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Procedures for Field Sampling and
Laboratory Measurement of Saturated
and Unsaturated Hydraulic
Conductivity on Large Soil Cores

N.J. McKenzie and D.W. Jacquier



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PROCEDURES FOR FIELD SAMPLING AND LABORATORY MEASUREMENT OF SATURATED AND UNSATURATED HYDRAULIC CONDUCTIVITY ON LARGE SOIL CORES

N. J. McKenzie¹ and D. W. Jacquier¹

Abstract

Methods for measuring saturated and unsaturated hydraulic conductivity on large intact soil cores are presented. Soil horizons are wet in the field using a trickle irrigation system before excavation and sampling of the large soil cores. A convenient and accurate method for measuring saturated hydraulic conductivity suited to the large cores is then described. The same cores are used for the measurement of unsaturated hydraulic conductivity at potentials close to zero. The system uses a drip infiltrometer to supply water at a constant flux. Unit gradient is achieved by adjusting the potential at the lower boundary with an adjustable outflow tube. Matric potential in the core is monitored using tensiometers and water content is measured gravimetrically. Detailed descriptions of the apparatus and calculations are presented. Alternative methods for supplying water using a constant potential device are also considered.

1. INTRODUCTION

1.1 Purpose

The relationships between hydraulic conductivity (K), water content (θ) and matric potential (ψ) are required for simulating the movement of water and solutes in soils. Measurement of $K(\theta)$ and $\psi(\theta)$ is time consuming and technically demanding. Furthermore, there is no standard method for measuring $K(\theta)$.

Many simpler procedures or surrogates have been proposed for generating estimates of $K(\theta)$ and $\psi(\theta)$ and van Genuchten and Leij (1992) provide a recent review. Land resource survey agencies in particular have been interested in developing predictive relationships between the morphology of soil horizons and the relevant hydraulic properties (e.g. McKeague *et al.* 1984; Bouma 1989).

In a previous study we investigated the predictive capacity of several published morphological systems for predicting hydraulic properties and concluded that, with some modifications, they may have utility (McKenzie *et al.* 1991). In the light of these findings, we devised a system for characterizing soil morphology that should provide coarse level predictions of $K(\theta)$ and $\psi(\theta)$ for individual soil horizons. The system was calibrated by making detailed measurements of $K(\theta)$ and $\psi(\theta)$ on approximately 100 soil horizons from south eastern Australia.

In the earlier study we also recognized that errors associated with the measurement of hydraulic conductivity may contribute substantially to the apparently poor predictive capacity of soil morphology. As a consequence we developed a method for measuring $K(\theta)$ and $K(\psi)$ on large cores at potentials close to zero. This report describes the method.

1.2 Selection of Method

Dirksen (1991) provides a useful review of methods for measuring hydraulic conductivity and his criteria for selecting methods are used here. We required a method for measuring $K(\theta)$

¹ CSIRO Division of Soils, P.O. Box 639, Canberra City, A.C.T.

that was accurate and precise. Our previous experience with the disc permeameter and well permeameter, both field based transient methods, indicated that substantial errors were sometimes possible. In particular, the disc permeameter is prone to error when:

- any degree of water repellence is present;
- the initial soil water content profile is non-uniform;
- preferential flow occurs so violating the assumptions relating to an even wetting front (this may occur during unsaturated measurements at potentials close to zero);
- swelling of the initially dry soil during measurement alters its effective porosity; and
- less permeable layers below the disc interfere before steady state conditions have been obtained.

The well permeameter is prone to error when:

- smearing of the auger hole occurs;
- the soil is augered in a dry condition to avoid smearing but slaking occurs when water is poured into the hole;
- estimates of soil texture/structure parameters used in the analytical solution (Reynolds 1993) are inaccurate; and
- less permeable layers below the auger hole interfere before steady state conditions have been obtained.

Several steady state laboratory methods and two field procedures were possible. Of the field methods, the instantaneous profile (Hillel 1980) required extended periods at a site and was not feasible given the broad geographic range of our study. The sprinkling infiltrometer (Ross and Bridge 1985) has the advantage of allowing measurement on a large soil volume *in situ*. It provides reliable estimates of K_s but not of unsaturated K . The sprinkling infiltrometer is more suited to measurements at or near the soil surface.

We required sample volumes to be as large as possible and preferably larger than the Representative Elementary Volume (Bear 1972; Wagenet 1985; Bouma 1985; Lauren *et al.* 1988). Variants of the isolated soil column method (Bouma *et al.* 1971; Dirksen 1991) had several attractive aspects. The common feature of these variants is the isolation of a large soil column in the field by careful excavation. A plaster (Bouma and Dekker 1981) or fibreglass cast is placed around the column and measurements can be made *in situ* or the column is detached and returned to the laboratory. Tensiometers are normally installed to measure the hydraulic gradient. Water content can be measured either gravimetrically or via Time Domain Reflectometry (Topp *et al.* 1980; Topp 1993).

The supply of water has been controlled most commonly with successive cement and sand crusts of decreasing resistance. There are several experimental problems in the use of crusts and Dirksen (1991) recommends that they be replaced by either a drip infiltrometer or spray device. These devices supply water with a controlled flux rather than potential. Dirksen (1991) provides some information on a system under development where water is supplied using a pulsating pump to a set of hypodermic needles.

We have implemented the suggestions made by Dirksen (1991) for measuring unsaturated hydraulic conductivity and in the following sections provide detailed information on the necessary equipment and its use.

Saturated hydraulic conductivity was measured on the large cores used for the unsaturated measurements. We have modified the system described by Forrest *et al.* (1985) and this is described below. We begin with guidelines on the collection of large cores from the field.

2. FIELD OPERATIONS

2.1 Selection of soil layers

We have used cores with a length of 200 mm and an external diameter of 250 mm. The large

size has the advantage of providing a representative sample of soil but the disadvantage of requiring relatively thick and uniform soil layers. Soil layers are selected after an inspection of soil profile morphology revealed in a freshly dug soil pit.

In most circumstances, three soil layers are selected for physical characterization. Emphasis is placed on layers that exert most control on the water regime and this will normally include: the A1 horizon; top of the B horizon, particularly if it is constricting to water and air movement; and the base of the profile. Once the layers have been selected, 1.5 m wide ledges are excavated back from the side of the pit (Figure 1). The ledge should be approximately 1.5 m long if triplicate cores are to be collected.

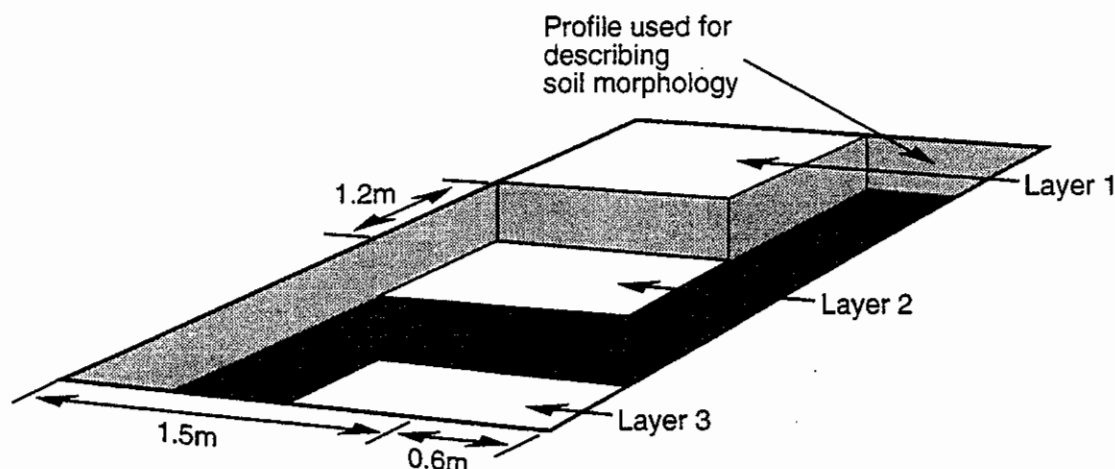


Figure 1. Field arrangement for describing a soil profile and collecting cores at three levels.

We have used a 1.5 tonne mini-excavator for field operations. The mini-excavator is towed behind a standard four wheel drive vehicle. This arrangement is advantageous because:

- directing contractors to cut back ledges corresponding to pedological horizons can be difficult;
- the excavator is used at various stages during field operations (e.g. digging the pit; removing excess soil from the pit during sampling; and pushing in sleeves) and hiring a backhoe for the duration of sampling would result in excessive costs because of the unavoidable idle time;
- the mini-excavator is very manoeuvrable compared to a standard backhoe and has sufficient power to dig large pits (deeper than 2m) in most conditions. A hand held jack hammer can be connected to the excavator hydraulics and used to break tough layers.

The final 0.10 m above the layer to be sampled is picked back manually to avoid accidental disturbance with the teeth of the backhoe. In most parts of Australia, it is uncommon for profiles to be at water contents suitable for obtaining undisturbed cores and the ledges will have to be wetted prior to coring.

2.2 Wetting

We have found it most efficient to use a simple trickle irrigation system for wetting ledges. It is much faster to wet individual layers once they have been excavated rather than to attempt to wet the whole profile. The dimensions and specifications of the trickle irrigation system are given in Figure 2. Seventy five litres of water are sufficient to wet a volume 1.0 m x 1.5 m x 0.20 m in most types of soil. Less water can be applied if the layer is already moist. The trickle irrigation system is fed by gravity from three 100 L tanks that remain in the back of the field

vehicle or on the pile of excavated soil. A hydraulic head of 1.0 m is sufficient for the system to run when adjustable drippers are used.

Some care is needed in obtaining reliable water in drier regions. CaCl_2 is added to the water supply make a 0.01 M solution. This suppresses dispersion but can be omitted when dealing with stable soils in areas having high rainfall.

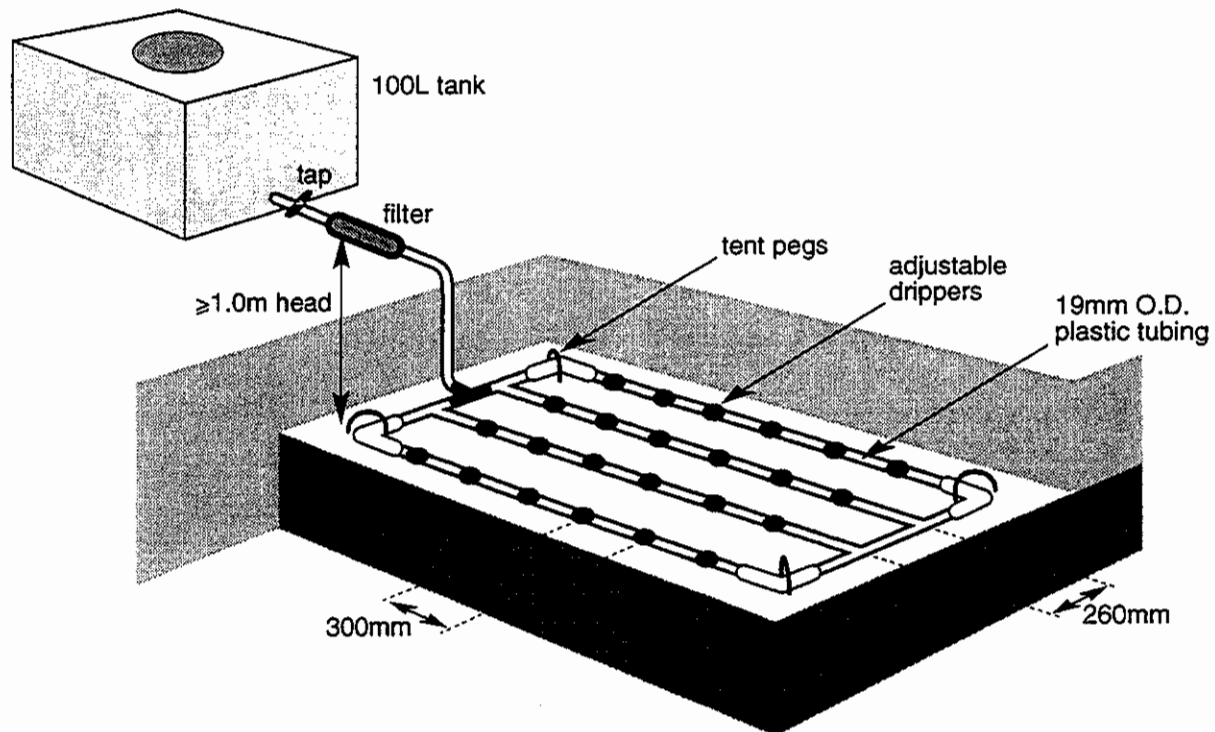


Figure 2. Trickle irrigation system for wetting soil layers prior to sampling

2.3 Core Sleeve and Coring Guide Design

Large sleeves with a reinforced cutting edge were fabricated from 225 mm diameter standard PVC sewer pipe. The inner reinforcing ring, shown in Figure 3, is made from a short length of sewer pipe with a small segment removed to allow it to fit inside the main sleeve. It is essential for the inner ring to have excellent contact with the main sleeve when it is glued with PVC cement. The bevelled edge is cut with a lathe. The inner ring not only reinforces the sleeve but it creates an air filled annulus that allows a sealant to be used to ensure that edge flow is minimized (Cameron *et al.* 1990 and Section 2.4). The resulting soil core has a diameter of 223 mm.

A large coring guide was built with an internal diameter of 254 mm (Figure 4). The main pipe of the coring guide was rolled from 8 mm mild steel and then machined to ensure the internal shape was circular. The coring guide has three large legs with 18 mm holes at each end. The holes are for steel spikes with a diameter of 16 mm and length of 220 mm. These are hammered into the ground to provide a secure anchorage. The first and second legs of the coring guide have an angle between them of 115° and the second and third leg has an angle of 130° . This increases the number of configurations that can be achieved in the field to avoid disturbing adjacent cores or excavated pedestals.

2.4 Coring, Excavation and Sealing

The thick wall of the sleeve and large angle for the cutting edge make it impossible to push the sleeve straight into the soil. Instead, a channel is excavated around the core to a depth slightly in excess of its length. Various implements can be used for excavating but we have found that an asparagus knife and abundant physical energy are best. The coring guide is

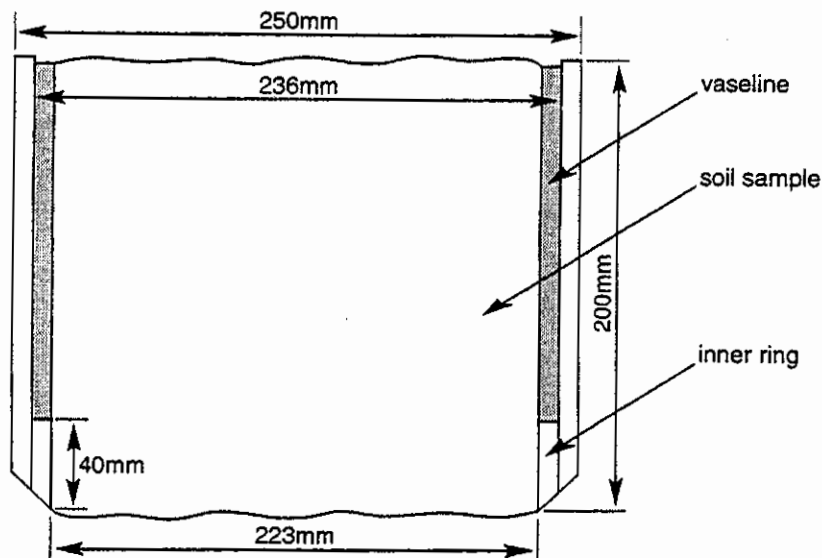


Figure 3. Dimensions of the soil core and sleeve

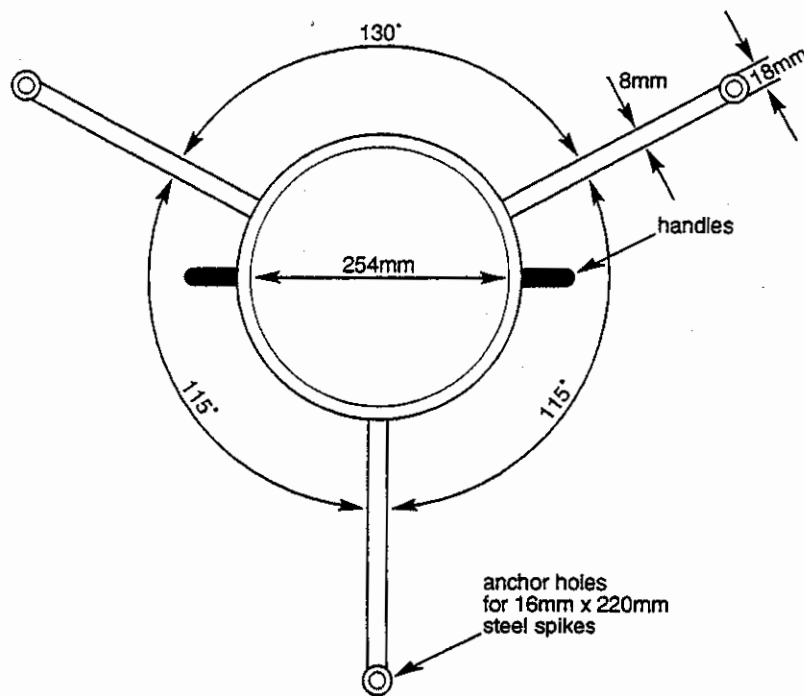


Figure 4. Design of the coring guide for collecting large cores.

secured once the channel has been dug and the soil pedestal exposed. The arrangement of the coring guide, sleeve and excavated channel is shown in Figure 5.

A sleeve is placed in the coring guide followed by a spacing tube with a length of 400 mm. An external scale in millimetres on the spacing tube allows for precise depth control during sampling. A 10 mm thick steel plate with retaining lugs is placed on top of the spacing tube. A hydraulic jack (1.85 tonnes load minimum) is placed on the plate. It is then jacked against the bucket of the backhoe to force the sleeve down. If the operator is skilled and the hydraulics of the backhoe have fine control, then the backhoe can be used to push the sleeve in directly. Only the thin inner ring of the sleeve comes into contact with the soil to be sampled and this minimizes the potential for lateral forces to crack the sampled material.

As noted earlier, the inner cutting ring of the large sleeve produces a small annular gap and vaseline slightly above melting point (approximately 50°C) is injected into it using a grease gun

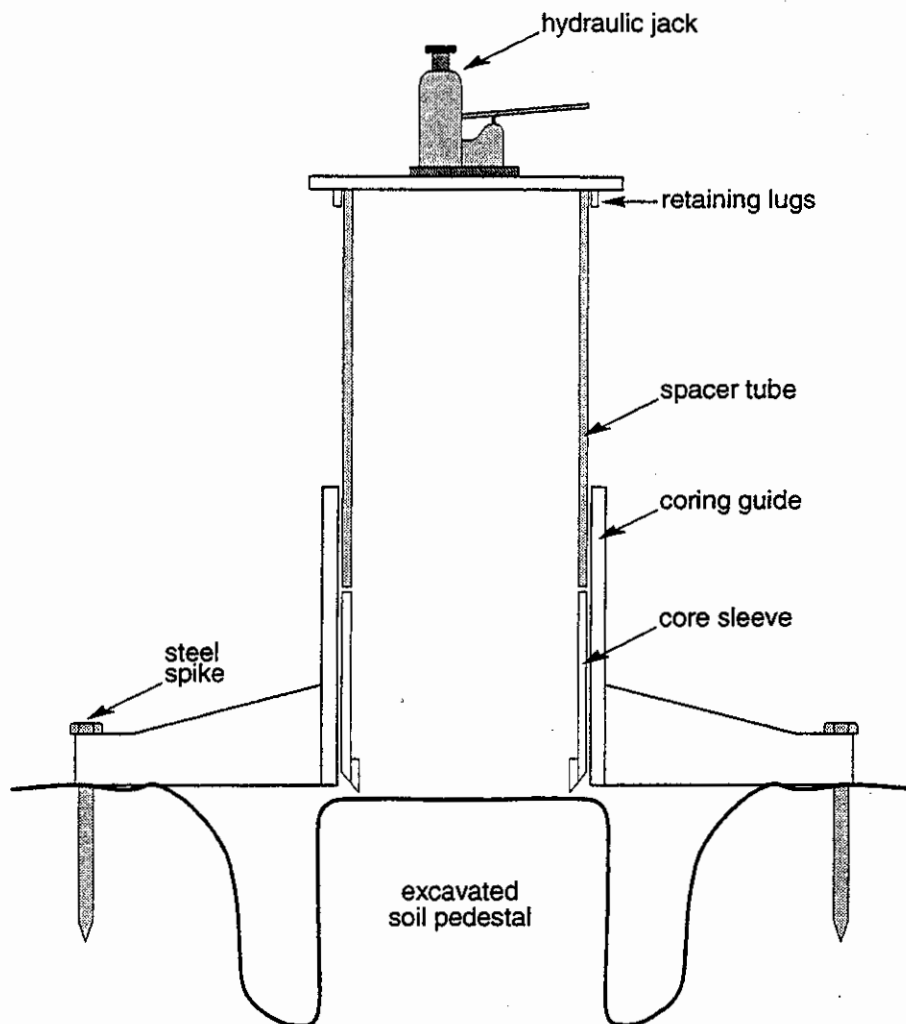


Figure 5. Excavation of a pedestal and equipment for obtaining a large core.

as recommended by Cameron *et al.* (1990). Each core requires about 600g of Vaseline. The smearing of the side of the soil sample by the sleeve prevents Vaseline from entering the soil. The soil sample is moist and has sufficient thermal mass to ensure the Vaseline sets on contact. However, it is essential for the soil to be close to field capacity otherwise Vaseline may infiltrate. It is also important to avoid overheating the Vaseline. We have observed flow beyond the annular gap on only a few occasions in soils with abundant and large (>5 mm diameter) horizontally inclined macropores.

The Vaseline is allowed to set and the intact core is removed by chiselling underneath and levering the sample out of the ground. The bottom of the soil sample is then trimmed. Cores are sealed in large plastic bags with wooden boards at each end. These are secured with packing tape. Large foam mats are placed under cores to ensure minimal disruption during transport to the laboratory. Cores may have to be left overnight before removal during very hot weather to ensure complete setting of the Vaseline. Alternative compounds noted below can be used to avoid this problem. Apart from preventing edge-flow, the Vaseline provides a secure support for the soil sample.

A potential problem with Vaseline is the risk that it may change the surface contact angle of the soil and so alter hydraulic properties. An alternative to Vaseline that may reduce this potential problem is rubberized asphalt (Kluitenberg *et al.* 1991).

The large cores are transported to the laboratory as soon as possible after sampling. They are then stored at 4°C to suppress biological activity. Suppression of earthworm activity during

transport is difficult. Methods using electrical currents or addition of organic compounds are either hazardous or only partially effective or both.

2.5 Collecting Cores in Difficult Soils

The procedure for collecting large cores can be modified for difficult soils where a sleeve cannot be pushed in because of gravels, tree roots or brittle pans. A soil pedestal is isolated by carving or chipping a volume of an appropriate shape (usually a cylinder). Protruding rocks and roots are trimmed. An encapsulation tube made from PVC is placed over the free standing pedestal. The air gap is then filled using an appropriate compound. Lewis *et al.* (1990) recommend polyurethane foam although they did not test whether the resultant seal will prevent edge-flow if measurements of saturated hydraulic conductivity are attempted. Buchter *et al.* (1984) used concrete as the compound but the resulting cores can be very heavy. Vaseline or paraffin could be used as well. The encapsulation tube and the compound used for filling can be replaced by fibreglass or gypsum (e.g. Bouma and Dekker 1981) but this makes handling and transport more difficult.

3. SATURATED HYDRAULIC CONDUCTIVITY

3.1 Principle

The apparatus for measuring saturated hydraulic conductivity is shown in Figure 6. It is a large scale version of that described by Forrest *et al.* (1985).

A thin collar is attached to the base of the core and it is inverted and gently lowered into the large plastic container containing 0.01 M CaCl_2 . The water level in the large plastic container is kept constant using a standard floating valve.

The core is allowed to equilibrate overnight with the water level approximately 20 mm above the base of the core. Longer times for equilibration are only required for heavy dispersive

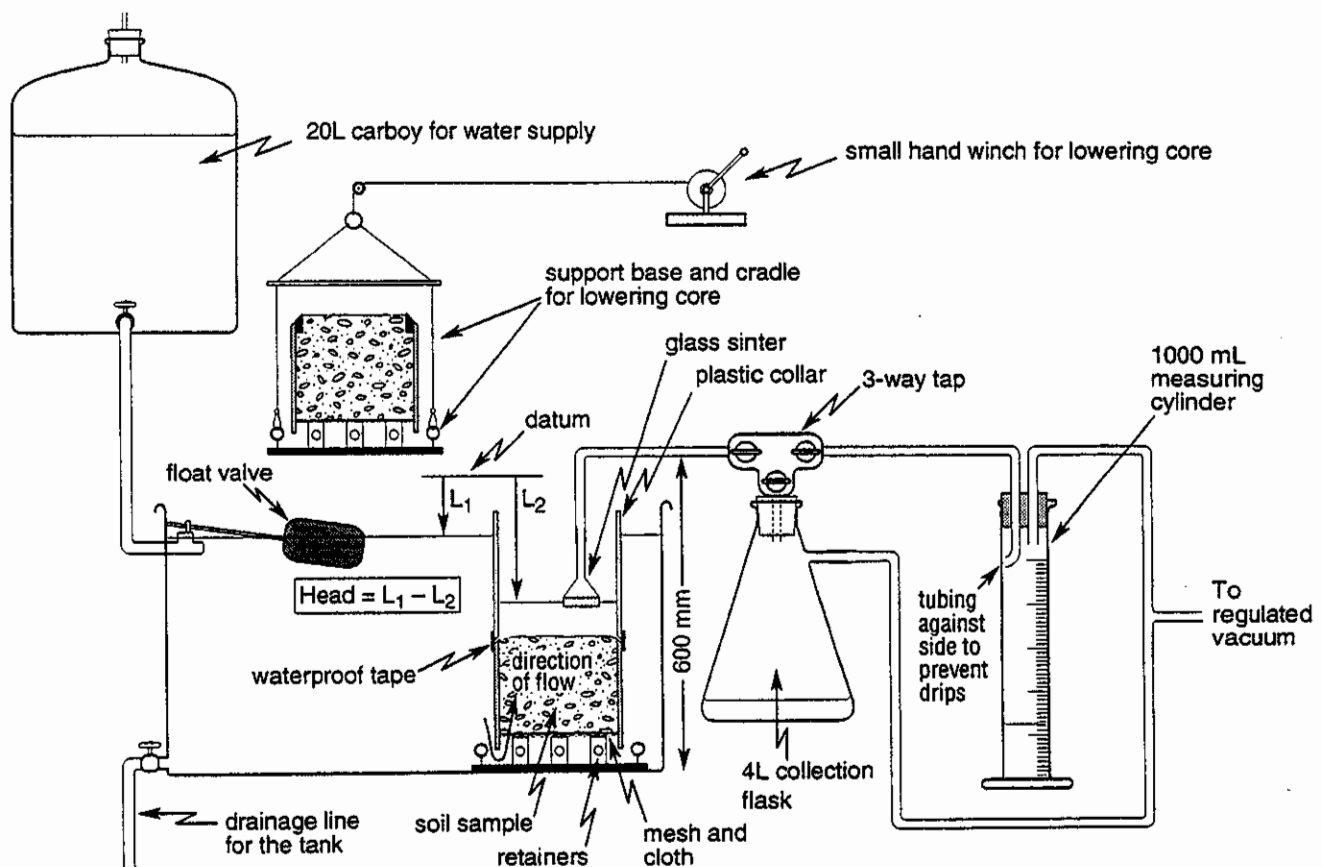


Figure 6. Apparatus for measuring saturated hydraulic conductivity on large cores.

clays. The relatively short equilibration time is possible because the soil has been wet with the trickle irrigation system in the field.

After equilibration, water will have flowed through the core and the height of water in the collar should be the same as that in the large plastic container. Water is then removed from the collar using a vacuum leading to a collection flask. Measurements are made when the flow rate has stabilized and a single run can usually be completed in less than an hour. The apparatus can be used as a falling head device for very slow soils by measuring the rate of rise of water within the collar.

3.2 Apparatus

(i) Core preparation and support

The ends of the field moist cores are carefully picked back using a small chisel or scapel. It is essential for the surface to be level and freshly broken rather than smeared. A vacuum cleaner is used for removing excess soil. Vaseline should be removed from around the soil core with a knife in a careful manner. Vaseline should not come into contact with the soil surface.

A thin (100 mm) plastic collar is taped to the bottom of the core - the collar has an internal bevel to ensure good contact with the core. Fine nylon mesh is placed over the top surface of the core and a circle of 2 mm woven stainless steel mesh is used as a retainer. Small lengths of PVC pipe with holes drilled in their walls are used as spacers and water flows freely upwards through the base of the inverted core. Water flows in the same direction as during drainage in the field.

The core is lowered into the constant level water bath using a small winch and supporting harness (Figure 6). Small clips at the top of the harness restrain the core and prevent it from sliding. The core is lowered into the bath in a series of steps over several hours or longer and left to equilibrate (refer to section 3.3). When the core has equilibrated the level of water within the retaining ring will equal the external level of the constant level water bath.

If cores were initially dry then a procedure for wetting under tension would be necessary.

(ii) Water supply

The 0.01 M CaCl_2 solution is made using distilled rather than deaired water. If deaired water is used, the entrapped air in the core will be dissolved more quickly than with distilled water during measurement of the "saturated" hydraulic conductivity. However, special apparatus is necessary to provide large quantities of deaired water. Entrapped air is dissolved by water passing through the core and will lead to a gradual increase in water content during the measurement period along with an increase in flow. It is therefore essential to take measurements at a consistent time after flow through the apparatus has begun.

A 20 L Carboy is used as a supply tank. It is placed at least 0.75 m above the surface of the constant level water bath to ensure sufficient hydraulic head. It is filled with distilled water prior to a sequence of measurements. Calcium chloride is added to water in the filled Carboy to make a 0.01 M solution. A standard float valve controls the level in the water bath. Water bath levels should not vary by more than 1 mm during a run.

Water in the constant level bath should be replaced regularly to prevent the accumulation of fine colloidal material and an outlet tap and drainage system is required.

(iii) Offtake and measurement

Water is then removed from the collar at the top of the inverted core using a glass sinter attached by plastic tubing which leads to a four litre collection flask and one litre measuring cylinder (Figure 6). The sinter, tubing, flask and measuring cylinder are connected to a vacuum line. Excessive air must not enter via the glass sinter during a measurement run. Continual and steady removal of water from the core cannot be achieved if this occurs and accuracy and

precision are greatly reduced. Three factors control successful removal of water from the inverted core.

- *Regulation of vacuum:* The applied vacuum must not exceed the air entry potential of the glass sinter but it must be sufficient to lift water to the maximum height of the tubing. A standard bubbling tower can be used as a regulator on the vacuum line. With the arrangement shown in Figure 6, a potential of -500 mm is sufficient.
- *Porosity and size of glass sinter:* The glass sinter must have enough porosity and area to cope with the maximum expected flow during measurement. Note that the maximum flow is a function of the K_s of the soil, core diameter and the applied head. The latter is controlled by the level of the sinter relative to the external level in the water bath. For the geometry of the system shown in Figure 6, a 50 mm diameter sinter with a 10 mm projection fused to a glass funnel is adequate for most soils; arrangements for very slow and very fast soils are described in sections (v) and (vi) below. The grade of the sinter is American coarse which is approximately equivalent to European Class 1.
- *Relative heights of the water bath, tubing, flask and cylinder:* It is best to minimize the height to which water must flow in the offtake system. Otherwise the potential of the vacuum has to be increased and a finer grade of sinter used. The finer grade sinters clog more easily and have much lower hydraulic conductivities. It is best for the flow line from the tap above the flask to be above the line leading to the measuring cylinder so that extra suction is not required to draw water into the measuring cylinder when the tap is turned to start a measurement run.

The glass sinter can be easily clogged by fine clay and organic material and the following maintenance is essential.

- The permeability of a new sinter should be checked by placing it in the constant level water bath and measuring the flow with the strength of vacuum used during normal operations. The permeability should be checked regularly and it should be replaced if its permeability deteriorates to the point where a constant water level cannot be maintained during operation.
- The sinter should be backflushed with warm water at the end of each day.
- The sinter should be cleaned every month or so by placing it in concentrated hydrochloric acid overnight. This should be done in a fume hood and extreme care exercised when dealing with the acid. Normal laboratory safety procedures must be followed. Less vigorous treatments, including immersion in H_2O_2 , boiling, and the use of organic solvents, do not satisfactorily clean the sinter presumably because they fail to dissolve clays.
- The water surface above the core should be cleaned before removing water with the sinter. When the core is initially immersed, some fine soil material floats to the surface within the collar and forms a gel-like film (Grossman and Lynn 1967). This can be removed by placing a tissue across the water surface. The wet tissue is then removed taking the residue with it.

(iv) Hydraulic head

The hydraulic head is determined by measuring the difference in height between the constant level of the water bath and level of water inside the core (Figure 6). This can be done by measuring the distance between a rigid datum and the two water levels using a depth gauge with graduations of 0.5 mm or finer. A metal bar placed across the top of the water bath acts as a suitable datum. Water levels should not change by more than 1.0 mm during a measurement run. A bright light shone onto the surface of the water in the tank and within the collar increases the accuracy of measurement because the precise point can be determined at which the depth gauge touches the water surface. Alternative methods of measurement using electronic sensors can also be devised.

(v) Modifications for very permeable soils ($K_s > 1000 \text{ mm h}^{-1}$)

It is more convenient with very permeable soils ($K_s > 1000 \text{ mm h}^{-1}$) to replace the sinter with another device for removing water from within the collar. At such high flows the sinter can be limiting the rate and a constant water level within the collar cannot be obtained. The simplest device is a J-shaped piece of glass tubing connected to the vacuum line.

(vi) Modifications for very impermeable soils ($K_s < 1 \text{ mm h}^{-1}$)

Very impermeable soils ($K_s < 1 \text{ mm h}^{-1}$) may take many hours to obtain a reading and it is more efficient and accurate to use the apparatus as a falling head permeameter. After the core has been saturated, the water level within the collar is lowered to within a few millimetres of the soil surface and the vertical distance to the datum is measured. The core is left for a day or more depending on its permeability and a second or series of readings of the water level is made.

3.3 Measurement and Calculation**(i) Standard method**

The sinter is lowered into the core collar at the beginning of a measurement run to the desired level. Water above this level can be quickly and conveniently removed using a syphon. The water is collected in the large flask while the water removal system is checked and a constant head obtained. The head is then recorded, the tap to the measuring cylinder is opened and that to the flask closed. The time for a given volume to be collected in the measuring cylinder is then recorded. The hydraulic head is checked midway and at the end of the run to ensure that steady state conditions have prevailed. Several measurement runs should be performed and an average calculated.

Assuming Darcy's Law applies, calculation of K_s is as follows

$$\frac{Q}{A} = K_s \left[\frac{\Delta\psi}{\Delta z} \right]$$

where $\frac{Q}{A}$ is the flux density with Q being the volume flowing through the core in time t (M^3T^{-1}) and A the core area. The system is saturated and as a consequence $\Delta\psi$ is the head difference across the core and Δz is the length of sample. The head difference is the distance ($L_2 - L_1$) between the water level in the large plastic container and the water level within the core collar. K_s is calculated as:

$$K_s = \frac{Q \cdot \Delta z}{A(L_2 - L_1)}$$

At the end of a set of measurements, the core is slowly winched out of the constant level water bath over several hours. It is then allowed to drain before removal from the apparatus. The ends of the core are picked back again before transfer to the equipment for measuring unsaturated hydraulic conductivity.

(ii) Very Permeable Soils ($K_s > 1000 \text{ mm h}^{-1}$)

The calculation of K_s for very permeable soils, where readings have been made with a J-tube or similar device, is the same as for the standard method.

(iii) Very impermeable soils ($K_s < 1 \text{ mm h}^{-1}$)

The K_s is calculated using

$$K_s = \left[\frac{d_c}{d_s} \right]^2 \frac{\Delta z}{t} \ln \left[\frac{h_1}{h_2} \right]$$

where d_c is the inside diameter of the collar, d_s is the diameter of the soil within the core, Δz is

the length of the soil sample, h_1 is the initial head and h_2 is the head after time t (Klute and Dirksen 1986). Successive measurement of n levels for h_2 during a run allows for the determination of $n-1$ measurements of K_s and a more representative mean value can then be obtained.

3.4 Repeatability of Core Measurements

The role of entrapped air and its gradual dissolution has already been mentioned as a factor that can lead to an increase in hydraulic conductivity over time. A decrease in hydraulic conductivity is often observed in unstable or swelling soils when measurements are repeated over several days.

Unstable soils can erode internally during measurement if a large head is applied. It is therefore preferable to use the smallest convenient head to minimize such effects. These soils are also prone to sealing at the base of the core at the contact with the support mesh (Figure 6). This can only be minimized by treating the cores with great care. If a substantial decline in hydraulic conductivity occurs during a set of measurements then the core should be carefully inspected. If structural collapse has occurred then only the initial measurement should be used. The ionic concentration of the CaCl_2 solution should also be checked with an electrical conductivity meter. A solution of 0.01 M CaCl_2 at 21°C has an electrical conductivity of 2.1 dSm^{-1} .

If cores have been collected using the trickle system described in Section 2.2 and several or more weeks pass between sampling and measurement, then most soil swelling should have occurred and detection of a decrease in hydraulic conductivity during measurement is unlikely. We have avoided strongly swelling soil horizons (i.e. Coefficient of Linear Extensibilities greater than around 12%) because of difficulties in applying appropriate overburden potentials, the very slow hydraulic conductivities and the often long periods required for equilibration.

4. UNSATURATED HYDRAULIC CONDUCTIVITY

4.1 Principle

The apparatus for unsaturated hydraulic conductivity is illustrated in Figure 7. The large core is placed on a sand bath and sealed around its base. Water is initially supplied to the core via the outflow tube which is raised above the core surface until the core is saturated and ponding has occurred. Wetting from below allows air to escape through the top of the soil sample. The outflow is lowered prior to measurement so that drainage of the core commences.

Measurements are made by controlling the flux at the upper boundary and potential at the lower boundary so that unit hydraulic gradient is obtained (i.e. the matric potential is the same throughout the core). Matric potential in the upper and lower portion of the core is monitored with tensiometers and when unit hydraulic gradient has been achieved, the flux is equivalent to the unsaturated hydraulic conductivity at the measured matric potential. Water content is also measured at this equilibrium so that points can be plotted on both the $K(q)$ and $K(y)$ curves. A series of measurements is made at successively larger negative potentials.

4.2 Water Supply and Infiltrometer

A peristaltic pump is used to supply 0.01 M CaCl_2 to a small drip infiltrometer placed above the core. Each component of this system will be considered separately.

(i) Water supply to the peristaltic pump

The flow rate of peristaltic pumps can be influenced by the supply pressure. It is necessary to have a constant level supply reservoir and this requires a more complicated system than for the saturated hydraulic conductivity apparatus where a falling level reservoir could be used. The complication arises because the concentration of CaCl_2 must not change.

A large 50 L reservoir with a small garden fountain pump is used to supply water to a

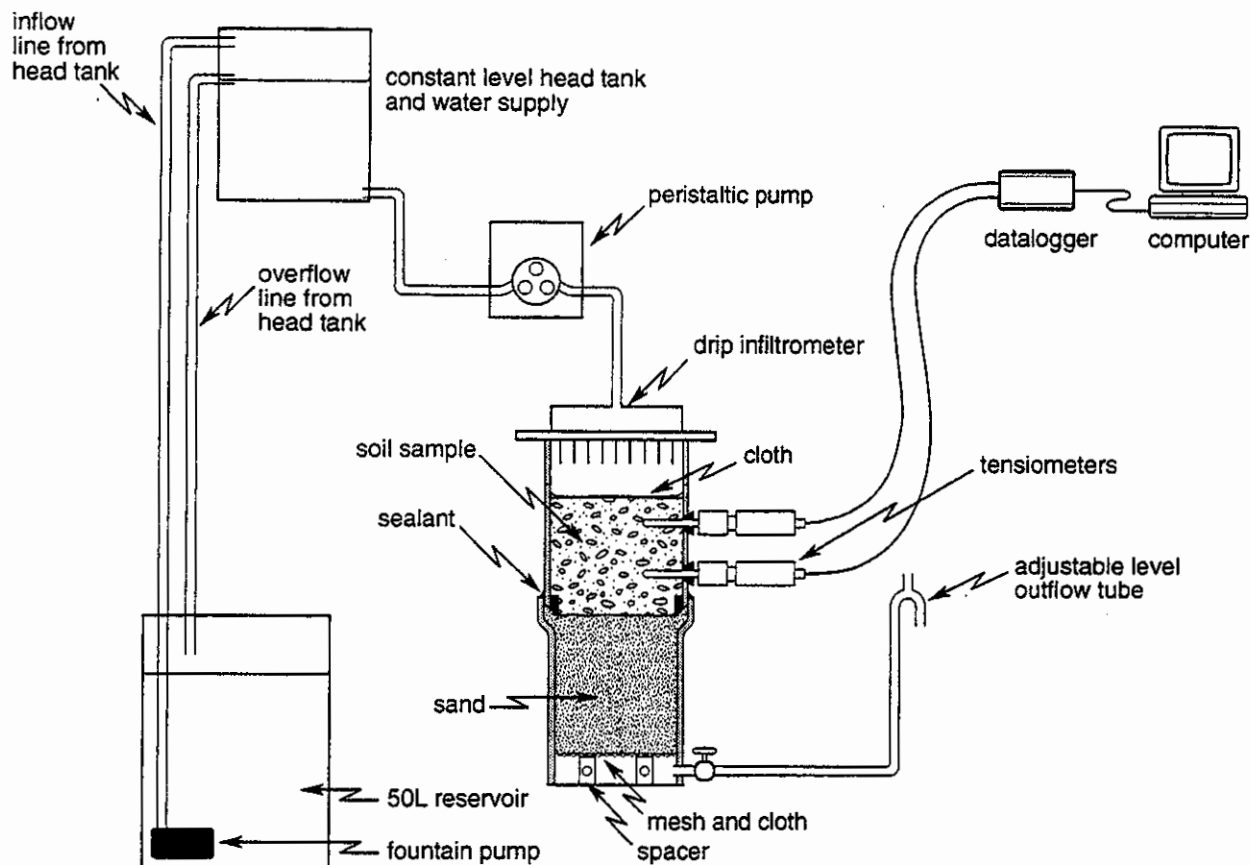


Figure 7. Apparatus for measuring unsaturated hydraulic conductivity on large cores with a constant flux water supply

smaller head tank. The pump operates continuously and overflow from the head tank drains back to the large reservoir. This arrangement precludes the use of deaired water because aeration occurs as the water drains from the head tank.

CaCl_2 is mixed with distilled water in the large reservoir prior to starting the system.

(ii) Peristaltic pump

A peristaltic pump with a flow range of between 0.5 mL min^{-1} and 380 mL min^{-1} is required for the core sizes used here (larger cores would require a greater range). We have used a Masterflex Digi-staltic Pump with two Easyload Pump Heads. It is an advantage to have a pump that can be easily calibrated. Silicon tubing of different diameters (Size 14, 18 and 25 Masterflex tubing) is used to achieve a wide range of flows. Two tubes can be run to one infiltrrometer to achieve very high flow rates. The arrangement shown in Figure 7 has a flow range of between approximately 1 mL min^{-1} to 760 mL min^{-1} and for the core sizes used corresponds to a range of fluxes from 1.5 mm h^{-1} to 1170 mm h^{-1} .

Slower rates can be obtained by incorporating a pulsing system where the pump switches on for short periods. We were not concerned with such measurements. It would be necessary to minimize evaporation at very slow rates.

(iii) Drip infiltrrometer

The drip infiltrrometer unit (Figures 7 and 8) is constructed from 10 mm clear Acrylic sheet and stainless steel. The top can be loosened or removed to release entrapped air. The replaceable hypodermic needles are on a triangular grid and placed 20 mm apart. Two infiltrmeters are used with different sized needles. Very fine needles (Size 30) are used for slow flows ($< 20 \text{ mL min}^{-1}$) and coarser needles (Size 26) for faster rates ($> 20 \text{ mL min}^{-1}$). The range of

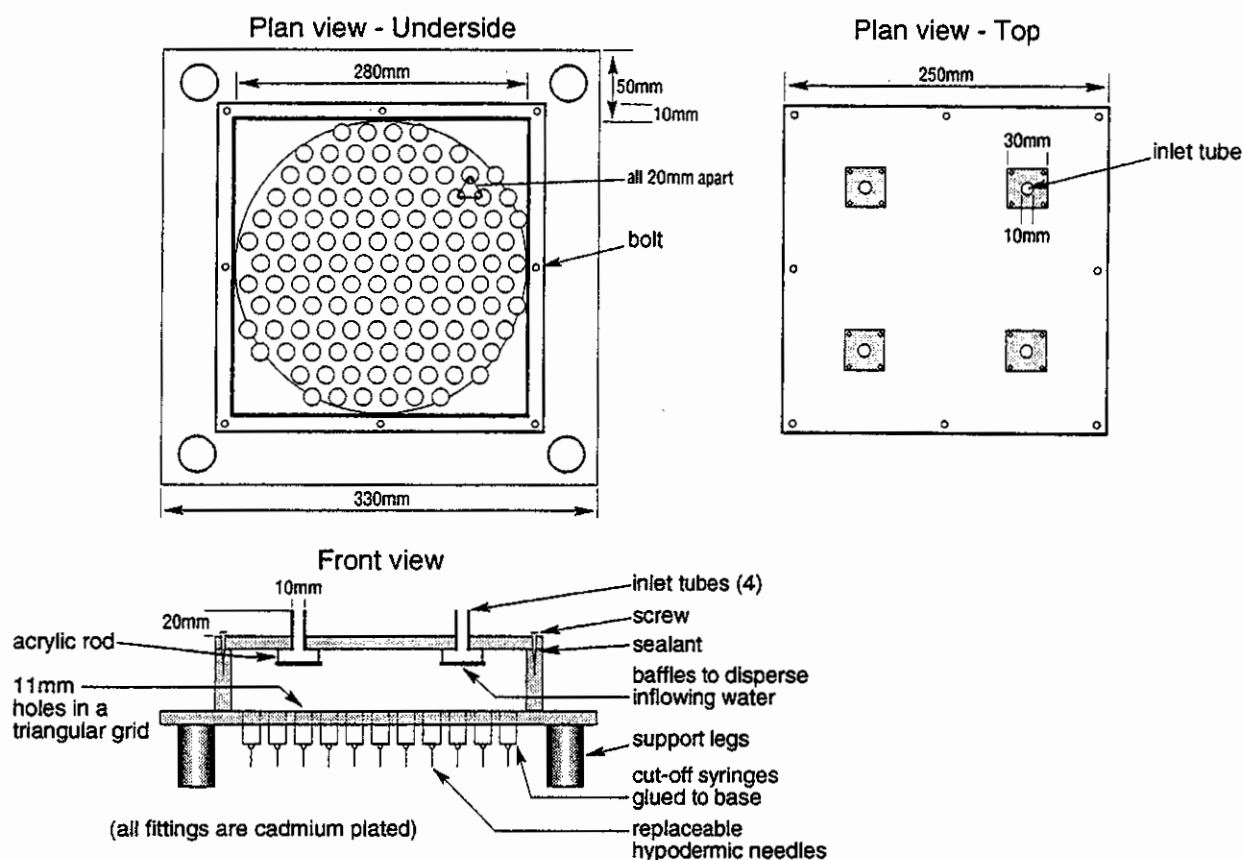


Figure 8. Design of the drip infiltrometer which is used as a constant flux water supply for the measurement of unsaturated hydraulic conductivity.

the two units has substantial overlap to avoid changes during a set of measurements.

The peristaltic pump should be recalibrated each time the infiltrometer is changed because different backpressures will be produced. The calibration should be performed with the infiltrometer at the level that it will be at during measurements on cores.

The hyperdermic needles should be replaced every six months and disposed of appropriately.

A thin cellulose tissue (Chux dishcloth) is placed across the top of the core to absorb the impact of raindrops and to distribute water evenly across the surface of the core.

4.3 Measurement of Hydraulic Gradient and Water Content

Two tensiometers are installed into the side of the core prior to saturation (Section 4.4). Holes with a diameter of 22 mm are carefully cut using an electric drill with a 22 mm hole saw. The Vaseline is removed using a scapel to expose the soil and a smaller hole with a diameter of 10 mm is then drilled horizontally into the core for the tensiometer. Considerable care is necessary to prevent damage to the soil. The size of the hole will depend on the dimensions of the ceramic tip used with the tensiometer. The arrangement shown in Figure 9 uses one bar ceramic tips with a length of 100 mm and diameter of 10 mm. Various types of tensiometer can be used but we have found the system developed by the CSIRO Division of Soils in Townsville to be very accurate and reliable. The system uses Motorola MPX100D pressure transducers and these are connected to a data-logger using a Dallas DS5000 microcontroller with a program written by Peter Ross (CSIRO Division of Soils, Townsville). The data-logger has a serial link to a personal computer and continual logging of matric potential to within ± 1.5 mm is possible.

The ceramic tips are glued to a clear polycarbonate connector (Figure 9) and this allows for easy detection of air bubbles. The connector screws onto the casing of the tensiometer and teflon plumbing tape with a smear of vacuum grease is used to ensure an airtight seal. The ceramic tip

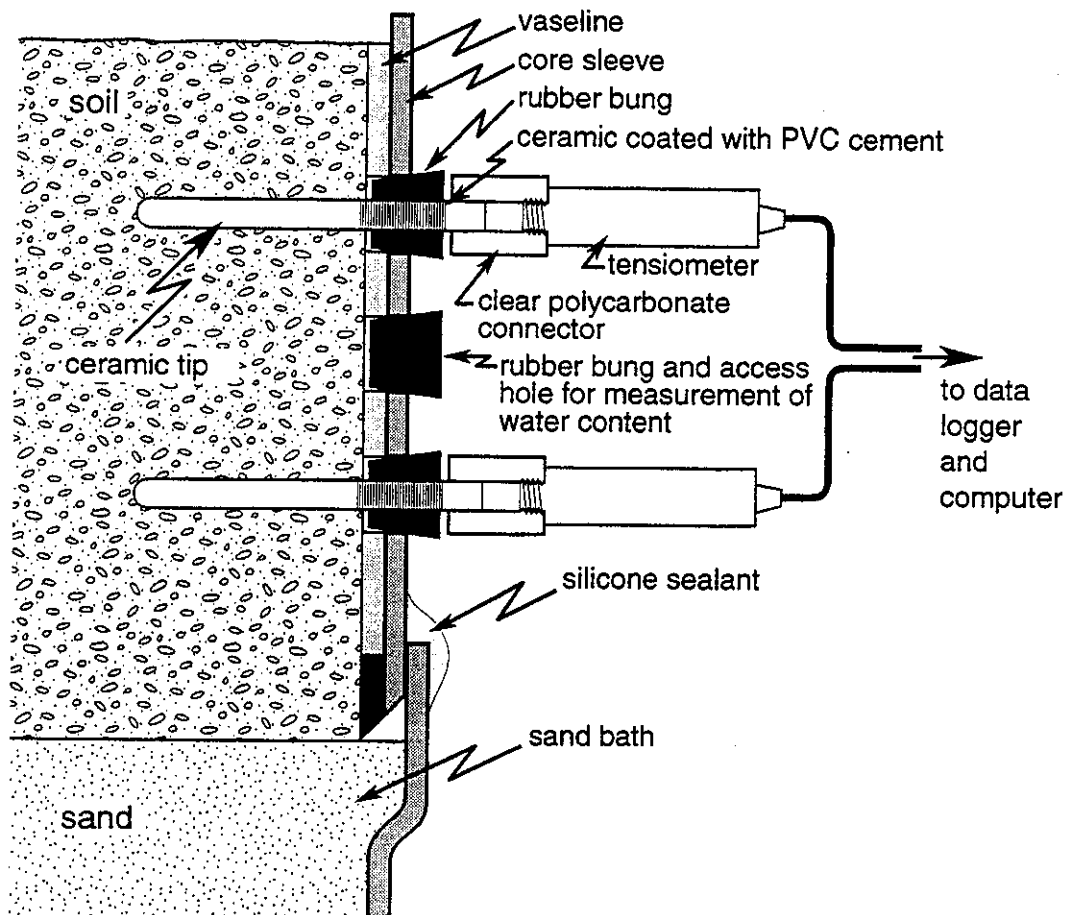


Figure 9. Cross section of a large soil core showing the installed tensiometers, the access hole for measuring water content and the sealing system with the underlying sand bath.

must be firmly fitted into the soil core to ensure good contact. A large rubber bung is used to retain the tensiometer and ceramic tip and to prevent leakage when the core is initially saturated. Duct tape wrapped around the rubber bung and connector ensures an even better seal between the tensiometer and core. The tape must be removed prior to measurement to ensure correct equilibrium between the tensiometer and soil because the air enclosed by the tape cannot escape and may therefore influence readings.

The soil water content can be measured gravimetrically or by using Time Domain Reflectometry (TDR). We have used gravimetric sampling because it was known that the universal calibration for TDR (Topp *et al.* 1980) did not apply to several of the soils sampled because of their very high or low bulk densities or appreciable contents of iron segregations and separate calibration curves would have been required (Dirksen and Dasberg 1993).

Gravimetric sampling was achieved by cutting access holes of the same diameter used for the tensiometers into the side of core. The access holes are located at the mid-point of the core and away from the lower tensiometer to prevent interference. Vaseline is removed and the hole then sealed with a large rubber bung until sampling. The bungs can be removed during a measurement run because unsaturated conditions prevail.

A thin-walled sampler with a length of 100 mm and diameter of 20 mm is used to extract the gravimetric sample when unit hydraulic gradient is achieved. Large cork borers act as suitable samplers. When the sampler is inserted, it is rotated and the extruded end sealed with a finger to ensure that the complete soil sample is extracted. A sample mass of 30g is adequate for most circumstances.

Unsaturated measurements are made at successively larger negative potentials and the disturbance due to gravimetric sampling is relatively minor.

4.4 Sand Bath

The cores are placed on a sand bath prior to saturation and subsequent measurement. The design of the sand bath is shown in Figure 10. Several vertical slits, 2 mm wide and 20 mm long, are cut into the top of the PVC connector pipe which forms the main body of the sand bath. The slits are filled with silicone sealant but allow the upper part of the connector pipe to expand slightly. Soil cores can be then installed and removed without jamming onto the sand bath. A reservoir of water beneath the sand and a relatively coarse grade of sand (0.8 mm - 1.5 mm) are necessary to ensure sufficient flow. The sand bath is saturated and the sand stirred to release entrapped air. The core is then gently placed onto the sand bath and sealed with a liberal application of silicone sealant. Holes for the gravimetric sampling and tensiometers are drilled. The tensiometers are installed and rubber bungs used to plug the holes for the gravimetric sampling. The sealant is left to set overnight before the water level in the core is raised by gently supplying water to the raised outlet.

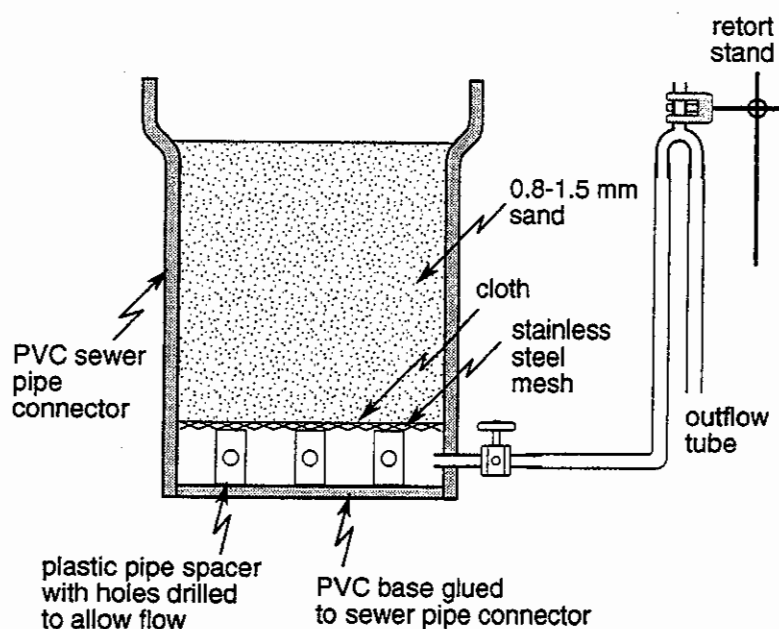


Figure 10. Design of the sand bath and outflow used for measuring unsaturated hydraulic conductivity on large cores.

4.5 Attaining Equilibrium

A measurement run begins with the peristaltic pump calibrated for the specific infiltrometer and the soil core saturated and slightly ponded. An approximate indication of expected flow rates can be gained from the saturated hydraulic conductivity. The pump is started and the outflow gently lowered to several millimetres below the bottom tensiometer. All movement of the outflow should be gentle and gradual to avoid sharp changes in hydraulic gradient. Sharp changes can lead to a break in hydraulic continuity. If a break has occurred, the tensiometers will not respond directly to changes in flux or outflow level.

Two procedures can be followed for the measurement of unsaturated hydraulic conductivities. The matric potential and water content can be measured at a set of predetermined fluxes or the water content and flux can be measured at predetermined potentials. If a TDR is used then the flux and potential could be measured at a set of predetermined water contents but this would only be sensible when similar soils are being compared.

The first procedure is simplest and requires setting the pump to supply the predetermined flux followed by adjustment of the outflow to ensure the attainment of unit hydraulic gradient.

The tensiometers are closely monitored and the outflow adjusted very slowly so that the negative potential at which unit gradient is reached is not exceeded. If this happens and the outflow is then raised to compensate, hysteresis will occur. Routine measurements are made on the drainage limb of the $K(\psi)$ and $\theta(\psi)$ curves. The core should be saturated and the measurement run started again whenever overshooting of the appropriate potential occurs.

The second procedure produces measurements of K and θ at predetermined potentials. This form of data has become common with the advent of the disc permeameter. It can be readily obtained with the apparatus described here except the upper and lower boundary conditions (i.e. flux and outflow height respectively) must be adjusted simultaneously and closer monitoring is required. It does not take long to acquire the experience necessary for avoiding problems with hysteresis but it is a great advantage to have a tensiometer system that has a quick response time and is easy to read.

Our routine procedure has been to measure the flux and water content at potentials of -10 mm, -20 mm, -50 mm and -100 mm. These readings can be obtained in normal conditions and for most soils in one day. Potentials beyond -100 mm can be obtained but the measurement range is limited by the pump which has a minimum reliable rate of 1 ml min^{-1} using Size 25 tubing. This translates to a hydraulic conductivity of 1.54 mm h^{-1} for the size of core used here. Slower rates (i.e. 0.5 mm h^{-1}) can be achieved but close monitoring is required.

4.6 Calculations

When unit hydraulic gradient has been obtained, the unsaturated hydraulic conductivity at that potential is simply:

$$K(\psi) = Q/A$$

where Q is the flow rate ($\text{mm}^3 \text{ h}^{-1}$) and A the area of the core (mm^2).

Unit hydraulic gradient can sometimes be difficult to achieve because of variations of hydraulic properties within the core. In these cases, an approximate or average hydraulic conductivity ($K_{\bar{\psi}}$) can be calculated using the flow rate (Q), matric potential readings from both tensiometers (ψ_{m1} , ψ_{m2}) and the distance between the tensiometers (h). The approximate hydraulic conductivity is derived from Darcy's Law (Hanks and Ashcroft 1980).

The unsaturated hydraulic conductivity between the tensiometers at a potential of $\bar{\psi}$ is:

$$K_{\bar{\psi}} = \frac{Q}{A} \left[\frac{h}{(\psi_{m1} - h) - \psi_{m2}} \right]$$

where

$$\bar{\psi} = \frac{\psi_{m1} + \psi_{m2}}{2}$$

4.7 Problems in Attaining Unit Gradient

Unit gradient can in some instances be difficult to attain and adjustments to the flow rate of the drip infiltrometer and the outflow height do not have a direct affect on the matric potential measured with the tensiometer. There are several causes.

(i) Preferential flow and filling of pores intersected by the tensiometer

In our experience, the most common problem occurs when macropores are intersected and blocked by the tensiometer. When this occurs, film flow down the side of the macropore can fill the pore. Water may not be able to flow through the walls of the macropore fast enough and as a consequence the tensiometer will respond to the potential of water in the macropore which will differ from the potential of the surrounding soil. In these circumstances, unit gradient may be achievable by adjusting the flow rate and outflow height but it cannot be confirmed because of the erroneous readings from the tensiometer.

The problem is more significant in soils with abundant channels or fissures that connect directly to the surface of the core. It may also occur if the top tensiometer is installed too close to the surface of the core. Fine cracks from the ceramic tip through the soil to the surface of the core can act as pathways for preferential flow. These problems can be overcome by using several small tensiometers, particularly for the top tensiometer. The problem is minimised by ensuring that tensiometers are not installed close to the surface of the soil core (i.e. depth > 40 mm).

(ii) Disruption of hydraulic gradient

Rapid movement of the outflow tube can disrupt the continuity of the hydraulic gradient. All movements should be gentle. In our experience, this problem is often associated with the preferential flow and filling of pores intersected by the tensiometer. The tensiometers do not respond quickly or proportionally to a decrease in the level of the outflow tube. As a consequence, the outflow tube is lowered to exert a large suction on the base of the core and hydraulic continuity is often disrupted during the process.

(iii) Variations within the core

Variations within the core in terms of bulk density, structure and clay content make the attainment of unit gradient difficult. This problem is best avoided by careful selection of layers for sampling in the field

4.8 Constant Flux Versus Constant Potential Water Supplies

An alternative system for measuring the unsaturated hydraulic conductivity is to replace the constant flux drip infiltrometer with a constant potential source such as the disc permeameter. The commercially released disc permeameter (White *et al.* 1992) fits well with the equipment described above. Some of the problems associated with the filling of macropores intersected by the tensiometer can be minimized because it is only necessary to use one tensiometer at the base of the core. This is possible because the potential at the top of the core is controlled by the disc permeameter. The performance of the disc permeameter and drip infiltrometer is being evaluated at present. Faster hydraulic conductivities are being obtained with the drip infiltrometer but the reasons are not yet clear. It is important to note that large differences in unsaturated hydraulic conductivity are caused by hysteresis effects. The procedures described above provide measurements on the drainage limb of the $K(\psi)$ curve while disc permeameters are normally used to provide measurements on the wetting limb.

5. WATER RETENTION MEASUREMENTS

The large cores are allowed to drain after the unsaturated measurements and they are then removed from the sand bath and subsampled using 72 mm diameter brass cores. A hydraulic press is used to push the core into the soil (Figure 11).

Water retention measurements are undertaken using standard suction plates and pressure chambers to obtain the full water retention curve ($\theta(\psi)$). Measurements on the subsampled cores are made to calculate bulk density. Standard methods for the measurement water retention and bulk density are described by Loveday (1974).

The bulk density (ρ Mg m⁻³) is used to convert gravimetric water contents to volumetric and to estimate the volumetric water content at saturation (θ_s). We have used the relationship determined by Forrest *et al.* (1985):

$$\theta_s = 0.93 \left[1 - \frac{\rho}{2.65} \right]$$

It is useful to measure water retention at a potential or water content matching one of the points

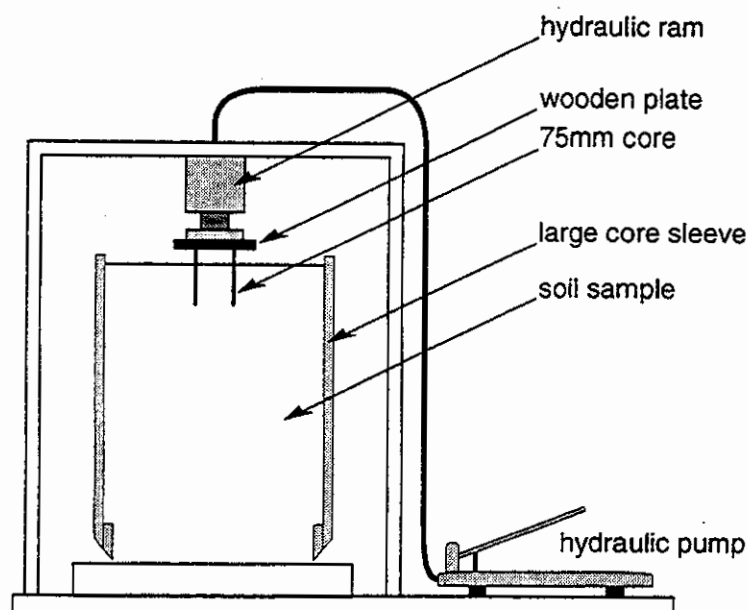


Figure 11. Cross section of the hydraulic ram and coring apparatus for sub-sampling large soil cores after measurement of saturated and unsaturated hydraulic conductivity.

used for measurement of the unsaturated hydraulic conductivity. We have used a potential of -100 mm as a matching point.

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APPENDIX ONE: AUSTRALIAN SUPPLIERS

Most of the materials can be readily obtained from laboratory suppliers, hardware stores, irrigation suppliers and fabricators of metals and plastics operating in most capital cities.

- Bulk Vaseline:* Vaseline in 20kg containers is available from petroleum distributors.
- Plastic Pipe:* PVC sewage pipe and sewage pipe connectors for the sand baths are available from most plumbing suppliers.
- Glass sinters:* The sinters were constructed by a glass blower using American coarse grade sinter. Glass blowers operate in most capital cities.
- Three way taps:* These are available from most irrigation suppliers as are taps for the constant water level tank and sand bath.
- Floating valve:* 20 mm valves are available from most rural suppliers.
- Water tank:* The constant water level tank should be quite rigid and the large plastic bins used by butchers are suitable - they can be obtained from plastic suppliers.
- Peristaltic pumps:* DIGI-STALTIC digital flow controllers are supplied by Extech Equipment Pty. Ltd, Wantirna South, Victoria. Other brands of peristaltic pumps are available.
- Ceramic tips:* A range of ceramic tips is supplied by Irricrop Technologies Pty. Ltd in Narrabri, NSW.
- Tensiometers:* CSIRO Division of Soils, Townsville.
- Sieved sand:* Sieved sand with the appropriate range of particle size is available from swimming pool suppliers.