Manual for soil physical measurements

Version 3

J. Stolte (ed.)

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ABSTRACT

Stolte, J. (ed.), 1997. *Manual for soil physical measurements; version 3* . Wageningen, DLO-Staring Centre. Technisch Document/Technical Document 37. 77 pp.; 18 Figs; 2 Tables.

Manuals are provided for several laboratory methods to determine hydraulic conductivity, water retention and shrinkage characteristics of soil. Measurement techniques described are: the constant and falling head method for the saturated conductivity; the drip infiltrometer for the unsaturated conductivity; Wind's evaporation method for both the water retention and unsaturated conductivity characteristic; hanging water column method and pressure plates for the water retention characteristic. A method for shrinkage characteristic is described. Descriptions of taking soil samples and pre-treatment of tensiometers are also provided.

Keywords: hydraulic conductivity, water retention, shrinkage characteristic, determination method, soil sampling, manuals

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Preface

In 1991, a first attempt to write down the procedures of the methods used at the soil physical laboratory of the DLO Winand Staring Centre resulted in a manual version 1.0. The language of this version was Dutch, and was therefor not very useful for other laboratories. So, version 2.0 was introduced in 1992 which was a translation of version 1.0. The manual for soil physical measurements, version 3, is an update of version 2.0. The major difference is the use of co-authors for writing the manuals, all experienced users of the methods. Updates of individual manuals will not have new version numbers, but will be called 'replacement of manual ... of version 3'.

All authors are gratefully thanked for there contribution to this manual.

Introduction

Studies on water and solute movement in the unsaturated zone require knowledge of physical properties of the soil. This manual provides practical guidelines for several measurement and sampling techniques. The different chapters of the manual are written by frequent users of set ups, available at the Soil Physical Laboratory of DLO Winand Staring Centre. This ensures that practical guidelines are given for conducting the specific measurement.

This version (3) is an update of version 2.0. The number of manuals is increased. Chapter 10 (shrinkage characteristic) is added. Also, remarks from users of version 2.0 are incorporated.

Descriptions are given for taking soil samples and pre-treatment of tensiometers and pressure transducers. Measurement of the saturated conductivity is described by two different set ups (constant and falling head methods). The unsaturated conductivity measurement is described by using an infiltrometer and the evaporation method. The water retention characteristic measurement is described by three measurement techniques (evaporation method, hanging water column, pressure plates). Finally, a measurement technique of the shrinkage characteristic is given.

The manual is not exhaustive with regards to the number of available measurement techniques. Especially for the measurement of the unsaturated conductivity, a large number of measurement techniques is available. A comparison of six methods is given by:

J. Stolte, J.I. Freijer, W. Bouten, C. Dirksen, J.M. Halbertsma. J.C. van Dam, J.A. van den Berg, G.J. Veerman and J.H.M. Wösten. Comparison of six methods to determine unsaturated soil hydraulic conductivity. Soil Sci. Soc. Am. J. 58:1596-1603 (1994).

Raw measured data often cannot be used as model input. In most cases, a curve-fitting procedure has to be used to parameterize the measurements. One of the commonly used ways to do this is fitting the measured data with the Mualem-Van Genuchten model. The RETC code provides this parameterization and is published by:

M. Th. van Genuchten, F.J. Leij and S.R. Yates. The RETC code for quantifying the hydraulic functions of unsaturated soils. U.S. Salinity Laboratory, U.S. Department of Agriculture, Agricultural Research Service, Riverside, California 92501

Though the authors tried to be as complete as possible, there may be errors in the manual. The authors are not responsible for the outcome and interpretation of the data. Please send your remarks to the editor.

1 Taking soil samples in the field for laboratory determination

J.Stolte, G.J. Veerman and M.C.S. Wopereis

Subject

Sampling guidelines are given for laboratory determination of soil physical characteristics, i.e. water retention and hydraulic conductivity.

Application

Samples can be used for several laboratory techniques to measure the soil physical characteristics.

Principle

A representative field site is selected with an Edelman auger. At this site samples are taken in soil horizons (or at desired depth intervals). Disturbance of the internal structure of the samples should be avoided and the samples have to be transported carefully to the laboratory.

Time

Sampling time depends on the amount of samples to be taken and on the depth of the sampling layer. Take your time for sampling, working accurately is the basis for reliable results.

Materials

- Sample rings (for examples see table) + covers (for hanging water column and evaporation method).
- Edelman auger.
- Spade and shovel.
- Guidelines for soil profile description (e.g. FAO guidelines) + field form.
- Knives.
- Spirit level.
- Marker pen (waterproof).

	Constant head Drip infiltrometer	Evaporation method	Hanging water column	Falling head
material	ss	PVC	ss	ss
diameter (out) (cm)	20.4	11.0	7.62	11.0
wall thickness (cm)	0.17	0.35	0.16	0.4
diameter (in) (cm)	20.06	10.3	7.27	10.4
height (cm)	20.0	8.0	7.17	5.0
volume* (cm^3)	6321.0	667.0	300.0	408.5

PVC = poly vinyl chloride; ss = stainless steel
* subtract the volume of the tensiometers which are installed in the samples for total soil volume

- Measuring tape.
- Perforated disks, 200 mm diam, and nylon cloth for constant head and drip infiltrometer methods.
- Pen and notebook.
- Waterproof tape.
- Plastic bags for collecting disturbed samples for textural analysis, etc.
- (Paper) towels (for cleaning rings etc.).
- Plastic trays to carry and transport samples.
- Cutting edge, fitting the several PVC-sample rings.
- Plastic sheet (2 m x 2 m) for collecting soil.
- Tray for transporting tools.
- Case for "soil sampling kit for hydraulic sampling".
- A kit for hydraulic sampling (if available) containing:
    - anchor rods with extension rods and coupling nuts;
    - anchor beam with spirit level;
    - hydraulic jack;
    - adapter for jack/sample rings, adapted to the sizes of the sample rings;
    - hydraulic pump with high-pressure tube and couplings.

Procedures

Selecting sample site

Select, with the use of an Edelman auger, a representative profile for the area under study.

✓ Depending on the objective of the research and the heterogeneity of the area several representative profiles might be selected.

Each layer must be homogeneous and must have a thickness that is equal or more than the height of the sample ring.

✓ If a sample ring of for instance 20 cm is used the sampling layer should be over a depth of at least 20 cm homogeneous.

When the soil is very hard, sampling should be postponed as sample disturbance and sometimes equipment damage will be unavoidable. When postponement of sampling is not acceptable slowly wet the plot by using drip irrigation under a cover. This normally allows sampling in two or three days.

Preparing sample site

Mark out a work space of at least 1.5 m x 1.5 m on a level area. Remove the upper part of the soil until the horizon to be sampled is reached. Collect the different horizons separately on a plastic sheet. Place the anchor rods at the desired distance in the soil. Lengthen with rods and coupling nuts and fasten them with ground plates and ropes if necessary. Connect a hydraulic jack to the anchor beam. Slide at each anchor rod a lock nut. Hang the anchor beam between the anchor rods. Slide at the bottom of the PVC sample rings a metal cutting ring and put the sample ring on the soil layer right under the beam.

✓ Maintain at least 20 cm distance to the profile wall, it might cave in due to the pressure.

Adjust an adapter on the sample ring (adapted to the sample size) and connect with extension rods the adapter and the hydraulic jack. Move the anchor beam downwards until a tight fit is obtained. Level the beam and secure the beam with the use of two other nuts. See Figure 1.1 and 1.2 for a view of the set up.

Taking samples

Push with the help of the pump the sample ring slowly and perpendicularly in the soil. Repeat this with all the rings that are needed from one horizon. Then dig up the rings carefully.

✓ Not all samples can often be taken under the beam of the sample kit. One anchor must be moved to take supplementary samples.

✓ If a soil sampling kit is not available or for one or the other reason not usable, push the sample rings in the soil by hand. For small rings (max. diameter 70 mm) a core sample with a hammering head can be used. Large rings have to be driven in very carefully using a wooden plate and a mallet, while carving the soil along the edge of the ring.

Label the rings clearly with the help of tape and a waterproof marker pen.

Place the 20.4 cm x 19 cm samples on a perforated plate, covered with nylon cloth. Put it in a tray. In the laboratory, fill the tray with water to saturate the sample from below. Put at top and bottom of the 11 cm x 8 cm sample rings a thin plastic disk and close both sides with a tight fitting lid. Put also at top and bottom of the 7.6 cm x 7.2 cm and 11 cm x 5 cm sample rings a thin plastic disk and close them using fitting lids.

To avoid disturbance of the samples start the measurement as soon as possible after taking the samples.

✓ Most measurement techniques require a saturated sample to start with. Saturation is taken place in separate trays, except for the hanging water-column and falling head methods for which samples are saturated on the devices themselves.

Soil profile description

Make a detailed description of the soil profile at the sampling site. Use standard soil profile description forms for this purpose and guidelines for soil profile description (e.g., FAO guidelines, FAO, 1977). If possible, ask an

experienced soil surveyor to help with the profile description and the soil classification.

Set up

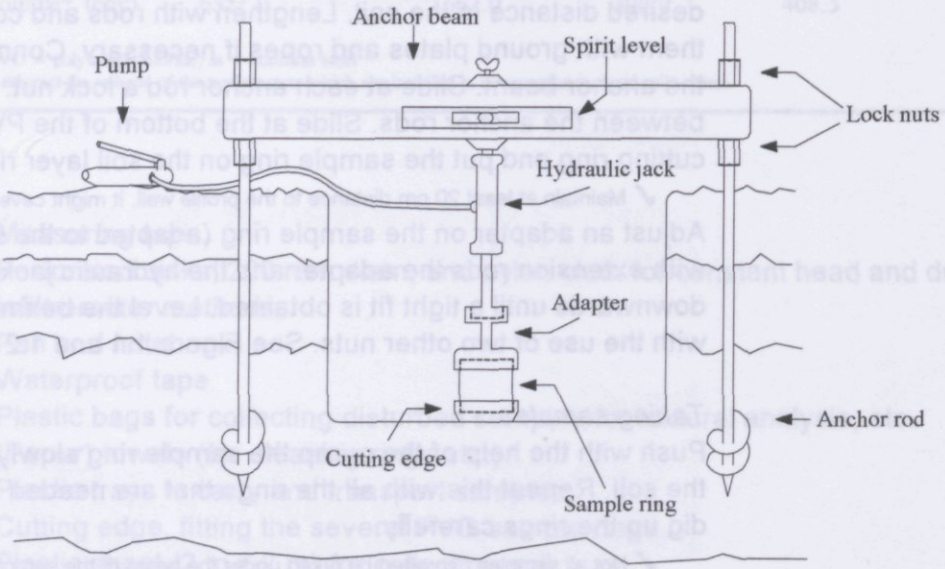

Figure 1.1. Set up for taking soil samples in the field for laboratory determination

Figure 1.2. Soil sampling equipment

Notes

The use of standard volumes can lead to erroneous results. Soils differ significantly with respect to structure and therefore representative elementary volumes (REV) differ significantly. This is especially true for the measurement of hydraulic conductivity. A REV should contain at least 20 structural units.

For sandy soils, relatively small sample sizes can be used but for clayey soils large sample sizes are needed. For practical reasons a standard size of 20 cm height and 20 cm diameter is used for the saturated (using the constant head method) and unsaturated hydraulic conductivity (using the drip infiltrometer method).

Literature

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2 Flushing, testing and installation of tensiometers for laboratory determination

J. Stolte and G.J. Veerman

Subject

A description of filling tensiometers with de-aired water, and of testing tensiometers is given. Also, the installation of tensiometers in soil samples is described.

Application

Tensiometers measure the hydraulic potential in the unsaturated zone of the soil in the laboratory and in the field. The hydraulic potential that is measurable with tensiometers ranges from 0 cm till approximately -80 kPa.

Expression and definition

Tensiometer: A porous, with water filled high water-conducted cup, connected to a pressure indicator. The cup is commonly made of ceramic material. Fig. 2.1 shows three types of frequently used tensiometers. A pressure transducer is commonly used as pressure indicator.

Principle

When a water-filled tensiometer is in contact with unsaturated soil, water will flow out of the cup until hydraulic equilibrium is reached, i.e., until the (negative) pressure inside the cup equals the pressure potential of the soil water outside. This process results in a pressure change in the tensiometer cup that can be registered by a pressure transducer (or mercury manometer). The tensiometer (included the cup) should be air-free, to avoid slacking of the measurement.

Time

Flushing, testing and installation of tensiometers take, depending on the amount of tensiometers that have to be installed, 1.5 (one sample with four tensiometers) till four hours (ten samples with four tensiometers each).

Materials

- Tensiometer consisting of a porous cup of unglazed ceramic and provided with accessories to connect the tensiometer with a measurement instrument to measure the hydraulic potential.
- Set of augers for installation of tensiometers.
- Vacuum exsiccator filled with water.
- Erlenmeyer flask with rubber stopper containing two lengths of clear nylon tubing.
- Pressure gauge.
- Nylon tubing (inner diameter 1.5 mm) with three-way stopcock.
- Vacuum pump.
- Beaker.
- Syringe.

Procedures

Flushing

Place the tensiometer upright in a beaker filled with water and allow the ceramic cup to soak overnight. Place the beaker with the tensiometer in a water-filled exsiccator. Close the exsiccator and connect it to a vacuum pump. Make sure a pressure gauge is connected. Start the pump and apply a pressure of at least -90 kPa to the exsiccator. Maintain this pressure during at least one hour.

✓Check the pressure with the pressure gauge. If it does not reach -90 kPa the set up must be checked on leakage.

Stop the pump and open the air inlet of the exsiccator.

Testing for air leakage

Use an Erlenmeyer flask containing a stopper with two nylon tubes. Connect one tube to the pressure gauge. The other tube must contain a three-way stopcock at the end and is used to test the tensiometer. Connect the tensiometer (under water!) to this three-way stopcock and suck till about -85 kPa. Keep the cup under water and wait till all the air is out of the cup and tubing. Take the cup out of the water. Allow an air bubble to enter the nylon tubing by opening the three-way stopcock. Dry the outside of the ceramic cup and check the drift of the air bubble. If the tensiometer is leak-free, the air bubble will stop drifting after about five sec. If not, the tensiometer is unusable.

Testing for conductivity

Put the tensiometer under water and apply a pressure of -50 kPa. Monitor the time required for an air bubble to move 25 cm in the nylon tube (inner diameter 1.5 mm) for the 6 mm outer diameter cup (Fig. 2.1 B). This should take no longer than 50 sec. If the air bubble moves too slow, the conductivity of the ceramic cup is too low to use. Replace the cup. For the 2 mm diameter cup the movement of the air bubble should be visible.

Disconnect the tensiometer under water and close the tube(s).

☞ Be sure that air cannot enter the tensiometer and no air bubble, however small, is left in the tensiometer or tubing. Otherwise, the above procedures have to be repeated.

Installation of tensiometers

Tensiometers with an outer diameter of 6 mm or 2 mm are normally used for laboratory purposes. A special set of small augers, adjusted to the correct diameter and length, is needed to install these tensiometers.

✓ It is important that the soil samples are not too wet or too dry. For a wet clay soil, smearing of the auger-hole walls might occur; in a sandy soil the hole might collapse. This shows that the tensiometers must be installed before saturating the samples. If the soil samples are to dry the air-entry value of the tensiometers will be exceeded immediately.

✓ Place tensiometers one by one.

Maintenance

After completion of the measurements, clean the tensiometers in hot water and store them in a container filled with dry sand, to avoid algae's growth.

Set up

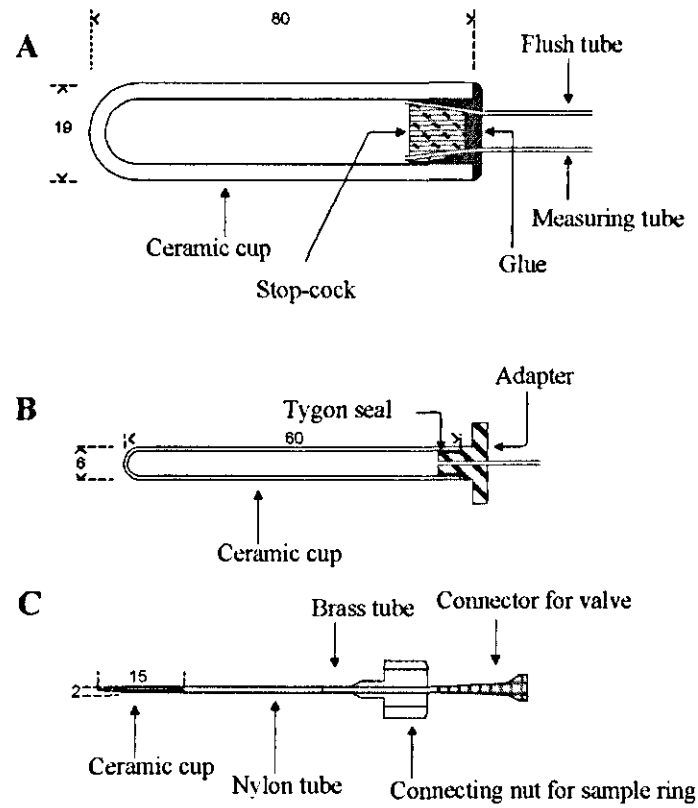

Figure 2.1. Three types of tensiometers. **A** *for field use and* **B** *and* **C** *for laboratory use. Values in mm.*

Notes

For tensiometers to be installed in the field for a long time (several months), tensiometers with two tubes should be used as in-situ flushing may be needed (Fig. 2.1 A). The use of copper tubing to prevent air entry or evaporation is strongly recommended under such circumstances.

Literature

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ISO 11276. *Soil Quality - Determination of pressure potential - Tensiometer method.* ISO, Geneva.

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not published:

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3 Filling of pressure transducers with de-aired water

J.Stolte and G.J. Veerman

Subject

Guidelines are given for filling pressure transducers with de-aired water.

Application

A pressure transducer is used to register soil-water pressure potentials. The transducer should be air-free and filled with de-aired water before use. The method is only suitable for so-called 'dry - wet' transducers, for which the membrane can endure a pressure of - 100 kPa.

Expression and definition

Pressure transducer: A sensor that by means of a membrane converts a pressure difference into an electric voltage.

✓ A mechanical conversion is also possible but is not described in this manual.

Principle

A pressure transducer must be completely air-free to avoid air bubbles disturbing the measurement. Removal of entrapped air can be accomplished by applying a vacuum at one side of the membrane, replacing the air with water vapor and filling the system with de-aired water.

Time

Filling a pressure transducer with de-aired water takes about 30 min.

Materials

- Pressure transducer.
- Vacuum pump.

- Erlenmeyer flask.
- Support base and rod (retort stand).
- Stopper with tubing for Erlenmeyer flask.
- Three 2-way valves.
- Heat source.
- T-connector.

Procedures

Installing the apparatus

Use a set up as shown in Figure 3.1. Make sure that the pressure transducer is placed higher than the Erlenmeyer flask. Use a heat source (lamp or fan) to increase the temperature of the tubes and transducer a few degrees. This temperature must be higher than that of the water in the Erlenmeyer flask. This prevents condensation of vapor what might result in 'water lenses' in the tubes and/or transducer.

✓ When using a water-jet air pump, the water in the flask must be warmer than the water from the water pump.

Connecting the apparatus

Connect the Erlenmeyer flask with the pump. Fill the Erlenmeyer with water to a level just below the outlet. Close the flask using the stopper. Make sure that the tube through the stopper reaches the bottom of the Erlenmeyer flask. Make sure that the tube for air inlet is connected with a thin piece of tube meant as narrowing.

✓ The narrowing is to prevent air entering the flask suddenly, possibly damaging the membrane in the transducer

Open all valves to avoid pressure buildup in the transducer. Connect the tube to the pressure transducer with a T-connector. Connect the other two ends of the connector with the pump and the Erlenmeyer flask. Close the air inlet of the Erlenmeyer flask.

Replacing air with water vapor

Start the pump. The water in the Erlenmeyer flask starts to boil after some minutes.

✓ If the water does not start to boil the system leaks.

Apply a suction for at least 10 min. (Fig. 3.1. A). Check regularly if 'water lenses' occur in the tubes. These lenses can be removed by gently tapping the tubes. When the tubes are completely filled with water vapor close the valve to the pump and stop the pump.

Flushing the pressure transducer

Turn the Erlenmeyer flask upside down. Raise the flask gently until it is higher than the pressure transducer (Fig. 3.1 B). Water flows into the tube to the pressure transducer. Slowly open the air inlet of the flask. Water is now pushed into the pressure transducer. When equilibrium is reached, disconnect the pressure transducer. Avoid evaporation of water from the transducer.

Connect the transducer to a small, airtight reservoir (e.g., a sealed plastic bag) filled with de-aired water.

Testing the pressure transducer
Connect a syringe filled with about 5 cm^3 air to the pressure transducer. Make sure that there is an air bubble in the tubing, somewhere between syringe and transducer. Pull the plunger of the syringe out to about 10 cm^3 (thus creating a pressure of -50 kPa,). Be careful not to damage the pressure membrane, and watch the air bubble. If it moves, flushing has not been effective and the procedures outlined above should be repeated.

✓ Movement of the air bubble may also be due to the flexibility of the tubes. If they are too flexible, the tubes will contract. Replace the tubes and repeat the procedures.

Set up

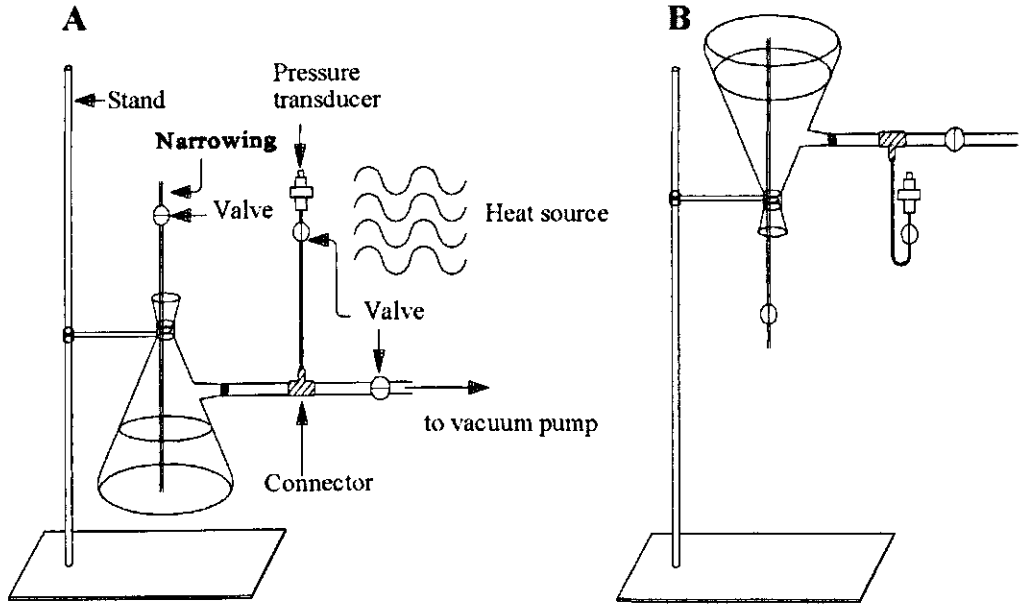

Figure 3.1. Filling a pressure transducer with de-aired water. **A** *for replacing air with water vapor and* **B** *for filling the transducer with de-aired water.*

Literature

Klute, A. (ed.), 1986. *Methods of soil analysis, Part 1, physical and mineralogical methods,2nd ed.* Agronomy 9 (2). American Society of Agronomy. Madison, Wisconsin.

4 Determination of the saturated hydraulic conductivity using the constant head method

J. Stolte

Subject

A steady state laboratory method is described to measure the hydraulic conductivity of saturated soils.

Application

The saturated hydraulic conductivity is an important parameter for predicting soil water movement. The method described is suitable for undisturbed, homogeneous soil samples. The method is not suitable for soils in which, due to high conductivities, the internal structure will change. This implies that with this method saturated conductivities up to 1000 $cm.d^{-1}$ can be measured. This method is also not suitable for low conductivity (< 1 $cm.d^{-1}$) measurements. The constant head method (Manual 5) can be used for measuring these low conductivities.

Expression and definition

Saturated conductivity, K_s : The value of the hydraulic conductivity of soil at a pressure head h = 0 cm (K_s in $cm.d^{-1}$).

Principle

The saturated hydraulic conductivity K_s is determined using a steady state constant head method based on Darcy's law. A constant water level is maintained on top of an undisturbed soil sample. The volume of water that percolates through the sample is measured over time.

Time

The time of determination depends on the soil type. To saturate a soil sample takes at least two days (sand) and maximal four weeks (clay). The determination takes at least one day.

Materials

- Stainless steel cylinders, 20 cm diam and 20 cm high.
- Support cylinder with funnel.
- Perforated disk, 20 cm diam.
- Extension ring, 20 cm diam (optional).
- Beaker.
- Balance.
- Rubber tube or waterproof tape.
- Clamping rings.
- Stop watch.
- Tray, at least 25 cm high.
- Constant head device.
- Clear flexible tubes to use as siphons between constant head device and sample surface.

Procedures

Preparing soil samples
Take soil samples with minimum disturbance (see Manual 1). Saturate the samples in the laboratory by placing them on cloth-covered perforated disks in a tray of at least 25 cm high filled with about 5 cm water. Increase the water level in the tray daily until the upper rim of the sample is reached. The size and number of steps to increase the water level depends on the soil type. Two steps (days) may be sufficient for sand, but it is better to saturate the samples more gradually (5 steps in 5 days).

Installation
Place the saturated soil sample, including cloth-covered perforated disk, on the support cylinder (Fig. 4.1). Use waterproof tape or rubber tubing and clamping rings to connect the sample to the support cylinder. Connect, if necessary, a 5-cm high extension ring to the top of the sample ring using rubber tube and clamping rings or waterproof tape. Slowly pour a thin layer of water (about 1 cm) on top of the sample. Maintain this water height using a constant head device (Fig 4.1).

Measurements

Collect the percolating water in a beaker. Weigh the outflow in time using an accurate balance. The balance must have an accuracy of 0.1% of the total outflow volume.

✓ Thus a minimum volume of 100 ml water should be collected using a balance with an accuracy of 0.1 g.

✓ If conductivity is lower than 25 $cm.d^{-1}$ prevent evaporation from the measuring beaker. The evaporation (at 20°C and 50% humidity) is then larger than 0.1% of the conductivity (using receiving beaker with a surface area of 40 cm^2).

Repeat the measurement until steady state is reached.

✓ Steady state is reached when three successive measurements differ by 2% or less.

The three measurements are used to calculate the mean saturated conductivity.

Set up

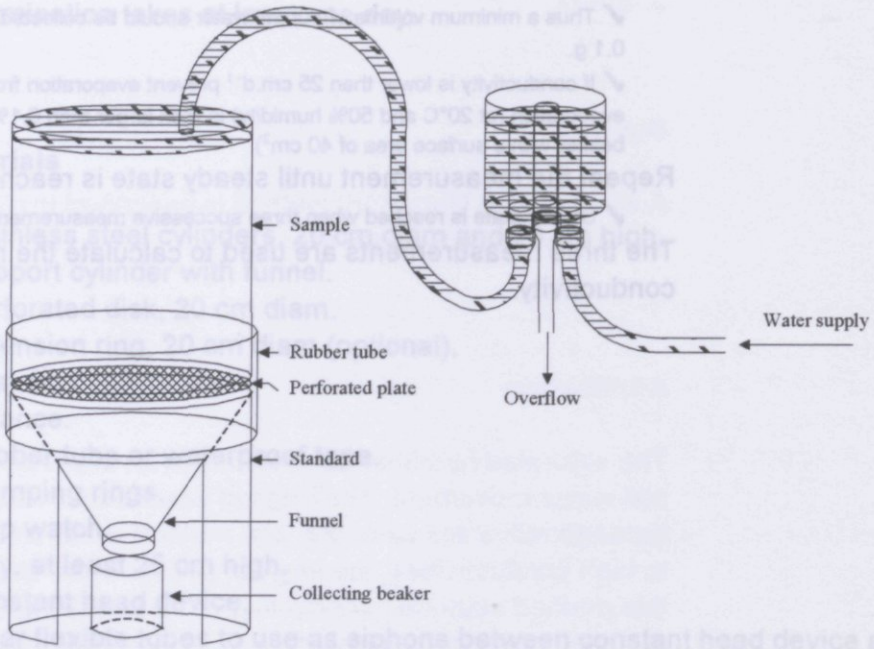

Figure 4.1. Set up of the measurement of the saturated hydraulic conductivity, using the constant head method.

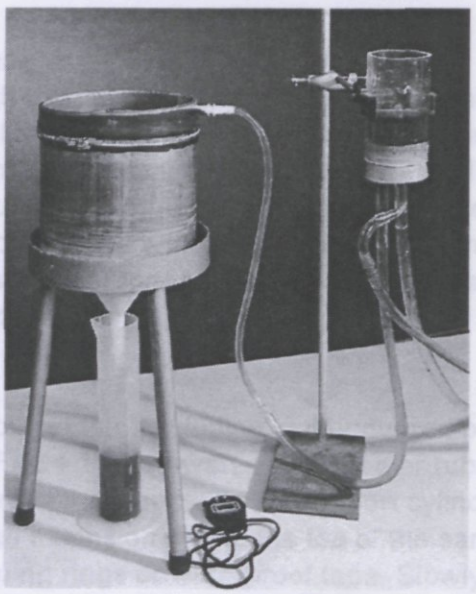

Figure 4.2. Measurement of the saturated hydraulic conductivity using the constant head method.

Calculations

Saturated conductivity can be calculated using the equation:

$$K_s = \frac{V}{t \times A} \times \frac{l}{l + d}$$

where:

K_s = saturated conductivity (cm.d^{-1});
V = outflow volume (cm^3);
t = time (days);
A = surface area of the soil sample (cm^2);
l = height of the soil sample (cm);
d = thickness of the water layer (cm).

Accuracy

The accuracy of the method depends on the accuracy with which measurements of time and outflow volume are recorded. The total error in the calculated K_s can be determined as:

$$\frac{\Delta K_s}{K_s} = \frac{\Delta V}{V} + \frac{\Delta t}{t} + \frac{\Delta A}{A} + \frac{\Delta l}{l} + \frac{\Delta l}{l + d} + \frac{\Delta d}{l + d}$$

$$\approx \frac{\Delta V}{V} + \frac{\Delta t}{t} + \frac{\Delta A}{A} + \frac{2\Delta l + \Delta d}{l}$$

where:

ΔK_s = error in conductivity measurement;
ΔV = error in flux measurement;
Δt = error in time measurement;
ΔA = error in surface area measurement;
Δl = error in measurement height of sample;
Δd = error in measurement thickness water layer.

The magnitudes of these errors depend on the equipment. For instance, the error in measurement of the flux will depend on the accuracy of the balance.

✓ When proper equipment is used, all relative errors will be negligible (maximal 0.1%). With very high saturated conductivity the relative error in time measurement will become maximal 2%. The relative error in measuring the thickness of the water layer will be negligible if the constant-head system is functioning properly.

All errors mentioned above are system errors. Sampling procedures and homogeneity of the sample will also influence the measurement outcome. Using representative, homogeneous and as little as possible disturbed samples is a prerequisite for getting reliable and reproducible results.

Report

Report by the presentation of the results:
- name (sampling and measurement);
- sample location (coordinates if possible);
- date of sampling and date of measurement;
- vegetation;
- profile description (see manual 1);
- sample depth;
- texture and density of the sample (included determination method);
- time of saturating the soil sample;
- list of instruments and apparatus;
- results of the measurements of the flux, time, surface and height of the sample;
- the three constant K-values, including the maximum and minimum value (error analysis);
- the mean K-value, including the maximum and minimum value;
- temperature during determination;
- other for the evaluation of the determination important remarks (weather during sampling, field moisture, root canals etc.).

Literature

Burke, W., D. Gabriels and J. Bouma (ed.), 1986. *Soil Structure Assessment.* A.A. Balkema, Rotterdam/Boston.

Klute, A. (ed.), 1986. *Methods of soil analysis, Part 1, physical and mineralogical methods, 2nd ed.* Agronomy 9 (2). American Society of Agronomy. Madison, Wisconsin.

5 Determination of the saturated hydraulic conductivity using the falling head method

A. Weitz, J. Stolte and G.J. Veerman

Subject

A laboratory method is described to measure the hydraulic conductivity of saturated soils.

Application

The saturated hydraulic conductivity is an important parameter for predicting soil water movement. The falling head method is suitable for undisturbed, homogeneous soil samples as well as for disturbed, artificial samples. The experimental design of the method implies that it is very suitable for low conductivities (< 1 $cm.d^{-1}$). Higher conductivities can be measured using the constant head method (Manual 4).

Expression and definition

Saturated conductivity, K_s: The value of the water conductivity of soil at a pressure head h = 0 cm (K_s in $cm.d^{-1}$).

Principle

The saturated hydraulic conductivity K_s is determined by measuring the volume of water, which percolates through a saturated soil sample in time while the corresponding hydraulic head gradient changes continuously. A (undisturbed) soil sample is placed in a cell and saturated from below. The cell is connected to a standpipe filled with water. Water flows out of the standpipe through the sample. The saturated soil hydraulic conductivity is then calculated from measured changes of the hydraulic head in time.

Time

The time of determination depends on the soil type. To saturate a soil sample takes at least two days (sand) and maximal four weeks (clay). The

determination takes at least one week and can last more than six months, depending on the conductivity.

Materials

- Stainless steel sample rings, 10.4 cm inner diameter, 5 cm high.
- Cell in which the stainless steel sample ring fits air-tight (using rubber o-rings).
- Perforated disk (sieve or high conductance porous stone) and filter cloth with the same diameter as the sample ring.
- One three-way stopcock and two two-way stopcocks.
- Standpipe with measurement scale (diameter standpipe 1-2 cm^2).

  ✓ The required diameter of the standpipe depends on the conductivity to be measured. Make sure that a reading within the measurement time is feasible. The diameter necessary can be estimated by:

$$d = \left(K \times t \times \frac{D^2}{L} \times (\log H_r) \right)^{1/2}$$

  where d is diameter of the standpipe, K is estimated conductivity, t is chosen measurement time, D is diameter of sample, L is height of sample and H_r is hydraulic head ratio.
- Rubber tubes.
- Syringe.
- Cylinder to collect outflow.
- High permeable sand for filling purposes.
- Silicon grease.
- De-aired water.

Procedures

Preparing soil samples

Take soil samples with minimum disturbance (see Manual 1). Clean the outside of the sample ring. Grease the rubber o-rings and place them into the o-ring dimple of both cell parts. Put the metal sieve in the bottom part of the cell. Cover the bottom of the soil sample with a filter cloth and fix the sample ring into the bottom part of the cell. Cover the top of the sample with filter cloth and sieve, and close the cell air-tight.

Saturating soil samples

Fill the standpipe with de-aired water by using a syringe and a three-way stopcock. To fill the bottom part of the cell with water, turn the cell upside down and open the ventilation at the bottom part of the cell. Fill the cell with water, by injecting water through the ventilation opening using a syringe with needle. When the bottom part of the cell is filled with water, close the ventilation opening, connect the cell to the standpipe using rubber tube (avoid air bubbles entering the cell), and turn the cell upright. Let the sample saturate by applying a maximum water pressure of 60 cm on the sample.

✓ Don't exceed the pressure of 60 cm to avoid internal damage of the soil structure.

After the water level reached the sieve in the top part of the cell, fill the cell completely by adding de-aired water through the two-way stopcock on top of the cell, using a syringe. Close the stopcock and test the set up on leakage. Start all over again in case of leakage. See Figure 5.1 for a view of the set up

Measurements

Adjust the water level in the standpipe 50 cm above the opening of the outlet. Note the water level in the standpipe and the date and time of reading. Refill the standpipe when it is almost empty.

End of measurements

Continue measurements untill five successive measurements have been carried out with a deviation of maximal 2% of the calculated average K_s values

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Set up

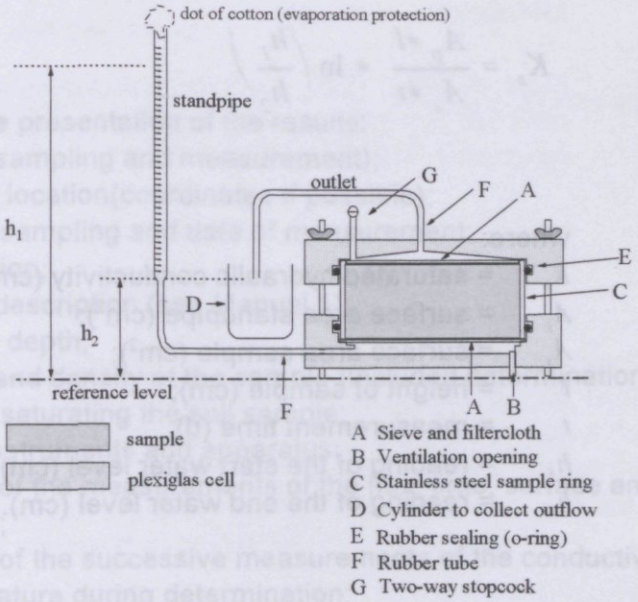

Figure 5.1. Set up of the measurement of the saturated conductivity using the constant head method.

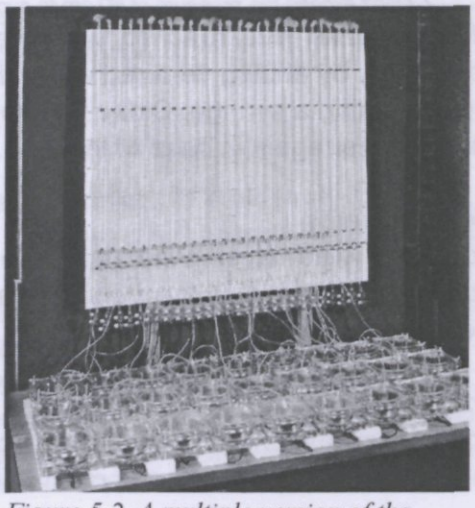

Figure 5.2. A multiple version of the measurement of the saturated conductivity using the constant head method.

Calculation

Calculate the saturated hydraulic conductivity using:

$$K_s = \frac{A_p * l}{A_s * t} * \ln\left(\frac{h_1}{h_2}\right)$$

where:

K_s = saturated hydraulic conductivity (cm.d^{-1});
A_p = surface area standpipe (cm^2);
A_s = surface area sample (cm^2);
l = height of sample (cm);
t = measurement time (d);
h_1 = reading of the start water level (cm);
h_2 = reading of the end water level (cm).

Accuracy

The accuracy of the method depends mainly on the accuracy in the measurements of water level changing in time. The total error in the calculated K_s can be determined as:

$$\frac{\Delta K_s}{K_s} = \frac{\Delta h_1}{h_1} + \frac{\Delta h_2}{h_2} + \frac{\Delta t}{t} + \frac{\Delta l}{l} + \frac{\Delta A_s}{A_s} + \frac{\Delta A_p}{A_p}$$

where:
ΔK_s = error in conductivity measurement;
$\Delta h_{1,2}$ = error in standpipe readings;
Δt = error in time measurement;
Δl = error in measurement height of sample;
ΔA_s = error in measurement surface area sample;
ΔA_p = error in measurement surface area standpipe.

The magnitudes of these errors depend on the equipment. When proper equipment is used, the error in conductivity measurement is less than 0.1%. All the errors mentioned are system errors. Sampling procedures and homogeneity of the sample will also influence the measurement outcome. Using representative, homogeneous, and undisturbed samples is a prerequisite for getting reliable and reproducible results.

Report

Report by the presentation of the results:
- name (sampling and measurement);
- sample location(coordinates if possible);
- date of sampling and date of measurement;
- vegetation;
- profile description (see Manual 1);
- sample depth;
- exture and density of the sample (included determination method);
- time of saturating the soil sample;
- list of instruments and apparatus;
- results of the measurements of the flux, time, surface and heigth of the sample;
- results of the successive measurements of the conductivity;
- temperature during determination;
- other for the evaluation of the determination important remarks (weather during sampling, initial moisture content, root canals etc.).

Notes

This method is also suitable for conductivity measurement in artificial layers, used for instance as impermeable layers underneath a dump. Measurements on this material will take at least three months and samples have to be made artificial instead of taken in the field. Measurements on artificial samples differ from measurements on soil samples in the following way:

- The height of the artificial sample might be smaller; use high conducted material to fill up the sample ring.
- For calculating K_s use a period of constant decrease of the logarithm of the water level in the standpipe. Due to changes in atmospheric pressure, these values will oscillate around a linear function. Determine h_1 and h_2 within the period of constant decrease and calculate K_s, using the mentioned equation.
- This calculation procedure introduces more error terms, such as the accuracy of the determination of the linear function (regression analysis) and the determination of the period of constant decrease.
- By the presentation of the results, also the atmospheric pressure and its influence on the measurement have to be reported.

Literature

Klute, A. (ed.), 1986. *Methods of soil analysis, Part 1, physical and mineralogical methods, 2nd ed.* Agronomy 9 (2). American Society of Agronomy. Madison, Wisconsin.

6 Determination of the unsaturated hydraulic conductivity using the drip infiltrometer method

J. Stolte

Subject

A steady state laboratory method is described for measuring the unsaturated hydraulic conductivity of soils.

Application

Many soil-water flow problems require knowledge of the unsaturated soil hydraulic conductivity. The method which is described is only suitable for undisturbed, homogeneous soil samples. The pressure head of the measurement ranges from h = - 1 cm to maximal h = - 100 cm.

Expression and definition

Hydraulic conductivity characteristic: The relation between soil water conductivity K (cm.d^{-1}) and the pressure head h.

Principle

A saturated soil sample is placed on a sandbox with an overflow-system. A flux, lower than the saturated conductivity of the sample, is applied to the sample, using a pump and a device with needles on top of the sample. At least two tensiometers are used to monitor the pressure head in the soil sample. The infiltration rate, together with the pressure head gradient is used to calculate the unsaturated conductivity.

Time

The time of the determination depends on the soil type. To saturate the soil sample takes minimal 2 days (sand) and maximal 4 weeks (clay). The determination takes minimal 2 weeks.

Materials

- Stainless steel sample rings with a diameter and height of about 20 cm.
- Perspex lid fitting the sample ring. The lid contains a large number of evenly spread, hypodermic needles.
- Tensiometers with length of 8.5 cm and diameter of 2 cm.
- Pressure transducer.
- (Pulsation) pump, with a capacity of at least 0.1 up to 300 cm/d.
- Stopwatch.

Procedures

Preparing soil samples

Take in the field as little as possible disturbed, homogeneous soil samples (see Manual 1).

Install, in the laboratory, at least two tensiometers in the soil sample: one at 5 cm under the top of the sample and one at 15 cm under the top. Connect the tensiometers to a pressure transducer.

✓ For installing, de-airing and connecting tensiometers see Manual 2.

✓ For de-airing pressure transducers see Manual 3.

Saturate the sample in the laboratory by placing the sample on a cloth-covered perforated plate in a tray of at least 25 cm height, containing 5 cm of water. Increase the water level in the tray daily until the upper rim of the sample is reached. The step size of the increase in water level depends on the soil type. Two steps (days) may be sufficient for sand, but it is better to saturate the samples more gradually (5 steps in 5 days).

✓ This is the same procedure as described in Manual 4 'Determination of the saturated hydraulic conductivity'. It is recommended to determine first the saturated hydraulic conductivity followed by the unsaturated hydraulic conductivity of the soil using the same soil sample.

✓ Another way of saturating the sample is to place it first on the sand box and connect the outflow of the sand box on a supply barrel with water. Set the level of the water in the barrel at desired height (most of the times this will be equal to the bottom of the sample). Notice that in this way the sample will not be saturated thoroughly.

Place the sample without the cloth-covered perforated plate on a sand box.

✓ The sand box must be saturated.

Testing needles

Test the needles by starting the pump and check the outflow of each needle. Use a stand with test-tubes. Replace a needle if the outflow differs more than 25% of the mean outflow of all the needles.

Seeking initial settings

Put the perspex lid on the sample and start with a pump setting that produces a flux which is a little smaller than the saturated conductivity of the sample. Set the overflow under the sandbox just under the bottom of the sample. Wait for about 15 min. and look if water ponds on the top of the sample or in the

sandbox. Adjust the pump setting and/or overflow system in such a way that no ponding of water occurs.

Adjusting overflow

To avoid large errors in calculation of the mean absolute value of the pressure head, the difference between the two measured pressure heads of a layer must not become larger then the difference in height of the two tensiometers. Adjust the overflow level if necessary.

✓ This is an arbitrary limit. More investigation is needed.

Starting measurement

Register the pressure head and wait for steady state.

✓ Steady state is reached when each tensiometer reads constant values for one day (i.e., deviation is within 10% of the mean value).

If the pressure head is lower than -5 cm for all the tensiometers, apply a larger flux on the sample. Record the flux. This can be done by using a buret connected to the supply vessel (see Figure 5.1).

✓ The time between the two measurements of the vessel level depends on the given accuracy of the measurement. In a buret of 100 cm^3 the total reading-error is maximal 0.24 cm^3. This implies that if a 1% measurement error is acceptable an outflow volume from the buret of at least 24 cm^3 is needed.

Note the flux, gravitational head and pressure head for every tensiometer.

Continuing measurement

Repeat the procedure as above with a pump setting that produces a lower flux until the conductivity gets lower than 0.1 cm/day or until the pump limit is reached.

✓ At a conductivity < 0.1 cm/day the system errors become significant. This can be errors like leakage along the tensiometers, evaporation out of the tubes, flow of water along the sides of the sample etc.

End of measurement

Stop the pump and disconnect the tensiometers with the pressure transducer and remove them from the sample.

✓ Clean the tensiometers with hot water and put them, to avoid algae growth, in a container with dry sand.

Remove the perspex lid of the sample and clean it. Lift the sample from the ceramic plate.

✓ If the sample will not be used for other purposes it can be discarded.

Set up

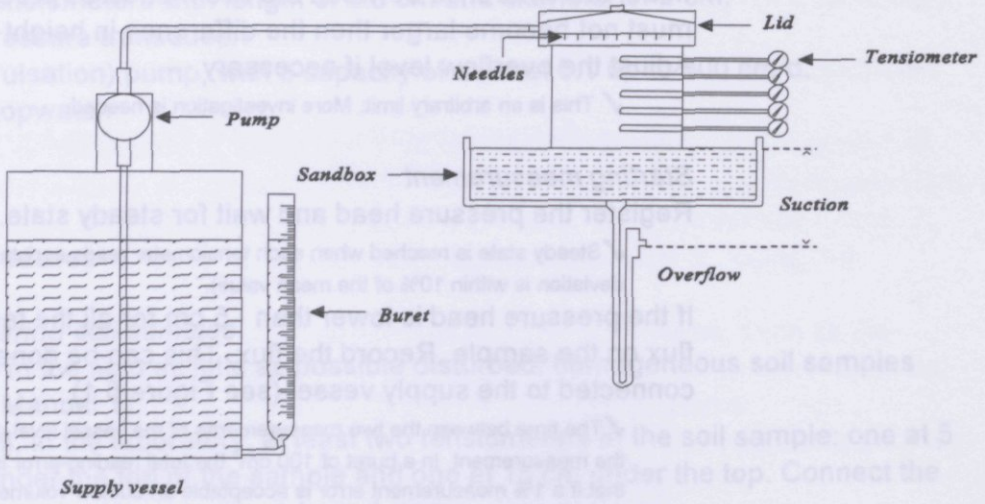

Figure 6.1. Set up of the dripinfiltro meter method.

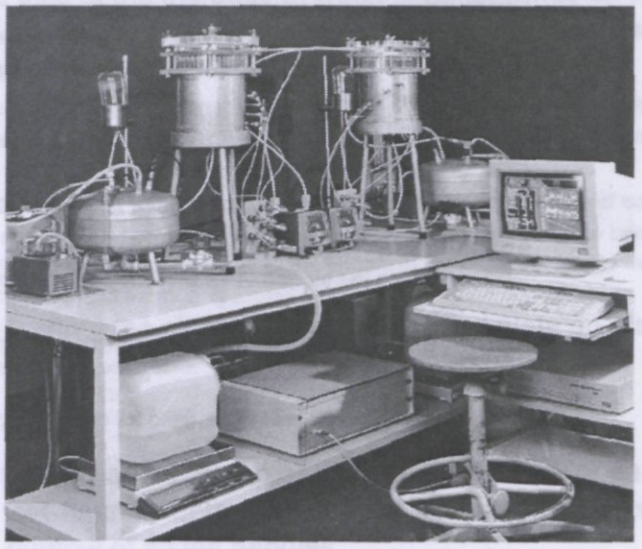

Figure 6.2. A fully automated set up in duplicate of the drip infiltrometer. The set up is present at the DLO Winand Staring Centre.

Calculation

The unsaturated conductivity can be calculated with Darcy's law:

$$q = -K(h)\left(\frac{dh}{dz} + 1\right)$$

where:

$K(h)$ = unsaturated conductivity (cm/day);
q = flux density (cm/day);
dh/dz = pressure head gradient (-).

The flux density can be calculated from:

$$q = \frac{V}{t \times A}$$

where:

V = volume of water (cm^3) that has flown out during time t (days) through a cross-sectional area A (cm).

The pressure head gradient can be calculated from the measurements of the hydraulic head. The $K(h)$ can then be calculated. The matching h - value can be established from calculating the geometrical mean of the two corresponding pressure head measurements.

✓ By using tensiometers the hydraulic head is measured. This value have to corrected with the gravitational head to derive the pressure head.

$$\bar{h} = \sqrt{h_x \times h_y}$$

where:

$\bar{h}$ = mean pressure head (cm);
h_x = pressure head tensiometer x (cm);
h_y = pressure head tensiometer y (cm);

Accuracy

The accuracy of the measurement of the flux density q depends on the accuracy of the buret readings and the time and surface area measurements.

The error in q can be determined as follows:

$$\frac{\Delta q}{q} = \frac{\Delta V}{V} + \frac{\Delta t}{t} + \frac{\Delta A}{A}$$

where:

Δq = error in flux density measurement;
ΔV = error in volume measurement;
Δt = error in time measurement;
ΔA = error in surface measurement;

✓ When working accurate and using accurate instruments the relative error in time and surface area measurements will be negligible (< 0.1%). The relative error in flux density measurement will be mainly caused by error in buret readings. This relative error becomes smaller if the volume of water added to the sample becomes larger.

The accuracy of the determination of the conductivity $K(h)$ depends on the accuracy of the flux density measurement and on the accuracy of the measurement of the pressure and gravitational head.

The error in conductivity can be determined as:

$$\frac{\Delta K}{K} = \frac{\Delta q}{q} + \frac{2\Delta z}{z_y - z_x} + \frac{2\Delta h + 2\Delta z}{(h_y - h_x) + (z_y - z_x)}$$

where:

Δk = error in conductivity measurement;
Δq = error in flux density measurement;
Δh = error in pressure head measurement ;
Δz = error in measurement position of the tensiometers;
h_x = measurement pressure tensiometer x (cm);
h_y = measurement pressure tensiometer y (cm);
z_x = position tensiometer x (cm);
z_y = position tensiometer y (cm).

✓ The error in measurement of the position of the tensiometer is hard to distinguish because of the hydraulic circumference of the tensiometer. The best place to measure is the centre of the tensiometer. The error in pressure head measurements depends on the kind of pressure transducer that is used. A pressure transducer with a range of 0 till - 100 kPa will have another accuracy than a pressure transducer with a range of 0 till - 10 kPa.

Other errors occur in determination of the mean pressure head $\bar{h}$. The first error is the measurement error of h_x and h_y. Additionally the way of taking the mean of the pressure heads adds to the uncertainty. This last error can not be quantified.

The sampling and homogeneity of the sample itself also influence the accuracy of the determination. Using representative homogeneous and as little as possible disturbed samples is a prerequisite for getting reliable and reproducible results.

Report

Report by the presentation of the results:
- name (sampling as well as determination);
- sampling location (coordinates if possible);
- date of sampling and date of determination;
- vegetation;
- profile description (see manual 1);
- sample depth;
- texture and density of the sample (and method of determination of the texture);
- time of saturating the soil sample;
- number of needles;
- list of instruments and apparatus;
- results of the measurements (flux density, time, surface, height sample, tensiometer values as well as the buret readings);
- the K - values, including maximum and minimum value (error analysis);
- temperature during measurement;
- other for the evaluation of the determination important remarks (wether during sampling, field moisture, root canals etc.).

Notes

- A wetting branch of the $K(h)$ curve will be obtained if one starts with a relatively dry sample and if the pump settings are increased rather than decreased.

- The drip infiltrometer method is an example of an infiltrometer method. Other examples are the crust method (Booltink, H.G.W., J. Bouma and D. Giminez, 1991. *A suction crust infiltrometer for measuring hydraulic conductivity of unsaturated soil near saturation.* Soil Sci. Soc Am. J.: 55:566-568.) and spray infiltrometer (Dirksen, C. And S. Matula. 1994. *Automatic atomized water spray system for soil hydraulic conductivity measurements.* Soil Sci. Soc. Am. J.: 58:319-325).

- At the DLO Winand Staring Centre a fully automated version of the drip infiltrometer is available (Fig. 6.2). A computer programme is controlling the set up decisions about e.g., steady state. This accelerates the measurement and is less laborious.

Literature

Burke, W., D. Gabriels and J. Bouma (ed.), 1986. *Soil Structure Assessment.* A.A. Balkema, Rotterdam/Boston.

Dirksen, C., 1990. *Unsaturated hydraulic conductivity.* In: K.A. Smith and C.E. Mullins (eds), Soil analysis, physical methods. Dekker, New York/Basel/Hong Kong

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7 Determination of the unsaturated conductivity and water retention characteristic using the Wind's evaporation method

J.M. Halbertsma and G.J. Veerman

Subject

This manual specifies a laboratory method for simultaneous determination of the unsaturated hydraulic conductivity and the soil water retention characteristic of an initial saturated soil sample.

Application

The soil water retention characteristic and the unsaturated hydraulic conductivity are important parameters for predicting soil water flow, using numerical models. The range of the determination of the conductivity depends on the soil type. It lies between pressure heads of approximately h = -50 cm to h = -700 cm. The range of the determination of the water retention characteristic lies approximately between h = 0 cm to h = -800 cm. The method is only applicable to measurement of the drying or desorption curve. Application of the method is restricted to soil samples which are presumed to be homogeneous.

Expression and definition

Soil water retention characteristic: The relation between pressure head h (cm) and soil water content θ ($cm^3.cm^{-3}$).

Hydraulic conductivity characteristic: The relation between soil water conductivity K ($cm.d^{-1}$) and the pressure head h.

Principle

Samples of soil are taken undisturbed from the field. The soil samples are first wetted to near saturation in the laboratory. Then during the experiment each sample is allowed to dry by evaporation from the top surface. Pressure heads are measured at different depths in the sample, using tensiometers. At known times the decrease of the mass of the sample and the pressure heads are recorded. The experiment ends when air enters the uppermost tensiometer. After drying the sample, its water content during the experiment is calculated. The duration of the experiment is dependent on the soil texture and can take a

few days to two weeks. The sample is regarded as two or more imaginary compartments above each other, as illustrated in Figure 7.1. The water content of each compartment is estimated from the water content of the whole sample and the tensiometer readings. From these data the water retention characteristic and the unsaturated hydraulic conductivity are calculated, using an adaptation (Halbertsma and Veerman, 1994) of Wind's evaporation method (Wind, 1968). The method assumes that the soil sample is homogeneous in its hydraulic properties and assumes one-dimensional flow.

Time

The time of the determination depends on the soil type. To saturate the soil sample takes at least two days (sand) and at most four weeks (clay). The experiment lasts approximately two days for clay and two weeks for course sand. Processing the data, using the Metronia program set on an IBM-compatible personal computer, will take a few hours.

Materials

- Equipment for sampling undisturbed soil samples. The dimensions of the soil samples are dependent on the soil type and the purpose of the investigation. The height of the samples shall be smaller than or equal to its diameter, to prevent the acquisition of redundant data. In most cases a height of 8 cm and a diameter of 10 cm are suitable for non-stony soils.
  - ✓ Usually metal or plastic sleeves with known dimensions are used together with equipment to push the sleeves into the soil. Usually the sampling sleeves are used to retain the sample throughout the experiment and therefore it is necessary to pre-drill holes for the tensiometers. Cover these holes on the inside of the sleeve with thin plastic tape to avoid problems during saturation of the samples.
- Container and hydrophilic polyamide mesh to saturate the soil samples.
- Balance, capable of weighing to within ± 0,1% of the mass of the soil sample.
  - ✓ A balance dedicated to a sample for the duration of the experiment is preferable to reduce possible disturbances.
- Tensiometer system, capable of measuring heads with an accuracy better than ± 1 cm. The lengths of the tensiometers shall be smaller than half the diameter of the sample. The diameters of the tensiometers shall be smaller than 5% of the height of the sample.
- Equipment to install tensiometers, i.e. an auger, or similar device, of suitable dimensions to bore holes into which tensiometers fit closely, and materials to effect a seal between the sleeve and tensiometer.
- Drying oven, capable of maintaining a temperature of 105 ± 5 °C.
- The Metronia program set and an IBM-compatible personal computer with the DOS operating system.

Procedures

Preparing soil samples

Take samples with as little disturbance as possible (Manual 1). Place a circle of mesh, or similar hydrophilic close woven material, at the bottom of the sample. Secure the mesh with an elastic band or similar and place the sample on a supporting sheet. The mesh and sheet will retain the soil sample. Place the sample in a container for wetting (the term sample refers to the soil in a sleeve with its retaining mesh). Wet the sample gradually from the bottom to prevent air entrapment. Set the water level in the container equal to or lower than the base of the sample. Ensure good contact between the mesh and water to enable wetting by capillary rise. Wait until it is apparent that the soil at the surface of the sample is moist. Depending on the soil type, raise the water level after one or two hours (sand) or a day (clay). Increase the water level gradually (in 5 steps) until 0,5 cm below the top of the sample. Maintain this level for at least one day. Set the water level just under the base of the sample and let it drain. Remove the sample from the container, when the drainage appears to be complete. Check the height of the sample and report any changes.

✓ The structure of some soils is not stable under saturated conditions. Such soils should not be completely saturated. They may be wetted either by placing them in a container in which the water level is maintained at the base of the sample, or by use of a suction table.

Seal the bottom and sides of the sample in a way that water can only evaporate at the top. Seal the top while the tensiometers are installed and until the beginning of the experiment. The sample is regarded as two or more compartments above each other (see Fig. 7.1A). The sample comprises as many compartments as it has tensiometers. Use compartments of equal height or use compartments which decrease in height towards the top of the sample. For instance, four tensiometers could be installed at 1, 3, 5 and 7 cm depth in a sample 8 cm high. The four compartments are each 2 cm high, see Fig. 7.1A.

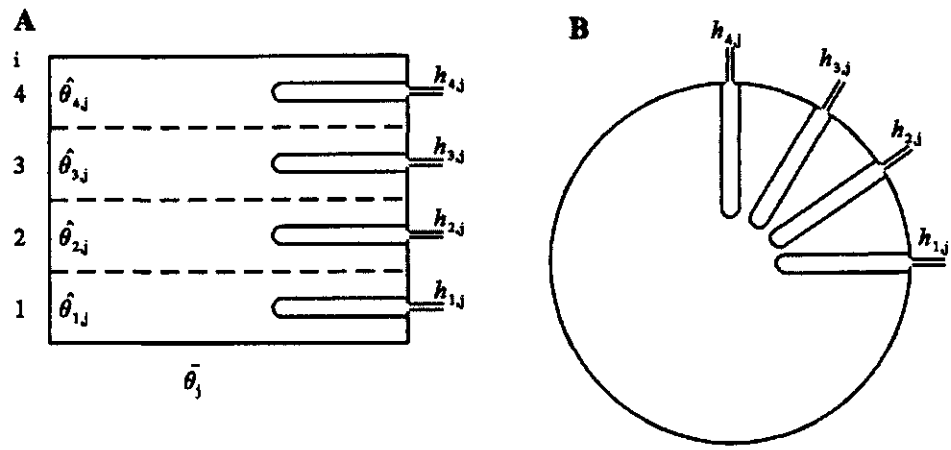

Figure 7.1. Schematic overview of the sample with compartments and tensiometers. A: side view; B: top view.

De-air and test the tensiometers (Manual 2).

Bore a close-fitting hole for a tensiometer into each compartment using an auger or similar device. This enables a smooth installation, minimum disturbance and a good contact between the soil and the porous tensiometer cup. Install the tensiometers horizontally in each compartment and in such a way that their vertical projections do not intersect (see Fig. 7.1B). Arrange the set up so that the vertical position of the tensiometers is in the middle of the hypothetical compartments. If applicable, seal the gap between tensiometer and sleeve to prevent evaporation.

Starting measurement

Record the temperature and humidity during the measurements.

✓ The measurements are preferably performed in a room with constant temperature and humidity.

Put the sample on a balance. Connect the tensiometers to a read-out unit (see Manual 3), if applicable. Let the sample and tensiometers equilibrate. Determine the hydraulic equilibrium by measuring the hydraulic heads and start the experiment when the hydraulic heads of all the tensiometers are equal to within ± 1 cm. Commonly this situation is reached after several hours. The mechanical contact between equipment on the balance and other parts of the set up (e.g. tubing or signal and power cables) influences the measured weight of the sample. Make sure that this mechanical contact is as small as possible and invariant during the experiment. Allow evaporation from the top of the sample. Determine the total mass, m_j (j = 1,..., number of measurements), the pressure heads, $h_{i,j}$ (i = 1,..., number of tensiometers) and time, t_j. Repeat the measurements regularly, for instance every 2 h. The maximum time between measurements shall not exceed 8 h.

End of measurement

The experiment ends when air enters the uppermost tensiometer. Usually this happens between h = -800 cm and -900 cm. If air causes problems at higher pressure heads, replace the tensiometer. Wet or saturate the sample again and restart the experiment. Determine the total mass of the soil sample at the end of the experiment, m_e. Dry the soil to constant mass at 105 °C and determine its water content, $\overline{\theta}_e$.

✓ Usually 24 h drying is sufficient.

✓ It is necessary to convert the measurements to hydraulic heads, when hydraulic pressures are measured. A conversion table may be used to convert the pressure reading to a pressure expressed in cm H_2O. Convert the latter pressure reading to a head reading in cm by multiplying by 1. If the pore water pressures are measured directly, the conversion of the Metronia programs can be used (see Calculations).

✓ It is necessary to calculate the pressure heads if the tensiometer system measures the hydraulic heads (e.g. the set up of Fig. 7.2). Use the following equation to calculate the pressure heads:

$$h_{i,j} = h_{h,i,j} - h_{g,i}$$

where:

$h_{i,j}$ = pressure head of tensiometer i of measurement j, in cm;
$h_{h,i,j}$ = hydraulic head of tensiometer i of measurement j, in cm;
$h_{g,i}$ = gravitational head of tensiometer i, in cm;

Note that $h_{g,i}$ is the vertical distance between tensiometer i and an arbitrary reference level. The reference level can be set by adjusting the read-out unit to zero and measuring at the same time the hydraulic head of free water at the same height as the reference level. For every tensiometer, $h_{g,i}$ is given by the vertical distance from the reference plane to tensiometer i.

Set up

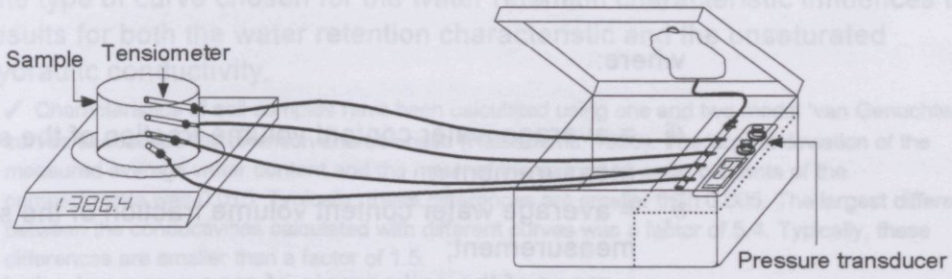

Figure 7.2. Set up of Wind's evaporation method (manual method)

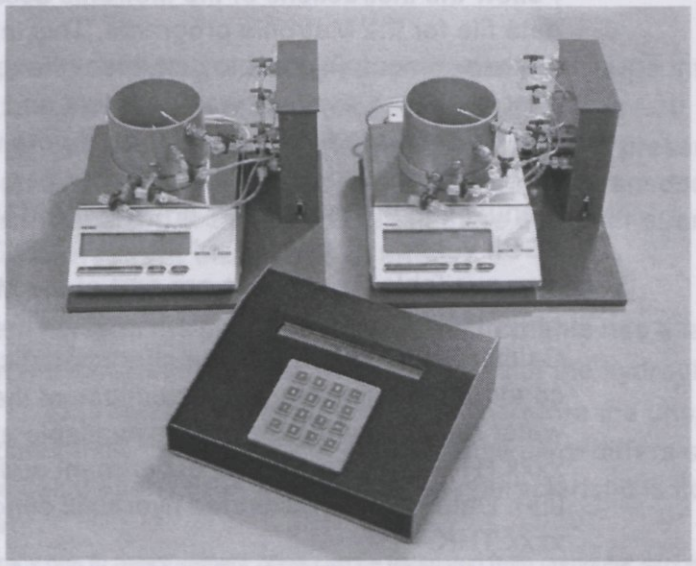

Figure 7.3. Automatic version of Wind's evaporation method, developed at the DLO Winand Staring Centre. Measurement data are stored using a data-logger.

Calculation

Correct the volume of the soil sample by subtracting the volume occupied by the tensiometers. Calculate the average water content, $\bar{\theta}_e$, as a volume fraction of the whole soil sample at the last measurement (end of the experiment).

Calculate the average water content as a volume fraction of the whole soil sample of measurement j using the equation:

$$\bar{\theta}_j = \frac{m_j - m_e}{\rho_w V} + \bar{\theta}_e$$

where:

$\bar{\theta}j$ = average water content volume fraction of the soil sample of measurement j;
$\bar{\theta}_e$ = average water content volume fraction of the soil sample at the last measurement;
m_j = mass of the soil sample of measurement j, in kg;
m_e = mass of the soil sample at the end of the experiment, in kg;
ρ_w = density of water, in $kg.m^{-3}$ ($\approx 1000\ kg.m^{-3}$);
V = corrected volume of the soil sample, in m^3.

Calculate the water contents for all measurements.

Follow the instructions of the Metronia user's manual to make an experimental data file for the Metronia programs. This input file contains (i) identification of the experiment, (ii) data to document the experiment and soil sample and (iii) a table of time, average water content and pressure heads. Pressure heads can be expressed in mm, cm or m. If pore water pressures are measured, they can be expressed in Pa, kPa, mbar or bar. A copy of the Metronia user's manual can be obtained by printing file MANUAL.PS on a postscript printer. An ASCII version of the manual (MANUAL.TXT), with a limited character set is also available. These files are part of the Metronia program set.

Calculate the water retention characteristic and the unsaturated hydraulic conductivity following the instructions of the Metronia user's manual. The water retention characteristic is available as a curve and as a table (file xxxx.HT, where xxxx is the experiment code specified in the experimental data file). Data of the unsaturated hydraulic conductivity can be found in file xxxx.THK.

✓Hydraulic conductivities cannot be measured accurately in the wet part of the unsaturated hydraulic conductivity characteristic, due to small gradients in the hydraulic head ($\approx$ 0). The results obtained with this method can be supplemented with measurements of the saturated hydraulic conductivity and near saturated hydraulic conductivity.

✓Program KHTH uses an threshold for the gradients in the hydraulic head. A default value of 0.24 cm is used for sd(h) to calculate this threshold. Set a lower or higher standard deviation of h. depending on your experimental situation.

✓The measurements of (i) the water retention characteristic (file xxxx.HT) and the combined measurements of (ii) the saturated, (iii) the near saturated and (iv) the unsaturated hydraulic conductivities (file xxxx.THK) can be described conveniently by a van Genuchten curve (Van Genuchten, 1980, Mualem, 1976).

Accuracy

Several factors influence the accuracy and precision of the results:

- The type of curve chosen for the water retention characteristic influences the results for both the water retention characteristic and the unsaturated hydraulic conductivity.

  ✓ Characteristics of soil samples have been calculated using one and two modal 'van Genuchten' curves to describe the retention characteristic (Halbertsma, 1996). The largest deviation of the measured average water content and the mean of the estimated water contents of the compartments was 0.015. Typically, these differences are smaller than 0.005. The largest difference between the conductivities calculated with different curves was a factor of 5.4. Typically, these differences are smaller than a factor of 1.5.

- The interval between measurements should be longer than 1 h. Shorter intervals lead to a relative increase of the error in the flux densities. This shows as a very high noise level in the calculated conductivities. The measuring intervals should not be longer than 8 h. Averaging data from longer intervals could decrease the accuracy of the conductivity (Tamari, 1992). The accuracy of the retention characteristic is not influenced by the measuring intervals.

- Bias in the pressure head gradient measurements has a large influence on the calculation of K at small gradients of the hydraulic head (≈ 0 or $dh/dz \approx -1$). This error can be caused by systems equipped with a pressure transducer on every tensiometer. Good quality pressure transducers, careful calibration and checking the system biases before and after every determination can reduce this source of error.

- Measurement noise in the pressure head measurements has a large influence on the calculation of K at small gradients of the hydraulic head (≈ 0 or $dh/dz \approx -1$). This can lead to biased results. Therefore the unsaturated hydraulic conductivity can be calculated only when dh/dz differs significantly from -1. The calculation of the water retention characteristic is not sensitive to this noise.

  ✓ The accuracy due to measurement noise can be estimated from computer simulations (see Tmarai *et al.*, 1993). At a given water content of the water retention characteristic, the relative difference between the true and calculated value of the pressure head is smaller than 4% of the true value. After removal of non-significant hydraulic gradients, the inaccuracy of the determination of the unsaturated hydraulic conductivity is bounded by its value divided by 3 and 3 times its value.

- The data originating from the top compartment influences the results more than the data of the other compartments, since the pressure head range of

the top compartment is always larger than the other ones. This can lead to biased results if the sample is not homogeneous or the tensiometer is not placed in the middle of the compartments.

Report

Report by the presentation of the results:
- name (sampling and determination);
- sampling location (coordinates if possible);
- date of sampling and date of determination;
- vegetation;
- profile description (see manual 1);
- sampling depth;
- texture and density of the sample (and method of determination of the texture);
- saturation time of the soil sample;
- total measurement time;
- name of data file;
- data listing;
- accuracy of instruments;
- temperature and relative humidity during measurement;
- the method of curve fitting used to describe the water retention characteristic and the criteria to stop the iteration;
- the threshold of the gradient of the pressure head used to discard non-significant gradients in the calculation of the conductivity.
- the method of curve fitting used to describe the the unsaturated hydraulic conductivity, if applicable;
- the results of the determination as tables or curves;
- irregularities during determination (e.g. air in a tensiometer);
- other for the evaluation of the determination important remarks (weather during sampling, field moisture, root canals etc.).

Literature

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8 Determination of the water retention characteristic using the hanging water column

G.J. Veerman and J. Stolte

Subject

A laboratory method is described to determine the water retention characteristic of a soil sample.

Application

Knowledge of the water retention characteristic of a soil is essential for soil- and water management studies, and for soil-water availability for plants. The pressure head of the method ranges from h = - 5 cm to h = - 150 cm. The method can determine an absorption and a desorption water retention characteristic, and can be extended up to - 700 cm pressure head by using a pressure vessel.

Expression and definition

Water retention characteristic: Relation between the pressure head h (cm) and the water content θ ($cm^3.cm^{-3}$).

Principle

An undisturbed soil sample is placed on a saturated porous plate (e.g., glass filter). A step change in suction at the bottom of the plate is induced by lowering a hanging water column (a buret) connected to the plate. The sample is subjected to varying negative pressures and the amount of outflow is measured. At the end of the measurements, water contents at each applied suction are calculated from the buret readings and the final water content.

Time

The time of the determination depends on the soil type. To saturate the sample takes minimal 2 days (sand) and maximal 2 weeks (clay). The determination of

the desorption curve takes at least 2 days (sand) till one week (clay) and of the adsorption at least one week (sand) till more than four weeks (clay).

Materials

- Sample cores, height 7.2 cm and diameter 7.3 cm (volume 300 cm^3).
- Glass filter funnel, inner diameter 90 mm.
- Glass filter, diameter 90 mm, pore size 10 - 16 µm (e.g., Scott Duran porosity number 4).
- Buret 100 cm^3.
- Two-way valve.
- Poly Ethylene tubing 3 mm x 5 mm.
- Stopper that fits the buret (with hole for PE tubing).
- Cover for funnel (with hole for PE tubing).
- Tygon O-ring that fits between cover and glass filter funnel.
- Measuring tape.
- Guide rod for buret.
- Ventilated drying oven.

Procedures

Sampling and preparing set up

Take samples with minimum disturbance (see Manual 1).

✓ If measurements can not be carried out right after sampling, saturate the samples in a tray by capillary rise from below.

Install the apparatus as shown in Figure 8.1. The funnel should be about 2 meters above the floor. One end of a clear flexible PE tubing is connected to the base of the funnel. The other end is connected to a buret. The funnel is connected with the top of the buret to minimize evaporation losses from the system. Make sure that the buret can move along a guide rod. Attach a measuring tape next to the buret. Fill the space under the porous plate, the tubing and a part of the buret with de-aired water.

✓ New or dry glass filters have to be de-aired before use.

For this, disconnect the funnel and tubes from the buret. Disconnect the funnel from the tubes and turn it upside-down. Fill the tubes and the funnel with de-aired water and connect them again. Remove all air in the PE tubing connected to the buret. Connect the funnel with PE tubing to the three-way valve and be sure that no air bubble is left in the system.

Saturating porous plate and sample

Place the sample on the filter. Remove the stopper from the buret (to avoid pressure build-up) and place a cover over the funnel to avoid evaporative losses. Use a rubber O-ring between funnel and cover for an air-tight fit.

✓ Don't use a piece of cloth under the sample to ensure a good contact between soil sample and porous plate.

Pour water in the buret until the water level in the funnel is about 2 cm. Leave the sample to soak for at least two days. After that, pour water in the buret (or directly in the funnel) until water has reached the top of the sample. Leave it again for another two days (sand) to about one week (clay).
Remove the water above the filter by lowering the level in the buret up to 5 cm under the filter. All water above the filter will now flow into the buret. (Or use a syringe to soak the water above the plate). Set the water level in the buret equal to the level of the porous plate. Drain the water from the buret with help of the three-way valve.

Starting measurements

Adjust the buret until the water level is at 1.4 cm below the bottom of the sample. At a sample height of 7.2 cm the applied pressure then equals -5 cm (half of the sample height +1.4 cm). Water will now flow from the sample in the buret. Re-adjust the buret height to maintain the desired suction as often as necessary and wait for equilibrium. Equilibrium is reached if the level in the buret does not change within 24 h.

✓ Equilibrium is reached when the mass of the sample changes maximal 0.02% a day (I.S.O. standard). That corresponds for a sample size of 300 cm^3 and bulk density of 1.5 $g.cm^{-3}$ to about 1 cm^3. When using a 100 cm^3 buret, this can easily be read from the buret when two successive readings take place after 24 h.

Note the established pressure and the readings of the buret. Then pull the buret downwards until the next desired pressure is reached. Repeat the procedure as written above to establish equilibrium and note the pressure and buret readings. Continue until all desired pressures are established.

✓ Usually the following sequence of suctions is applied: -5, -10, -30, -50, -75, -100, -125 and -150 cm.

✓ The pressure head is set from the middle of the sample.

✓ At a pressure head of h = -5 cm the pressure head at top of the sample is -8.6 cm and at the bottom -1.4 cm.

✓ Be sure to carry out the measurements at constant room temperature.

End of measurements

Determine the final water content of the soil sample at the final pressure head setting by taking the sample out of the filter funnel and dry it at 105 °C until constant mass.

✓ Usually 24 h drying is sufficient.

Set up

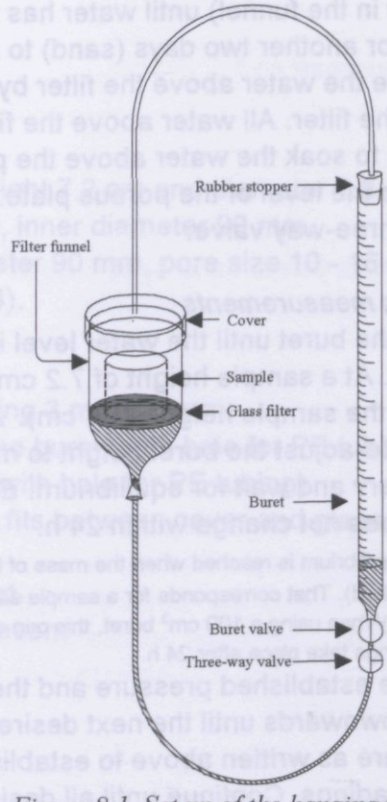

Figure 8.1. Set up of the hanging water column method, shown is the version with capillary.

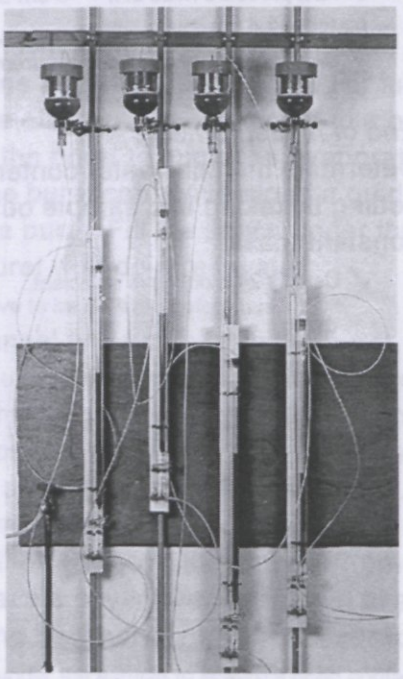

Figure 8.2. Four modules of the hanging water column method.

Calculation

A water retention curve from -5 cm to the final pressure head can be derived by calculating the final water content and adding the outflow, collected in the buret, at the various suctions applied.

The volumetric water content at the final pressure head can be calculated as:

$$\theta_e = \frac{m_e - m_d}{\rho_w \times V}$$

where:

θ_e = volumetric water content at the final pressure head setting ($cm^3.cm^{-3}$);
m_e = mass of the soil sample at the final pressure head setting (g);
m_d = mass of the oven dried soil sample (g);
ρ_w = density of the water ($g.cm^{-3}$), 1 $g.cm^{-3}$ can be assumed;
V = sample volume (cm^3).

Calculate the volumetric water content at a pressure head h according to:

$$\theta(h) = \theta_e + \frac{V_h - V_e}{V}$$

where:

$\theta(h)$ = volumetric water content at a pressure head h ($cm^3.cm^{-3}$);
$\theta(h_e)$ = volumetric water content at the final pressure head ($cm^3.cm^{-3}$);
V_e = buret reading at final pressure head (cm^3);
V_h = buret reading at pressure head h (cm^3);
V = sample volume (cm^3).

Accuracy

The accuracy of the determination of the final water content depends on the accuracy of the measurement of end weight and sample volume. This error is negligible when it is smaller than 0.1% which will be the case if a balance is used with an accuracy of 0.1 g (± 0.05 g) and a callipers rule with an accuracy of 0.1 mm (± 0.05 mm).

The accuracy of the determination of the volumetric water content at pressure head h depends on the accuracy of buret readings, on judging the equilibrium situation and of the determination of the volume of the sample. The error in determination of the water content is:

$$\frac{\Delta\,\theta(h)}{\theta(h)} = \frac{\Delta\,\theta_e}{\theta_e} + \frac{\Delta\,V_h + \Delta\,V_e}{V_h - V_e} + \frac{\Delta\,V}{V}$$

where:

$\Delta\,\theta(h)$ = error in measurement volumetric water content at pressure head h;
$\Delta\,\theta_e$ = error in measurement final water content;
$\Delta\,V_e$ = error in measurement volume of water at the final pressure head setting;
$\Delta\,V_h$ = error in measurement water volume at pressure head h;
$\Delta\,V$ = error in measurement volume of the sample.

✓ The error in measurement of the last water content is, as said before, negligible.

✓ When using a proper callipers rule the error of measuring the volume of the sample is also negligible.

✓ A buret of 100 cm^3 has a reading error of ± 0.12 cm^3.

The systematical error, made when equilibrium is assumed, is difficult to quantify. Preliminary studies indicate a possible systematic error of at least 2 volume % depending on soil type.

Report

Report by the presentation of the results;
- name (sampling as well as determination);
- sampling location (coordinates if possible);
- date of sampling and date of determination;
- vegetation;
- profile description (see Manual 1);
- sample depth;
- texture and density of the sample (and method of determination of the texture);
- time of saturating the soil sample;
- time of reaching equilibrium (in h);
- the results of the several buret readings;
- the volume of the sample;
- the calculated θ - values including the maximum and minimum value (error analysis);
- presentation of the water retention characteristic as a graph;
- other for the evaluation of the determination important remarks (weather during sampling, field moisture, root canals etc.).

Notes

The method is also suitable for determination of the absorption characteristic. In this case, the same procedure can be carried out, only with a reverse sequence of pressure steps. It is advised to use smaller samples with a height of maximal 2.2 cm, to accelerate the determination.

The measurement range can be extended by using a pressure vessel, connected to the top of the buret. By using a pump, a negative pressure can be established in the vessel. In this case, the pressure under the sample will decrease. The range can be extended up to -700 cm water. Notice that another type of glass filter has to be used with at these pressures.

To prevent algae-grow 5 cm^3 copper sulphate solution (1 g $CuSO_4$ in 100 g 0.1 $mol.l^{-1}$ HCL) can be added to the buret. Remove accumulated dirt under the filter by shaking with coarse sand. The filter can be cleaned by boiling it with concentrated sulphuric acid. Add a few grams potassium bichromate (2 g $K_2Cr_2O_7$ in 100 cm^3 sulphuric acid). This has to be carried out in a fume-cabinet!!! Afterwards, rinse the filter thoroughly with demineralised water.

Literature

Burke, W., D. Gabriels and J. Bouma (ed.). 1986. *Soil Structure Assessment.* A.A. Balkema, Rotterdam/Boston.

ISO/DIS 11274. *Soil quality - Determination of the water retention characteristic - laboratory methods*. ISO, Geneva

9 Determination of the water retention characteristic using the pressure plate extractor

J. Stolte and G.J. Veerman

Subject

A laboratory method is described to determine the water retention characteristic of a soil using high-pressure.

Application

Knowledge of the water retention characteristic of a soil is fundamental to soil- and water management studies and for soil-water availability for plants. The pressure head of the method ranges from
h = - 1000 cm till h = - 16 000 cm. Disturbed soil samples are used.

Expression and definition

Water retention characteristic: Relation between the pressure head h (cm) and the water content θ ($cm^3.cm^{-3}$).

Principle

Air pressure, of more than 1 bar, is applied to saturated soil samples which are placed on saturated, very fine porous ceramic plates. A water filled space below the plate is connected with the outside atmospheric pressure. The water is pressed out of the sample, through the ceramic plate. The determination is stopped after a given time.

Time

The time of the determination for each point of the water retention characteristic is 11 days (sand) till 17 days (clay). This includes saturating the soil samples. To saturate the samples takes minimal 1 day (sand) till maximal 7 days (clay).

Materials

- Pressure plate extractor.
- Cylinder with compressed air (or compressor).
- Reducing valve.
- Collecting beaker.
- Beakers.
- Numbered rings, diameter 3 cm, height 1 cm.
- Small disk.
- Spatula and small spoon.
- Small tray.
- Ventilated drying oven.
- Balance.

Procedures

Preparing soil samples

Put 100 g soil in a beaker. Add water to saturate the sample and stir, but do not mix thoroughly to avoid disturbance of the structure

✓ Write down the sample number and the matching beaker number.

Place a cover on top of the beaker and leave the soil to saturate for 1 day (sand) till 7 days (clay).

Preparing pressure extractor

Saturate the ceramic plate by placing it in an exsiccator and suck until vacuum. Leave the plate for 24 h. Then, fill the space between the plate and the rubber bottom with de-aired water, place the plate in the pressure plate extractor (be sure that no air can enter between the plate and rubber bottom), connect a tube to the drain tube and fill this tube with de-aired water. Hang the tube in a collecting beaker filled with de-aired water. Test the set up on leakage by putting on a certain pressure and close the valve to the air-cylinder. The applied pressure has to remain constant for at least 24 h.

Installing samples

Arrange numbered PVC rings on each ceramic plate. Put wet soil from the beakers in the rings, using the small spoon and spatula.

✓ Write down the sample numbers and corresponding ring numbers

Place on top of the samples a small disk with in water drenched cotton wool to maintain a high humidity in the extractor.

✓ Add a reference sample that has a known water retention characteristic. Use a soil that has higher water contents than the other samples. Often silt loam is used. If the measured water contents of the reference sample does not correspond to the known value, repeat the measurement.

Starting measurement

Close the pressure plate extractor tightly, using the lid and screws. Connect the pressure tube to the extractor. Open the air-cylinder and the valve to the pressure cell. Adjust the reducing valve of the air-cylinder until the desired pressure is reached (check with the pressure gauge). Close the valve to the air cylinder. Re-adjust the pressure every day, if necessary. Stop the measurement after 10 days (irrespective of the soil type).

End of measurement

Open the valve to the pressure cell and the release valve at the end of the pressure line. Turn, when the pressure has gone, the adjusting screw of the gas cylinder out. Remove the lid of the extractor. Put the soil samples with the help of a spatula in numbered and weighed trays and cover them immediately. Weigh the trays again. Dry the samples at 105 °C until constant mass.

- ✓ Remove the covers during drying. Use the same cover for the same tray.
- ✓ Usually 24 h drying is enough.

Weigh after drying the trays with cover and sample again and calculate the water content of the samples. Check the value of the reference sample with the known value. Repeat the measurement if this value does not correspond.

Set up

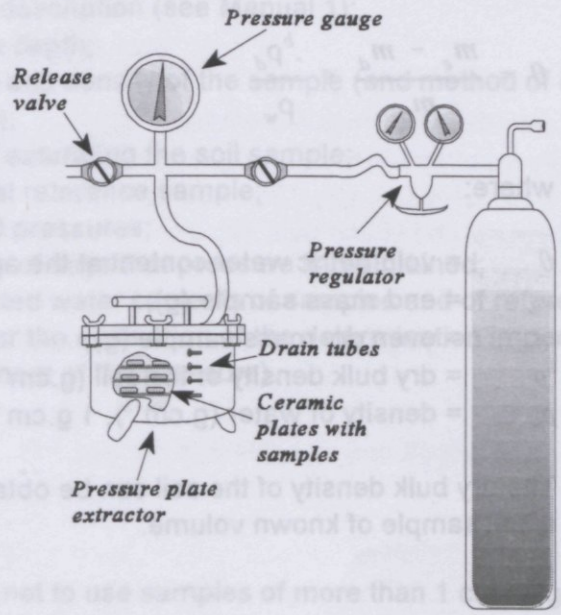

Figure 9.1. Schematic view of the set up of the pressure plate method

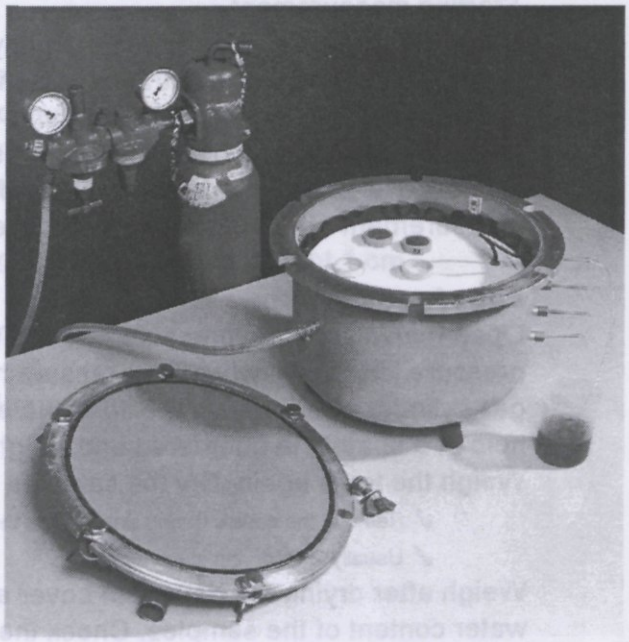

Figure 9.2. Set up of the pressure plate method. An extractor for maximal 5 bar pressure is shown.

Calculation

The volumetric water content of the sample is calculated as follows:

$$\theta = \frac{m_e - m_d}{m_d} \times \frac{{}^{b}\rho_d}{\rho_w}$$

where:

θ = volumetric water content at the applied pressure head ($cm^3.cm^{-3}$);
m_e = end-mass sample (g);
m_d = oven dry mass sample (g);
${}^{b}\rho$ = dry bulk density of the soil ($g.cm^{-3}$);
ρ_w = density of water ($g.cm^{-3}$), 1 $g.cm^{-3}$ can be assumed.

The dry bulk density of the soil can be obtained by taking the oven dry mass of a soil sample of known volume.

Accuracy

The largest uncertainty with this method is to determine when equilibrium has been reached and the measurement can be stopped. At the start of the

measurement water will be pressed out of the samples. After a while still water will come out of the samples, but this is no longer detectable. Water will evaporate through the tubing and out of the collecting beaker. To set a time limit as a boundary condition is a good option to make the measurements reproducible. The value of the measured θ will be a defined value and may not be the real value.

The small sample size may introduce errors. Moreover, disturbed samples are used which make the results hard to interpret. The greatest inaccuracy will occur for clay soils at relatively low pressures. For these soils the soil structure plays an important role in retaining soil-water.

Another error source is that the density of the dry soil mass in the pressure plate will be higher than the density that is separately determined for a less disturbed soil sample.

Report

Report by the presentation of the results;
- name (sampling as well as determination);
- sample location (if possible coordinates);
- date of sampling and date of determination;
- vegetation;
- profile description (see Manual 1);
- sample depth;
- texture and density of the sample (and method of determination of the texture);
- time of saturating the soil sample;
- material reference sample;
- applied pressures;
- number of days that pressure is maintained;
- calculated water contents of samples and of reference;
- other for the evaluation of the determination important remarks (re-adjustment of the pressure).

Notes

It is important not to use samples of more than 1 cm height because equilibrium time will increase correspondingly.
The pressure plate extractor that is shown in Figure 10.1 is only useable for a maximum pressure of 5 bar. Other extractors and pressure cells (using a cellophane membrane) are capable of higher pressures (15 bar). The measurement procedure for these set ups are more or less the same as

described in this manual. The extractors and cells are available at Soil Moisture Equipment Corp., P.O. Box 30025, Santa Barbara, CA 93105, U.S.A.

Literature

Burke, W., D. Gabriels and J. Bouma (ed.), 1986. *Soil Structure Assessment.* A.A. Balkema, Rotterdam/Boston.

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10 Determination of the shrinkage characteristic of clay soil aggregates

J.J.B. Bronswijk, J. Evers-Vermeer and J.J.H. van den Akker

Subject

A laboratory method is described to measure the shrinkage characteristic of clay soils.

Application

Clay soils exhibit swelling and shrinkage as a result of wetting and drying. Swelling and shrinkage has important consequences, for instance the occurence of preferential flow through shrinkage cracks. The present method quantifies the swelling and shrinkage properties of clay soils in the form of the shrinkage characteristic. Computer simulation models for water transport in swelling soils, such as the FLOCR model, require shrinkage characteristics as input.

Expression and definition

Shrinkage characteristic: Relation between void ratio and moisture ratio of soil aggregates. Alternative expressions for the shrinkage characteristic, such as for instance the relation between porosity and volumetric water content of soil, are sometimes also used and can also easily be obtained with the presented method.

Void ratio: The volume of pores of a soil aggregate divided by the volume of the solids (-).

Moisture ratio: The volume of water of a soil aggregate divided by the volume of solids (-).

Principle

A saturated clay soil aggregate is coated with a SARAN F310 coating. The SARAN coating is flexible, impermeable for water, and permeable for water vapour. The coated soil aggregate is subjected to evaporation. Upon drying

and shrinkage of the aggregate, the coating remains tightly fitted around the aggregate. At various times, the weight and the volume of the aggregate are determined by weighing and water displacement, respectively.

Time

The time of determination is about two to four weeks. Application of the SARAN coating takes 2 h. Each determination of aggregate weight and volume takes a few minutes. Data processing to construct the shrinkage characteristic takes one hour per sample.

Materials

Preparation SARAN F310 coating

- SARAN F310 resin (white powder)
  ✓ SARAN F310 is made by DOW chemicals and can be obtained from: Nordmann, Rasmann GMBH & Co., postfach 11 08 93, 20408 Hamburg, Germany (1994).
- solvent: Methyl-Ethyl-Keton (MEK)
- electric mixer
- beaker glass, approximately 8 cm diameter.

Determination shrinkage chracteristic

- SARAN F310/MEK solution
- saturated soil aggregates
- thin cotton wire
- balance (minimum range 1 kg, accuracy 0.01 g)
- stand
- beaker glass with water
- thermometer.

Data processing (optional)

- IBM compatible Personal Computer
- data processing program SHRINK on floppy disk

Procedures

Taking soil samples
Take soil aggregates in the field with a 10 cm diameter Edelman auger, or take the aggregates from the walls of a soil pit. The soil aggregates should have a diameter of 2 to 5 cm. At the time of sampling, the soil should be as wet as possible, preferably saturated. Samples should be stored in plastic bags to

prevent drying, and transported to the laboratory. If the samples are not field-saturated, place them on a saturated sand bed for about two weeks.

Preparation SARAN F310 coating
Prepare the SARAN coating in a fume-cupboard. Put 400 g of MEK in the beaker glass, and put the mixer in the solute. With the mixer on, slowly pour 100 g SARAN in the MEK. After putting all SARAN in the MEK, continue mixing for another 30 min. to remove all possible SARAN clods. The prepared SARAN/MEK solution can be stored in a dark cool place for about one year.

Preparation of SARAN coated soil aggregates
Tie a thin cotton wire around the aggregate to allow future under water weighing. Measure the weight of the aggregates including the wire. Measure the weight of the beaker glass filled with SARAN/MEK. Immerse the soil aggregate briefly into the SARAN/MEK. Repeat the weighing of the beaker glass filled with SARAN/MEK. After 10 to 20 min., when the first SARAN coating around the aggregate is hardened somewhat, measure the weight of the beaker glass with SARAN/MEK again, the soil aggregate is briefly immersed a second time, and the beaker glass is weighed again. The weight of the applied coating is determined from the changes in weight of the beaker glass with SARAN/MEK.

✓ In its standard form, the presented method and the accompanying computer program assume the weight loss of SARAN during the measurement period to be negligible. However, under normal laboratory conditions, the SARAN coatings loses already some weight. To correct for this, a rubber cork can be coated with SARAN and subsequently treated in the same way as the coated soil aggregates. In this way the weight losses from the coated aggregates can be corrected for weight loss from the SARAN.

Determination of weight and volume of the aggregates
Measure the weight and volume of the aggregate at approximately the following times after SARAN application: 1 h, 6 h, 1 d, 2 d, 5 d, 7 d, 9 d, 11 , and so on. If the weight changes of the aggregate have become negligible (less than 1% in 7 days), the aggregate is dried in the oven at 105 °C for 24 h. After oven drying measure the final weight and the volume. Each measurement of weight and volume is conducted in the following way: Measure the weight of the aggregate, including the wire, on the balance. The volume of the aggregate is determined by measuring the weight of the water displaced by the aggregate, according to Archimedes' law (see Fig. 10.1). First, measure the water temperature (0.1 °C accurate). Put the beaker glass with water on the balance. Measure the weight. Hang the aggregate in the water and measure the weight of the water displaced by the aggregate (see Fig. 10.1). Restrict immersion of the aggregates in water to a few seconds to avoid penetration of water into the coating. Especially for oven-dried aggregates, the hazard of water penetration is significant! In the oven, the SARAN coating loses weight. This should be accounted for (see Calculations).

✓ If, after oven drying, the SARAN coating is severely broken, it is advisable to apply a new SARAN coating before measuring the underwater weight. Obviously, weight and volume corrections are required then.

Set up

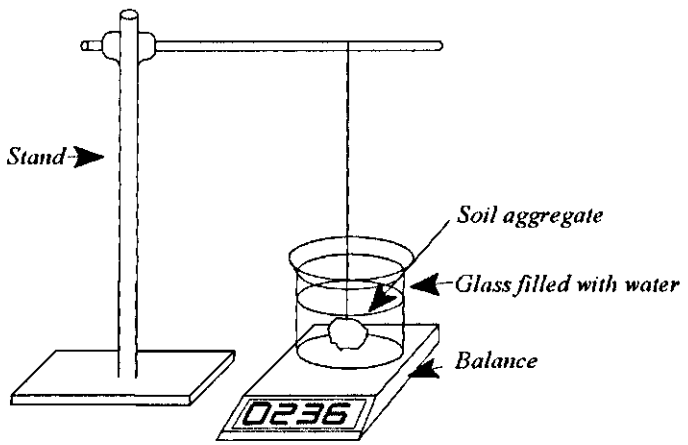

Figure 10.1. Set up of the determination of the volume of a soil aggregate.

Calculations

SARAN coating properties

– Specific density	1.5 $g.cm^{-3}$
– Specific density after oven drying	1.6 $g.cm^{-3}$
– Weight loss during oven drying	0.1 $g.g^{-1}$ SARAN
– Weight loss during hardening	0.4 $g.g^{-1}$ SARAN/MEK solution

Start of experiment:

Measure:

Weight of soil aggregate and wire: *A* (g)

Weight of beaker glass with SARAN/MEK before immersing the aggregate: *B* (g)

Weight of beaker glass with SARAN/MEK after immersing the aggregate: *C* (g)

Compute:

(1) Weight of applied SARAN coating: $0.6 \times (B-C)$ (g)

(2) Volume of applied SARAN coating: $0.6 \times (B-C)/1.5 = 0.4 \times (B-C)$ (cm^3)

Repeated measurements of weight and volume of soil aggregate:

Measure:

Weight of SARAN coated aggregate including wire: *D* (g)

Temperature water: *G* (C)

Weight volume water displaced by aggregate including wire (Figure 10.1)

(is weight beaker glass with water - weight beaker glass with immersed aggregate): F (g)

Compute:

Specific mass of water at measured temperature (from standard physical tables): E ($g.cm^{-3}$)

(3) Volume soil aggregate, SARAN, and wire: F/E (cm^3)

(4) Volume soil aggregate and wire: $F/E - (0.4 \times (B-C))$ (cm^3)

(5) Weight aggregate and wire: $D - 0.6 \times (B-C)$ (g)

When neglecting the weight and volume of the wire, the weight and volume of the soil aggregate follows from (4) and (5):

Weight of soil aggregate (5): *I* (g)

Volume of soil aggregate (4): *II* (cm^3)

Measurement of weight and volume after oven drying:

Measure:

Weight of SARAN coated soil aggregate including wire: P (g)

Temperature water: R (°C)

Weight volume water displaced by soil aggregate including wire (Figure 10.1) (is weight beaker glass with water - weight beaker glass with immersed aggregate): Q (g)

Compute:

(6) Oven-dry weight SARAN coating:

$0.6 \times (B-C) - 0.1 \times 0.6 \times (B-C) = 0.54 \times (B-C)$ (g)

(7) Oven-dry weight soil aggregate and wire: $P - 0.54 \times (B-C)$ (g)

Specific mass of water at measured temperature (from standard physical tables): S ($g.cm^{-3}$)

(8) Volume oven-dry soil aggregate, SARAN, and wire: Q/S (cm^3)

(9) Volume oven-dry SARAN coating: $0.54 \times (B-C)/1.6$ (cm^3)

(10) Volume oven-dry soil aggregate and wire:

$Q/S - (0.54 \times (B-C)/1.6)$ (cm^3)

When neglecting the weight and volume of the wire, the weight and volume of the soil aggregate follows from (7) and (10):

Weight oven-dry soil aggregate (7): *III* (g)

Volume oven-dry soil aggregate (10): *IV* (cm^3)

For each measurement, we can now compute volumetric water content, moisture ratio, etc. using:

Volumetric water content: $(I-III)/II$ ($cm^3.cm^{-3}$)

✓ (specific mass water = 1 $g.cm^{-3}$)

Gravimetric water content: $(I-III)/III$ ($g.g^{-1}$)

Dry bulk density: (III/II) ($g.cm^{-3}$)

Porosity: $(II-III/2.67)/II$ ($cm^3.cm^{-3}$)

Moisture ratio: $(I-III)/(III/2.67)$ ($cm^3.cm^{-3}$)

Void ratio: $(II-III/2.67)/(III/2.67)$ ($cm^3.cm^{-3}$)

✓ For mineral soils, a value of 2.67 for the density of the solid phase is acceptable. For soils rich in organic matter, the real density of the solid phase should be measured and used in the calculations.

The computations can be executed with the computer program SHRINK.

Accuracy

The accuracy of the determination of moisture ratio and void ratio is determined by the accuracy of:

The SARAN properties;
The measured weights of the SARAN coated clods;
The weight of the wire;
The volume of the wire;
The water temperature;
The specific mass of the water;
The specific mass of the soil particles.

Some of these parameters are easily obtained accurately (weights, temperature). Others can only be obtained accurately with relatively great effort (SARAN properties, volume of wire, specific mass of solid particles). The method, as it is presented here, uses standard values for these more difficult to determine parameters. Using error analysis, it can be shown that, in its presented form, the maximum error in void ratio is about ±6% and the maximum error in moisture ratio about ±7%.

✓ If the density of the soil particles, the SARAN properties, and the weight and volume of the wire are measured as accurate as possible, then the maximum error in both void ratio and moisture ratio reduces to about 1%. Below, a summary of the effectivity of various ways to reduce the error in the determination of the void ratio and the moisture ratio is given.

Maximum relative error of moisture and void ratio in various versions of the method

	Optimum value				
	standard method	density solid phase	SARAN properties	W_{wire},V_{wire}	all 3 param.
moisture ratio	0.07	0.07	0.05	0.03	0.01
void ratio	0.06	0.04	0.04	0.04	0.01

From this table it becomes clear that determining the weight (W_{wire}) and volume (V_{wire}) of the wire around the aggregates is most effective in reducing the measurement errors.

Report

Report at the presentation of the results:

- Name (sampling as well as determination);
- Sampling location (coordinates if possible);

- Sampling depth;
- Way of sampling;
- Structure description;
- Land-use;
- Date of sampling and dates of measurement;
- Saturation method (natural or artificial);
- Weight of SARAN coating.

For each measurement date:

- Weight of SARAN coated clod;
- Under water weight of clod;
- Water temperature;
- Computed gravimetric water content, volumetric water content, porosity, moisture ratio, dry bulk density, void ratio.
- Other for the evaluation of the determination important remarks (weather during sampling, root canals etc.).

Notes

Shrinkage characteristics of peat soils can also be measured with the presented method. Peat soils, however, have a density of the solid phase which is lower than 1, and thus float on water. Volume determination through water displacement requires attachment of an extra weight to the aggregate, which makes both the experimental procedure and the computations more complicated.

Literature

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