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# Methods for Measuring the Saturated Hydraulic Conductivity of Tills

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The texture of tills excludes many of the traditional methods for measurement of the saturated hydraulic conductivity. The hydraulic conductivity is scale dependent and for massive relatively homogeneous till a representative sample volume of $10^4$-$10^5$ $cm^3$ is suggested. There are no ideal methods for measuring the saturated hydraulic conductivity in till and type of method and equipment should be carefully selected. Studies comparing and evaluating different methods for use in till are few. Comparative studies should be carried out. In the unsaturated zone a variant of the inverse auger hole method using a constant head and a lined pit is recommended. In the saturated zone measurements in dug wells are considered as the most representative method. Correlative methods can only be used for very approximate predictions of the saturated hydraulic conductivity in till.

## Introduction

The saturated hydraulic conductivity ($K$) is a key parameter when considering flow through porous media and the flow parameter that does possess the largest uncertainty. Sophisticated models for treating flow through porous media are developed, but the accuracy of their prediction is no better than the accuracy or representativity of the input parameters.

There are many methods available for measuring the saturated hydraulic conductivity of sediments (Bouwer and Jackson 1974, Kessler and Oosterbaan 1974, Daniel, Anderson and Boynton 1985, Jenssen 1986a, b). However, the texture of tills excludes many of the traditional methods for direct measurement of the saturated hydraulic conductivity (Jenssen 1986a). Correlative methods are also difficult to apply mainly because of structural aspects which makes correlation of hydraulic conductivity to sediment properties and/or grain size parameters difficult (Haldorsen, Jenssen, Køhler, and Myhr, 1983, Jenssen and Køhler 1986). However, interesting development is now occurring with respect to use of correlative methods in till (Lind and Nyborg 1988).

In this paper methods are grouped and representativity and applicability are briefly evaluated.

## A Representative Sample Size

Till often possess a macropore system or fissility that may influence the hydraulic conductivity (Haldorsen *et al.* 1983, Fredericia 1987, Lind and Nyborg 1988). Fig. 1 exemplify the relation of *K* versus sample volume or characteristic length in a soil where fractures or a secondary macropore system is present. At small sample sizes the macropores may not be present in the sample and measurements yield the *K*-value of the matrix. On the contrary, if macropores are present in a very small sample a very high *K*-value may be observed. As the sample volume increases the variation in *K*-values will decrease and when the variation ceases the representative elementary volume (*REV*) (Bear 1979) is reached. Once the *REV* is reached the *K*-value will not vary with increasing size unless the sediment is heterogeneous.

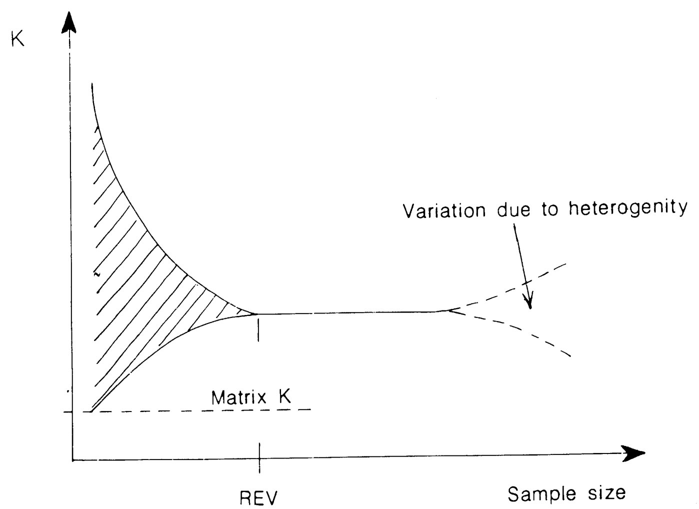


Fig. 1. Suggested relationship between sample size and the saturated hydraulic conductivity (*K*).

Bouma (1983) suggested hypothetical *REV*'s for soils.

Suggesting a representative sample size for till is still a matter of question. Bouma (1983) suggests a minimum size of $10^3$ $cm^3$ in pedal soils, but for soils with contiuous macropores or large peds the size suggested is $10^5$ $cm^3$. The work of Lind and Nyborg (1988) indicates that sample sizes around $10^3$ $cm^3$ may be used in the C-horizon of relatively homogeneous till. However, the fracture spacing and size found in some Danish clay tills indicates that large scale field tests (characteristic length of some metres, $> 10^6$ $cm^3$) may be needed in order to make representative measurements (Fredericia 1987). This size might also be appropriate for tills with a highly varying texture (melt out till or till with sorted lenses and bands). Based on own experience (Haldorsen *et al.* 1983, Jenssen 1986a, Jenssen and Køhler 1986) the author will suggest a characteristic length of 25 to 50 cm ($10^4$-$10^5$ $cm^3$) when making measurements in the B and C-horizon of massive relatively homogeneous sandy-silty till (*e.g.* lodgement till).

## Methods

There are few methods specifically developed for measuring *K* in till (Jenssen 1986a), hence the methods used may have a varying suitability and some are also susceptible to give very erronous results. In Table 2 different types of methods and some of their features are described. Each type represents the same principle of measuring. Within each type there are numerous variants that differ in suitability, equipment and water and time consumption. When a type of method is characterized as suitable it means that there are variants that are suitable. For a more detailed description and information about the different variants the reader is referred to the references given in Table 1 and the text below.

Suitability is evaluated both with regards to obtaining a representative measurement of the saturated hydraulic conductivity of an undisturbed sediment and with respect to practical applicability. The practical applicability reflects the amount of work and equipment needed to obtain a measurement. Correlative methods, where only a sediment sample and an analysis for grain size distribution are needed, or measurement in existing dug wells, is therefore given a higher ranking with respect to practical applicability than the piezometer method where pipes have to be hammered down before a measurement can be made.

The suitability ranking reflects the author's recommendations. The judgement is based on field experience from testing of different methods (Jenssen 1986a, b) and literature studies. In till with a low content of coarse particles (gravel size and larger), as found in many Danish tills, a higher suitability ranking than indicated in Table 1 might have been appropriate for some of the methods.

Table 1 – Methods for measuring the saturated hydraulic conductivity. Type, suitability in different till types, main direction for *K* measurement and approximate sample volume.

| Type of method | Zone mea-sure ment | Suitability: Representativity of field K – Clayey silty till | Suitability: Representativity of field K – Sandy gravelly till | Suitability: Practical applicability – Clayey silty till | Suitability: Practical applicability – Sandy gravelly till | Direction of *K* measurement | Sampeled volume $cm^3$ | References |
|---|---|---|---|---|---|---|---|---|
| FIELD METHODS | | | | | | | | |
| Inverse auger hole | U | ** | *** | *** | ** | H-V | $10^3$-$10^6$ | Bouwer & Jackson 1974, Kessler & Oosterbaan 1974, Reynolds & Elrick 1985, |
| Cylinder infiltrometer | U | ** | * | ** | * | V | $10^3$-$10^6$ | Bouwer & Jackson 1974, Kessler & Oosterbaan 1974, Ericsson 1978, VBB 1983 |
| Auger hole method | S | ** | ** | ** | * | H-(V) | $10^5$ | Bouwer & Jackson 1974, Kessler & Oosterbaan 1974, |
| Piezometer/ slug test | S | ** | ** | ** | * | H-(V) | $10^3$-$10^5$ | Hvorslev 1951, Cooper et al. 1967, Bouwer & Jackson 1974, Kessler & Oosterbaan 1974, Gustafsson & Nilssson 1986, Bouwer 1989 |
| Pumped dug well | A | *** | *** | ** | ** | H-V | $> 10^6$ | Engquist *et al.* 1978 |
| LABORATORY METHODS | | | | | | | | |
| Fixed wall | U,S | ** | * | ** | * | | $10^2$-$10^3$ | Jenssen 1986a |
| Flexible wall | U,S | ** | * | * | * | | $10^2$-$10^3$ | Daniel *et al.* 1985 |
| Sealed sample | U | *** | *** | * | * | | $10^3$-$10^4$ | Dahl *et al.* 1981 Lind & Nyborg 1988 |
| Packed samples | U,S | * | * | ** | ** | | $10^3$ | Fagerström & Wiesel 1972 |
| CORRELATIVE METHODS | | * | * | *** | *** | | $10^2$-$10^3$ | Langguth & Voigt 1980 |

U – unsaturated zone; S – saturated zone
*** Suitable; ** Fairly suitable; * Not really suitable
H – horizontal; V – vertical

## Field Methods

Methods are available for measurement of the saturated hydraulic conductivity both in the unsaturated (above groundwater) and groundwater or saturated zone. In the unsaturated zone methods can be divided into two groups; 1) inverse auger hole methods which includes pit infiltration 2) and cylinder infiltrometers. In the

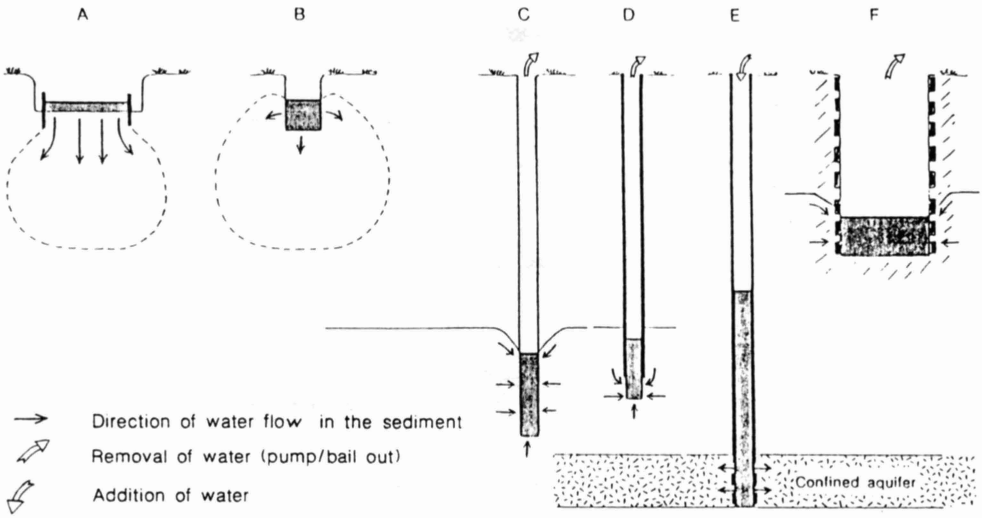


Fig. 2. Field methods for measuring saturated hydraulic conductivity. A) Cylinder infiltrometer, B) Inverse auger hole method (unsaturated zone), C) Auger hole method (groundwater zone), D) and E) Lined boreholes, F) Dug well.

saturated zone three main types are available; 1) auger hole methods, 2) methods for measuring in lined/cased boreholdes (piezometer methods) and 3) measurement in dug wells (Fig. 2).

Field methods usually measure on a larger soil volume than laboratory and correlative methods (Table 1), hence the variability should be lower than for the other methods. The main uncertainties when applying field methods are connected to the disturbance of the structure at the till/water interface and the models by which $K$ is calculated. Due to a larger sample volume, field methods are usually given a higher suitability ranking with respect to representativity than the other methods. However, the uncertainty present in the models for calculation of $K$ and their underlaying assumptions can be substantial (see text below). Knowledge of the textural and structural variation of the sediment and the hydrogeological conditions is therefore essential for selection of a proper field method and model for calculation of $K$.

*Measurements in the Unsaturated Zone* – Many variants of the inverse auger hole method are available both with respect to equipment and model for calculation of the saturated hydraulic conductivity. The simplest variant is measurement of the rate of decline in water level in an unlined hole. However, it is very important to minimize disturbance of the soil structure and preserve the borehole geometry when measuring. The borehole or pit should therefore be lined. The liner should cover both the sidewalls and the bottom. A simple porous plastic liner was recom-

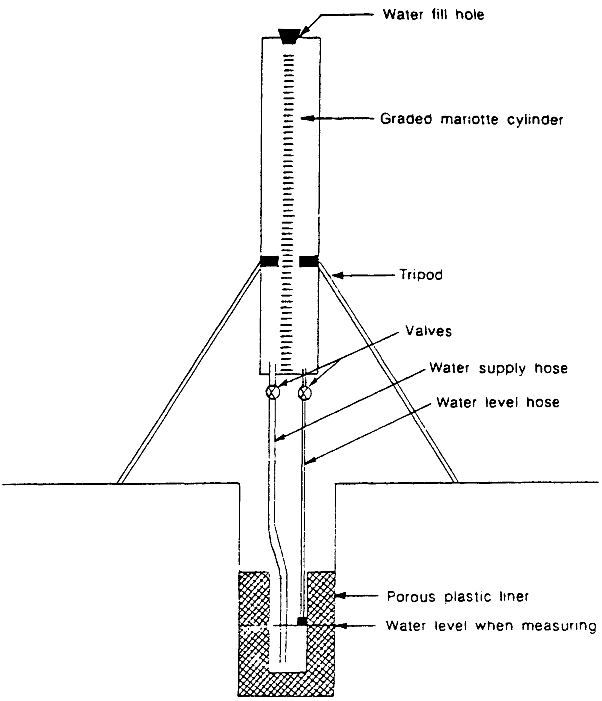


Fig. 3. A porous plastic pad and a Mariotte cylinder used in an improved edition of the inverse auger hole method (Jenssen 1986a).

mended by Jenssen (1982) and is shown in Fig. 3.

The equipment of Fig. 3 was especially developed for the use in till. Due to the high content of gravel size and larger particles, drilling a hole by hand is difficult in many tills. Equipment based on measurement in auger holes as the Guelph permeameter (Reynolds and Elrick 1985) is therefore difficult to apply in till. In Norway a square pit (25 × 25 × 30 cm) is found to be practical because it is almost impossible to dig a regular shaped pit in a till (Jenssen 1989). The error introduced by approximating this to a cylindrical pit when calculating $K$ is probably negligible.

If till the flux out of a hole above groundwater may be affected by capillarity. If capillarity is not taken into account an overestimation of the hydraulic conductivity of up to one order of magnitude might occur in silty sediments (Reynolds, Elrick and Chlotier 1985, Jenssen 1986b). Methods and theory that handle capillary effects are developed (Stephens and Neumann 1983, Philip 1985, Reynolds and Elrick 1985, Jenssen 1989), but these methods are not yet properly tested and adopted for use in till.

If a macropore system is present, the effect of capillarity is reduced and often negligible, hence, simpler models can be used for the calculation of $K$ from measurements with the different variants of the inverse auger hole method (*e.g.* Glover

1953). The calculation presented by Kessler and Oosterbaan (1974) (the Porchet method) neglects capillarity and should only be used when capillarity is insignificant and for borehole geometries where *h/a* (the ratio between the depth of water in the hole *h* and the hole radius *a* is less than 0.5 (Jenssen 1986b)).

Cylinder infiltrometers (Ericsson 1978) mainly measure the vertical hydraulic conductivity. The different variants of these methods all involve the hammering in of a steel cylinder into the sediment. In tills which normally contain gravel size or larger particles the chance of improper installation and leakage along the perimeter of the cylinder or damage to the equipment is high. Generally cylinder infiltrometers are therefore not recommended in till.

*Measurements in the Saturated Zone* – The methods for measuring in the saturated zone are either based on pumping/bailing water into or out of a hole and measuring the rate of recovery of the piezometric surface. All methods based on auger holes or flux into a small unlined cavity below a piezometer are susceptible to the uncertainty of borehole collapse or silting up of the lower part of the hole. It is therefore suggested that liners should be developed for these methods, for instance by using a porous plastic. However, the liner should be carefully selected, because the introduction of a liner also involves uncertainties with respect to correct description of the flow at the borehole perimeter.

Auger holes are often difficult to make in till and piezometers problematic to install due to the high compaction and stone content found in many tills. In Sweden dug wells are therefore used for assessing *K* in tills (Engquist, Olsson and Svensson 1978). This might be the most practical method of measuring *K* in phreatic till aquifers. The method involves a larger soil volume when measuring than the auger hole or piezometer methods (Table 1) and is therefore possibly the most representative of the field methods for making measurements in the saturated zone. There are, however, no comparisons made between this method and piezometer or auger hole methods.

A variant of the piezometer method that is much used in low permeable sediments like till is the "slug test" (Hvorslev 1951, Cooper, Bredehoeft and Papdoupolus 1967, Bouwer and Rice 1976, Bouwer 1989). A detailed description of the test and practical applicability is given in Gustafsson and Nilsson (1986).

Many models are given for the calculation of *K* from measurement of water level recovery *vs*. time in boreholes or piezometers. It is important to note that models are always based on a simplification of the actual and often complex field conditions. Different models and assumptions applied to identical conditions may therefore produce results that vary within one order of magnitude (Chirlin 1989). The model for calculation of *K* should therefore be given serious consideration and match the field conditions as closely as possible.

Pumping tests (Bear 1979) are impractical in till due to laborious and expensive well installation.

### Laboratory Methods

Laboratory methods are either based on "undisturbed" samples in fixed wall or flexible wall permeameters, encapsuled or sealed sediment samples or disturbed samples that are repacked into a cylinder for measurement.

In field measurements the flow is often multidimensional and the gradients may not always be exactly known; in laboratory measurements the flow is one dimensional and the gradients are exactly known. The main uncertainties in laboratory measurements are concerned with the representativity of the sample (size, density, structure) and possible interfacial flow along the tube/sediment interface.

The laboratory methods measure on a relatively smaller volume than the field methods (Table 1). More samples may therefore be needed than with the field methods, especially in as poorly sorted sediments as till. According to Anderson and Bouma (1973) $K$ is dependent on length of the sample in soil with macropores. They found $K$ to increase with decreasing sample length and if too short samples were used $K$ was overestimated due to "shortcircuiting" through macropores. This is probably also the case for tills.

Chan (1975) postulates that sampling with steel cylinders can alter the structure and density of the sample. This is not easy to check and will always be an uncertainty connected to the laboratory methods available today (Fredericia and Jenssen 1989). In most tills coarse particles will cause disturbance along the tube/sediment interface when a cylinder is forced into the sediment. This might cause too high a flow. A large particle might also fill most of the sample's cross sectional area, causing very low flow. The flow along the tube/sediment interface in fixed wall tubes can possibly be reduced if the tube is greased on the inside prior to sampling (Healy and Laak 1973, Jenssen 1986a). However, Daniel *et al.* (1985) conclude that flexible wall cells are better suited than fixed wall cells because boundary leakages are minimized.

In general, laboratory permeameters are hard to use in tills both due to uncertainty and because they are laborious. Measurements using fixed wall methods are less laborious than the flexible wall methods. The flexible wall method is usually very expensive due to the equipment and amount of laboratory work needed.

Sealed samples implies preparation of a sediment column in the field. Epoxy (Lind and Nyborg 1988) and wax (Dahl, Berg and Nålsund 1981) have been used for sealing. The sealed column is then brought to the laboratory where it can be mounted in a permeameter. The author assumes properly prepared sealed samples to be less disturbed than samples obtained by cylinders, however, the methods have not been directly compared. Preparation and sealing of samples is laborious.

In repacked samples (Fagerstrøm and Wiesel 1972) the natural structure of the sediment is destroyed. This normally gives $K$-values one to two orders of magnitude lower than direct measurements made on the same sediment (Haldorsen *et al.* 1983). Measurements on repacked samples are therefore only recommended in connection with certain geotechnical work such as dam building (Bjerrum, Torblaa and Kjærnsli 1964).

### Correlative Methods

Correlative methods are mostly based on correlation to textural properties. In till the structure may greatly influence $K$ (Haldorsen *et al.* 1983, Fredericia 1987, Lind and Nyborg 1988), hence, correlative methods can be expected to be less accurate than direct methods, because the influence of macropores is excluded. According to Kessler and Oosterbaan (1974) an estimate to the order of magnetude is what can be expected from correlative methods. Experience of the author indicates a confidence interval of two orders of magnitude when prediction of $K$ is made from grain size parameters in tills. Better accuracy can possibly be obtained by the method of Gustafson (1983) in some sandy or gravelly tills, because this method is calibrated to coarse grained not always well sorted sediments. In general, however, correlative methods should not be used in tills unless very approximate predictions are needed.

## Conclusions

Measurement of hydraulic conductivity is scale dependent and in till a sample volume of $10^4$-$10^5$ $cm^3$ or with a characteristic length of 25-50 cm is suggested. For very heterogeneous sediments and sediments with large fracture spacing larger samples may be needed.

The main uncertainty regarding field methods is connected to the model used to calculate the saturated hydraulic conductivity. The main uncertainties in laboratory measurements are concerned with the representativity of the sample (size, density structure) and possible interfacial flow along the tube/sediment interface. However, laboratory methods are much used and the uncertainty imposed by sampling with steel tubes should be quantified.

Field methods are considered to give better estimates of the hydraulic conductivity in till than laboratory or correlative methods because the disturbance of the sediment is less than for laboratory methods and because field methods measure on a larger sediment volume.

There are no ideal methods for measuring the saturated hydraulic conductivity in till and type of method and equipment should be carefully selected. Studies comparing and evaluating different methods for use in till are few. Comparative studies should be carried out in order to facilitate selection of appropriate methods and to give a basis for the optimizing of methods.

In the unsaturated zone inverse auger hole methods are recommended over cylinder infiltrometers. The holes should be lined and measurements made with a constant head.

A greater number of methods are suitable in clayey/silty till than in sandy/gravelly till due to a higher stone content in the latter.

Correlative methods can only be used for very approximate predictions of the saturated hydraulic conductivity in till.

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