Procedure and test of an internal drainage method for measuring soil hydraulic characteristics in situ. Soil Science 114: 395-400. (provides a specific example).
Richards, L.A., W.R.Gardner and G. Ogata. 1956. Physical processes determining water loss from soil. Soil Science Soc. Amer. Proc. 20: 310-314.

Wind, G.P. 1969. Capillary conductivity data estimated by a simple method. Proc. Symp. Water in the Unsaturated Zone, Wageningen, Netherlands.
Boels, D., J.B.H.M. van Gils, G.J. Veerman and K.E. Wit. 1978. Theory and system of automatic determination of soil moisture characteristics and unsaturated hydraulic conductivities. Soil Science 126:191-199.

Method 4.1. K_{unsat} - Sorptivity measurement, yielding D.

Principle: Water is applied under pressure to a soil sample through a porous plate. Pressure is applied in such a way that the cumulative adsorption of water is proportionate to $\sqrt{t}$. Sorptivity values obtained are used to calculate the diffusity (D) which can be transformed in K_{unsat}.

Equipment needed: A special apparatus is needed for applying water to a soil sample with a rate that is proportionate to $\sqrt{t}$. Additional equipment is minimal.

Procedure: Application of water occurs with a pump and special gears which allow the cumulative absorption of water (i) to be proportionate to $\sqrt{t}$. Various combinations of pumping velocities, gear size and pump-volume can be used to induce specific Sorptivity (S) values, where:

$$i = S\sqrt{t}$$

The water content and pressure head are measured in soil adjacent to the porous plate, as soon as S is constant. This is often the case after only a few minutes. Five to ten determinations can be made in each sample.

Calculations: Diffusity (D) is calculated from the obtained S values:

$$D(\theta_1) = \frac{\pi S^2}{4(\theta_1-\theta_o)^2} \cdot \left[\frac{\theta_1 - \theta_o}{1 + \gamma \log e} \cdot \frac{d}{d\theta_1} \log S^2 - \frac{1-\gamma}{1+\gamma}\right]$$

where γ = constant varying between 0.50 and 0.67.

Time required: Limited. A sample can be used for several determinations and calculations are rapid when a computer program is available.

Cost: Limited, once the special apparatus has been bought.

Accuracy: Good, although complex calculations for D are needed, which include the empirical factor γ. This new method has not yet been tested extensively.

Advantages: Simple, rapid method that allows mutiple measurements in a short time.

Disadvantages: Complex calculations for D. Additional error introduced when transforming D to K. Applications limited to sandy and silty soils. Swelling soils are more difficult to characterize with this method.

Remarks: This is a promising method that should be widely applied and tested.

Reference:

Dirksen, C. 1979. Flux controlled sorptivity measurements to determine soil hydraulic property functions. Soil Sci. Soc. Amer. J. 43: 827-834.

Method 4.2 K_{unsat} Hot-air method, yielding D

Principle: A moist soil sample is dried at the top for a limited period of time with hot air. The moisture content distribution in the sample after treatment is measured and is used to calculate D.
Equipment needed: A hot-air gun capable of producing a stream of hot air with a temperature of $\pm$ 200°C. A balance for weighing the sample.
Procedure: Undisturbed soil samples are taken in 10 cm high metal cylinders. After saturation, the samples are desorbed to a pressure head of approximately 30 cm. Hot air is blown onto the samples during a period of approx. 10 minutes. The soil is pushed from the cylinder and is cut in 5 mm thick slices, of which the moisture content is measured. Moisture content is plotted versus depth and this graph is used to calculate D.
Calculations: Diffusivity is calculated as follows:

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

where:
D = Diffusivity ($m^2 s^{-1}$)
θ_x = moisture content at depth x after t sec
θ_i = initial moisture content
t = duration of evaporation (s)
x = depth (m)

The following boundary conditions apply:
1) the sample should be homogenous
2) the evaporative loss, which is being measured repeatedly during the procedure, should be proportionate to $\sqrt{t}$ and
3) the moisture content in the bottom of the sample should remain constant (semi-infinite sample).

Time required: Little time needed. The measurement takes some 45 minutes all together. Calculations can be made with a computer.
Cost: quite limited.
Accuracy: Reasonable, but there are several sources of error: evaporation of water during sampling; viscosity changes of the water during the measurement and the approximate character of the calculation procedure.
Advantages: Rapid, simple method which allows mutiple measurements in a short time.
Disadvantages: Some theoretical limitations of the method have to be recognized: Water transport is not isothermal. The method does not work well in sands, probably because of irregular evaporation in a sandy matrix when applying a stream of forced air. Moisture retention curve is needed to obtain K_{unsat}.
Remarks: Some specific testing of the method is needed to evaluate theoretical limitations. So far, curves obtained yield good results when applied in simulation models, particularly in clay soils.
References:

Arya, L.M. , D.A. Farrell and G.R. Blake, 1975. A field study of soil water depletion patterns in presence of growing soybean roots. I. Determination of hydraulic properties of the soil. Soil Sci. Soc. Amer. Proc. 39:424-430.

Method 5.1 Column-outflow method (bypass flow)

Principle: A large, undisturbed dry column of a soil with macropores is subjected to sprinkling irrigation with a defined intensity and duration. The mass of the soil is determined. The moment that water first leaves the column is observed and the outflow rate is measured during sprinkling. The column is weighed after termination of the experiment. The [illegible] of the [illegible] mass is attributed to the adsorption of water. The [illegible] of water t[illegible] eft the still unsaturated soil mass is expressed a[illegible] of the applied water to obtain a percentage value for bypass [illegible]

Equipment needed: Large cylinders of soil. Sewer-pipe segments [illegible] meter and length of 2[illegible] cm have been used succesfully. A simple stand [illegible] allow collection of outflow from the column. Sprinkling equipment.

Procedure: see principle.

Calculations: None. The outflow at a given time is compared with the inflow to calculate the percentage of bypass flow. The determination of the dry mass at the start of the experiment allows an estimate of soil porosity and of the associated moisture content at saturation. According to Darcy flow theory, outflow from the column can only occur when the soil is saturated (or more precise: when pressure head h = 0 cm at the bottom of the core and h = -20 cm at the top of a 20 cm high core). Outflow during bypass flow occurs much more rapidly.

Time required: Little. When commercial sprinkling equipment is used, eight samples [illegible] be run in about 30 minutes.The measured outflow data are directly appli[illegible]; no additional calculations needed.

Cost: Very limited.

Accuracy: Good. The measurement of outflow is accurate. The inflow rate is more difficult to measure when intermittent sprinkling is applied.

Advantages: Simple, cheap and rapid method which allows mutiple measurements of an important phenomenon that has so far been ignored.

Disadvantages: Free outflow at the bottom of the core is only realistic in soils that have free macropore-drainage to the subsoil. If the macropores, such as cracks, end at a certain depth, they will fill up with water and water will have to slowly infiltrate into the soil matrix. Short-circuiting in a short core, with continuous pores, is then not representative for field conditions. Conditions after filling up of the macropores were described by Bouma and Wosten, (1984).

Remarks: Sample size should be such that macropore patterns are well represented.

References:

Bouma, J., L.W. Dekker and C.J. Muilwijk, 1981. A field method for measuring short-circuiting in clay soils. J. of Hydrol. 52: 347-354.

Bouma, J. and J.H.M. Wösten, 1984. Characterizing ponded infiltration in a dry cracked clay soil. J. of Hydr. 69: 297-304.

Bouma, J. 1985. Using soil morphology to develop measurement methods and simulation techniques for water movement in heavy clay soils. In: J. Bouma and P.A.C. Raats (Eds.). Proc. of the ISSS Symposium on water and solute movement in heavy clay soils. ILRI publication 37, Wageningen, Netherlands p. 298-316.