SOIL WATER DISTRIBUTION

A STATE OF THE ART REPORT

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4. FIELD MEASURING TECHNIQUES

4.1 Classification of methods

In order to facilitate the following presentation of methods for measuring soil water, some words must be said concerning the underlying aspects of approach for these methods. First of all it must be made clear that soil water can be characterized both as regards concentration and as regards energy status. Concentration is generally measured as percent by weight of the oven dry soil or as percent by volume of the soil in its natural state. The energy status of soil water is expressed as a potential, that is as a pressure difference of soil water in relation to some reference, generally atmospheric pressure. The units applied may be those of energy per unit mass or unit volume of soil water. For a given soil media there exists a relationship between the concentration and potential aspect of the soil water. If this functional relationship is known, then it becomes possible to derive the magnitude of one of these aspects from knowledge of the other.

Methods of determining soil water may also be differentiated according to the principle of detection of the water. When the water is determined by direct extraction from the soil medium, the methods are classified as direct methods. Such methods are generally based on sampling techniques and extraction of water from these by physical or chemical means. Methods based on properties of the soil medium or on properties of an object put in equilibrium with the soil that are dependent on the soil water conditions are classified as indirect methods, since it is not the water but some other property affected by the water that is measured. The direct methods involve such techniques as the gravimetric method with oven drying and, less commonly in use today, the pyknometer, densimetric and carbide methods. The indirect methods include the neutron, gamma ray, electrical resistance and capacitance, tensiometric and thermal conductivity methods. It is apparent that for stationary point measurements of soil moisture the direct methods are less convenient because they are elaborate and need sampling for each

moisture measurement. As the samples cannot be taken from exactly the same place, the observations are influenced by sampling errors, the magnitude of which depends on the non-homogeneous nature of the soil.

The indirect methods offer several advantages, especially for stationary point measurements. The measuring devices are permanently built into the soil, or they are inserted into access tubes. The physical quantities sensitive to moisture changes are measured, and the soil moisture is then read from calibration curves. Long-distance registration is possible with most methods. Some devices age during long-term measurement and as a consequence their calibration changes. It is therefore necessary to recalibrate them regularly. As the moisture is not measured directly, it is evident that the measured data will reflect, apart from the changes in moisture, changes in those soil properties which influence the physical quantities measured by the individual methods. The precision of the method then depends on the possibility of either eliminating the influence of these outside factors or determining how constant this influence is. Many physical properties of soils exhibit a hysteresis curve with respect to soil moisture similar to the suction moisture relation, Figure 4:1. If hysteresis takes place, the history of the soil moisture under measurement should be taken into account, which makes the method less useful as a standard type of measurement.

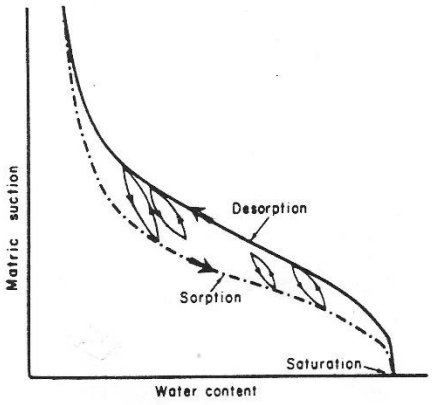


Figure 4:1 Soil water retention curve for state of sorption and desorption with intermediate hysteresis loops. (taken from Hillel 1971)

Apart from the above division, methods may also be divided according to the volume of soil for which the measurement is valid. If the method determines the moisture status in the immediate neighbourhood of the measuring device, the method is designated as a point method. Such are the gravimetric method in the usual system of measurement, the electrical resistance method, most tensiometer methods, and the thermal conductivity and electrical capacitance methods. Some methods determine the average moisture value of a larger volume of soil with a spatial extent of tens or even hundreds of centimetres. Such methods may be termed bulk methods and include the radiometric and lysimetric methods.

Regardless of the type of method applied, it is essential in every instance to determine the moisture in the soil at many test points in the area under examination, because of the high lateral and depth variability of the soil medium. A statistical analysis of the variability of the soil moisture values observed makes it possible to calculate the error of the mean and to find the limits within which the true mean result lies, which can be obtained only by an infinite number of determinations. This analysis of variance makes it possible to determine the number of test points required for solving specific problems.

4.2. Sampling techniques

Most methods involve making a hole either for the removal of a sample or for the insertion of an instrument. In addition, even indirect methods require samples, as they are calibrated with direct methods. Tools for these purposes range from trowels to power augers. A good sampler will allow uncontaminated samples to be taken as quickly as possible from the required depth with minimal damage to the site. Holes made should be filled, but damage to plant roots and the introduction of variable drainage and infiltration characteristics may be unavoidable. Since much replication is needed to characterize a typical experimental site adequately, disturbance is often considerable. These limitations do not apply to in situ methods, since instruments may be installed in a few holes before measurements commence. For some projects samples may be taken more quickly with power tools, perhaps at the expense of more damage to the site.

The main purpose of sampling is to obtain a representative soil sample from the intended soil layer in as undisturbed a state as possible. However, this involves numerous difficulties, while the success of the sampling naturally has a considerable effect on the reliability of the results. The heterogeneity of the soil layer, as well as the moisture status and the sampling method, impose such great restrictions that ideal conditions can hardly ever be reached in practice. Thus, even under the best circumstances, the sample only approximately represents the actual moisture status of the soil and is more or less disturbed. Sampling is especially difficult when the soil is very dry or very wet and when it contains stones, rocks, and other objects which preclude easy cutting using sampling equipment.

The technique and equipment used for sample collection should be such that the samples do not lose or gain moisture, or otherwise become altered or contaminated during sampling and transportation. In sampling through a wet layer into a dry layer, care must be taken to keep the sampling equipment as dry as possible and to prevent water from running down the hole into the drier material. If there is free water in the soil, the measured moisture content will probably be less than the correct value because some water will run off as the sample is being removed from the ground, or some may be squeezed out by compaction during sampling.

When fine-textured sediments are in a dry, hard state, it is difficult to drive the core barrels or to rotate the augers. When dry, coarse-textured sediments are sampled, the sample may slide out of the core barrel or auger as it is withdrawn. Moraine soils are very difficult to sample, especially volumetrically, owing to the danger of hitting stones with the cutting edges of the equipment, and because the representative samples must be large. Soils that contain a considerable amount of roots and organic matter also present difficulties. In soil moisture sampling, it is essential that all sampling operations - the transfer of samples to moisture cans and the weighing of the moist samples - be done as rapidly as possible to prevent undue moisture losses. Many difficulties in the use of sampling equipment, whether augers or core samples, may be overcome if all the equipment is kept clean, that is, free of moisture, oil, rust, and dirt.

Sampling equipment can be divided into two groups: that which takes disturbed and that which essentially takes undisturbed samples. A sampler can take point-like samples of the soil layer or long profile samples. The former are taken for determining the soil moisture status and the latter for studying the vertical moisture distribution. Sampling cohesive soils in their natural state is usually not so difficult. For instance, very long (10-30 m) undisturbed profile samples can be removed from clay with special augers. On the other hand, taking undisturbed samples from non-cohesive soils is often difficult, as has already been shown with regard to moraine soils.

Different kinds of sampling methods have been treated in detail in several soil sampling guide books, for example Statens Geotekniska Institut 1970, Tie-ja Vesirakennushallitus 1970, Kairausopas III (Finnish Auger Guidebook) 1972. There is also a recommendation from the Group on Soil Sampling (IGOSS) of the International Society of Soil Mechanics and Foundation Engineering (ISSMFE) in 1967. Only a few of the most important views will be presented here for consideration when sampling is required for the determination of the moisture status of the soil.

4.2.1. The sampling hole approach

A sample is best obtained from the surface layers of the soil by digging a sampling hole to the depth required for driving a sharp-edged, thin-walled metal cylinder into the undisturbed ground. The cylinder is driven into the soil either by hand or by using levers or, for instance, a pneumatic compressor. Use of an external guiding cylinder is recommended to help drive the cylinder straight into the ground without lateral displacements. The cylinder should not be struck, for the sample may then be disturbed. After careful insertion the filled cylinder is dug up from the soil. Figure 4:2 presents some different ways of taking undisturbed samples from a sampling hole.

The wall thickness of the sampling cylinder is generally 2-4 mm and the sharpening angle of the lower edge 45-60°. The walls must be at least so thick that the cylinder will retain its circular form during all normal handling in the sampling operation. The diameter of the cylinder

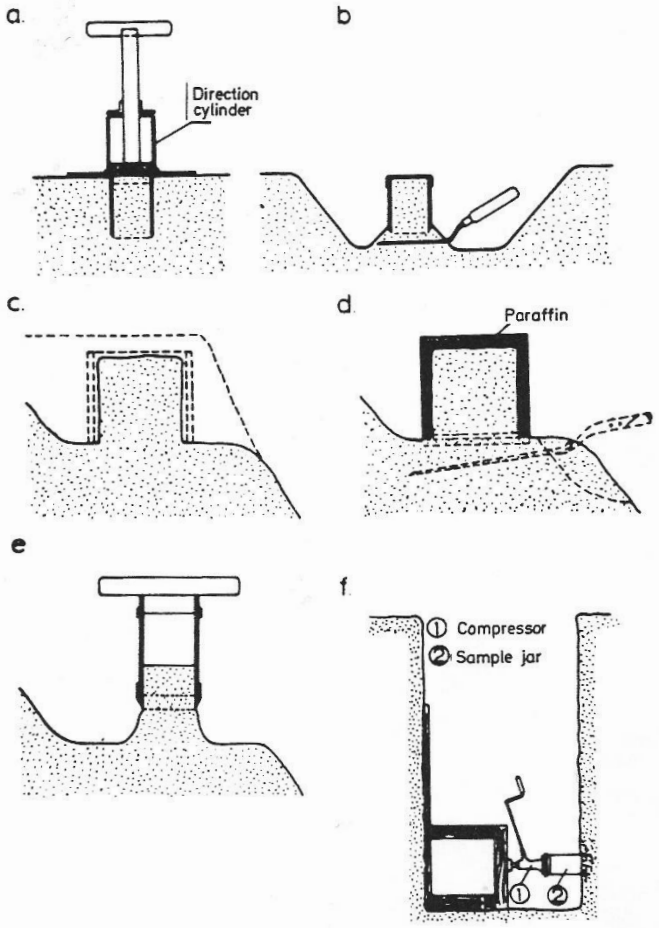


Figure 4:2 Removal of undisturbed soil samples from a sampling hole (soil pit):
a) and b) with a direction cylinder,
c) and d) by carving or moulding out a sample that is impregnated before removal to jar,
e) by using a jar into which a soil sample is moulded,
f) by means of a pneumatic compressor

must be at least 10 cm. The height of the sample depends on the type of soil. Cylinders that are 15-20 cm high can be used in clay or silt soil. In coarse-textured soils the ratio of height to diameter must be smaller than the measurements given above, and thus the height of the cylinder may only be 5-10 cm.

4.2.2. Sampling with piston drills

Sampling from layers at great depths beneath the surface is best done using different kinds of piston drills, which can produce volumetric samples for calculating moisture content on a volume basis. The sampling team generally consists of 2 or 3 men. Depths of down to 20 m can be sampled. The piston sampler is very useful, especially in sampling through loose or wet materials that tend to slough into the hole.

The piston drill is composed of a piston shaft and a sampler at the base of the shaft. The sampler has an open sampling cylinder with a moving drill. The piston's shaft is composed of a tube (case) as a continuation of the cylinder, and a rod as a continuation of the piston. The operating principle of the piston drill, see Figure 4:3, is that the sampler is driven into the ground to the desired depth with the piston in the lower position (at the base of the cylinder) so that it acts as the point of the drilling system. The piston is then kept in place with the aid of the drill rods, while the cylinder is pressed down. The cylinder then fills with soil from below the piston. When the drill is raised, the soil sample remains in the cylinder because of the friction between the inner surface of the cylinder and the sample and the vacuum between the piston and the sample. During the raising, the piston is locked in the upper position and the drill can be raised mechanically with a lifting jack or a tripod. After the cylinder has been emptied and cleaned, the procedure can be repeated to a greater depth. The case can be extended if desired with a metre long pipe and the piston, in turn, with a drill rod of the same length, so that longer samples can be taken.

The piston drill models generally used in the Nordic countries are standard piston drills St I and St II, Norwegian piston drill MN 54 and the foil piston drill. Figure 4:4 shows the piston drills in question.

St I type piston drill (Figure 4:4 a) works in exactly the manner just described. The St II type piston drill (Figure 4:4 b) differs from the principle of the St I in that no casing pipe is used. Instead, the sampler is driven into the ground with a simple handle, for instance with a rammer drill rod. The sampler is composed of two cylinders, one inside the other, the outermost of these acting as the protective cover.

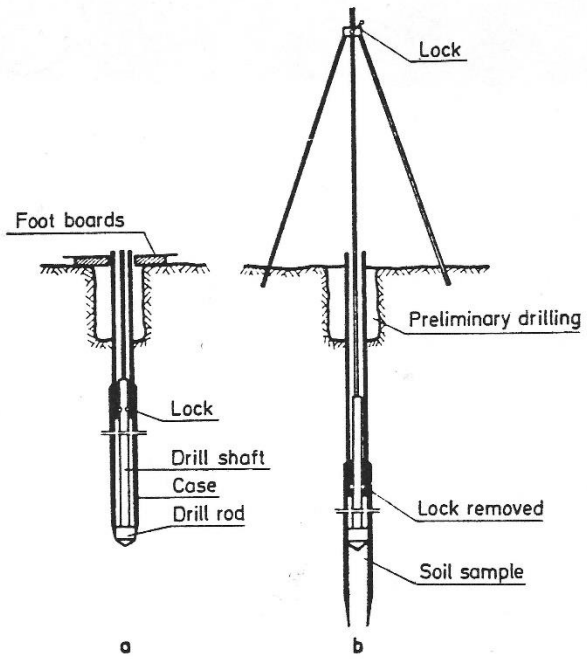


Figure 4:3 Operating principles of the piston drill (TVII 1970)
a) drill driven into the soil
b) filling the drill

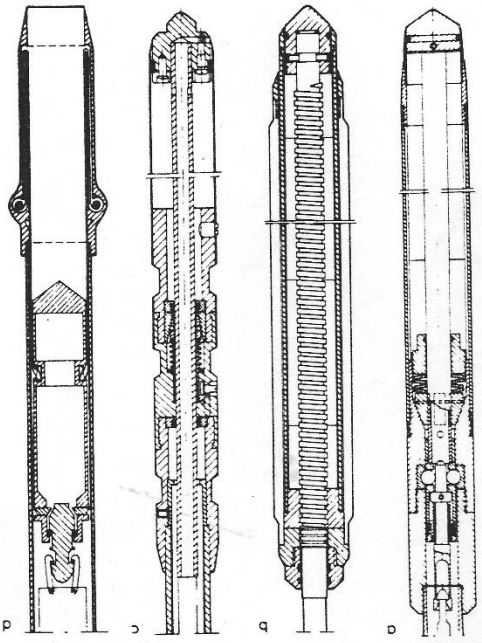


Figure 4:4 Different types of piston drills (Kairausopas II 1970)
a) St I type
b) St II type
c) Norwegian type
d) foil piston drill

The actual sampling process differs from sampling with the St I in that the inner cylinder is driven into the ground by turning the drill rods, while the outer cylinder and the piston remain in place. With both of the St drills the soil sample is driven straight into the sample jars that are contained in the cylinder, measuring 50 mm in diameter and 85 or 170 mm in length.

The Norwegian type of piston sampler (Figure 4:4 c) differs from the Swedish types in that its sample jar consists of only one sample pipe in which the piston moves and which after sampling is removed completely from the sampler. The sample pipe is an unseamed stainless steel pipe, usually 80 cm long and about 50 mm in diameter. The sampler is driven into the ground from a casing pipe. The casing pipe contains rods as extensions of the piston, just as in the St I type drill.

With the above type of ordinary piston drill only relatively short (<1 m) samples can usually be taken. For longer sample lengths the friction between the sample and the sample cylinder becomes so large that the sample is disturbed. For procuring longer uniform soil samples the foil piston drill (Figure 4:4 d) can instead be used. Here the friction between the sample and the cylinder is eliminated by use of metal sheets between the sample and the cylinder. The metal sheets are attached to the locking system at the bottom of the drill in the form of wounded rolls that surround the base of the drill. In sampling, the piston is kept motionless in relation to the soil surface while the piston itself is driven onwards. In this way the sample is pushed into the pipe and at the same time the rolled sheets unwind and surround the sample. When the drill is operated there is no movement between the sheets and the sample. Movement only occurs between the sheets and the interior of the sample cylinder. When the desired sample is in the pipe, the whole drill is raised from the ground and set down in a horizontal position. The sample is pushed out of the pipe with the piston. Even during extraction, the only friction is between the sheets and the interior of the pipe.

4.2.3. Other methods

In addition to sampling from sample holes and with piston drills, there are several other methods which can be used. With the exception of sampling from surface layers, they give disturbed samples which can only give values of water content expressed on a weight basis.

In sampling from surface layers different kinds of cylinder-like core samplers are usually employed. In Finland, for example, a core drill measuring 50 mm in diameter with a removable hard metal point has been used in inorganic soils. When the drill is driven into the ground, the soil sample should fill either the bare cylinder or plastic or fibre-glass jars in the cylinder. A metal sampler made of two steel profiles is used for taking profile samples. One of the profiles is a U-profile and the other a sheet blade made of spring steel which with the U-profile forms a case measuring 30 mm x 40 mm x 100 cm (or x 200 cm depending on the length of the profile desired). The U-profile is first driven or struck into the ground to about 3/4 of its length and then the sheet blade with the sharp point first is driven to the same depth along the open edges of the U-profile. The samplers are then lifted up and with them the profile sample, which is usually fairly disturbed in rough inorganic soil, but less disturbed in clay or silt soils.

For sampling from deeper layers of soil, hand augers attached to weight drill rods are the simplest equipment. The samples thus taken are always disturbed, however. Suitable samplers are, for instance, post-hole, helical and spoon-tipped augers. None of these are suitable for sampling in soft or miry layers or under the ground water level. The tube-like sampling auger of the miniature piston drill, on the other hand, is also suitable for sampling in soft soils. Especially suitable for use in wet and miry soils is the can auger, which is composed of a cylinder-like sampler with handles attached to it. The handles are attached with a special coupling which allows the drill to rotate both clockwise and counter-clock-wise. Samples can also be taken using vibrating, monkey, or spoon type samplers, air pressure and diamond drills and/or by using water and air pressure washing techniques.

4.2.4. Sampling from peat

Sampling from peat poses special problems because of the structure of the peat. For this reason a completely satisfactory sampler is very difficult to develop. Larger samples must be taken from peat than from mineral soils, because of its inhomogeneity and fibrosity. The large water binding ability of peat and its large water permeability have the same effect. Above all, sampling requires effective cutting of the sample from its surrounding soil, because peat fibres can be fairly tough and can easily get packed into the sampler. In this case the sample is apt to be under pressure and its water content will decrease. The water content also changes very easily during other phases of sampling.

Usually, special cylindrical core samplers are used for sampling in peat. For instance, a polyethelene pipe 200 mm in diameter is used in Finland. It has a metal cutting blade with a wavy edge which can be tightened with screws at the lower end and a turning handle attached with wing nuts at the upper end.

A special drill has also been developed especially for peat soils made of a thin-walled cloven steel pipe 120 cm long, with an inside diameter of 94 mm (Figure 4:5). When using the drill, one side is driven into the ground first. When the second side is driven in, the welded guide strips direct it as it presses against the other side. In addition, the blade, which leans inward, helps the two sides to press closely together. This kind of sampling is suitable only for highly decomposed peat, because the point edge of the sampler cuts rather badly since the sampler cannot be turned.

In the newest type of peat samplers special attention has been paid to the construction of the cutting point and to the dimensions of the sampler, as well as to the friction between the peat and the sampler, (Helenelund & Lindqvist & Sundman 1972). Special types of round and square samplers have been developed with various cutting point constructions (Figure 4:6). The round cylinder samplers are 125 cm and 135 cm long, and 150 mm and 250 mm in inside diameter. The square cylinder sampler is 140 cm long and 150 x 150 mm wide. The material

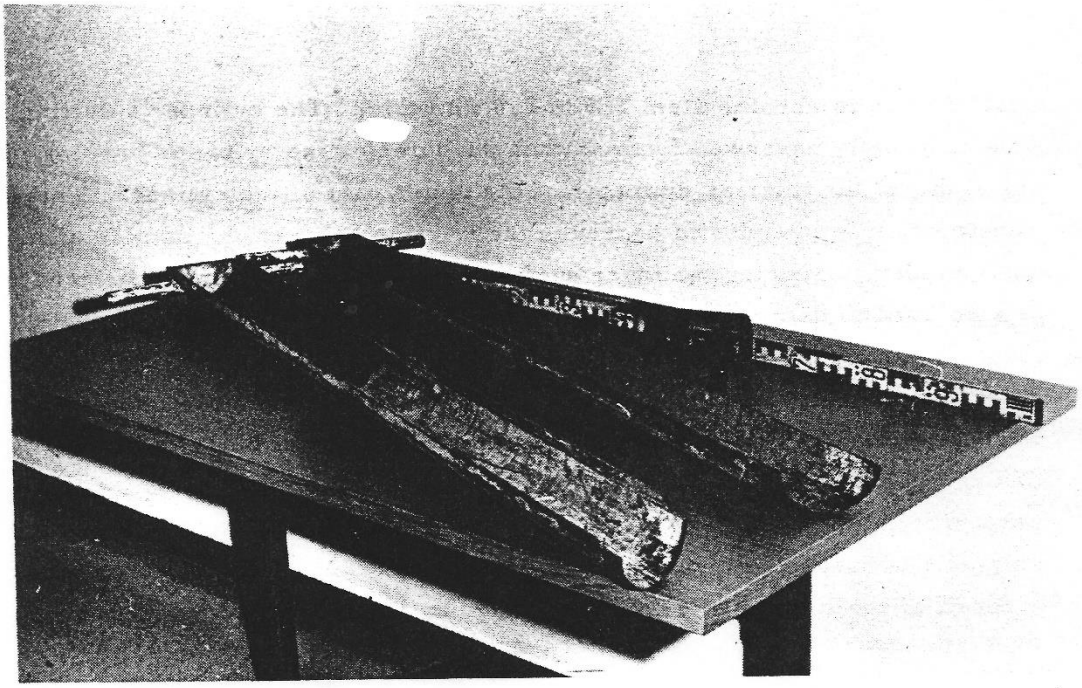


Figure 4:5 A peat-drill made of a cleft steel pipe (Hooli 1971)

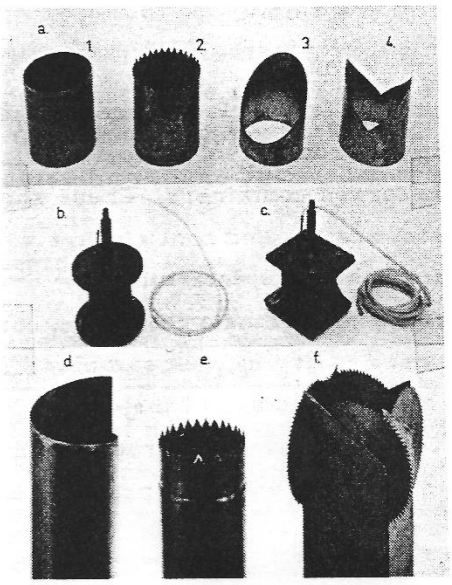


Figure 4:6 Different types of cutting edges and pneumatic pistons for thin-walled samplers used in sampling tests in fibrous peat (Helenelund & Lindqvist & Sundman 1972)

usually used is chrome steel 1,5 to 2,5 mm thick. The cylinder's cutting edge is usually narrowed 5 cm so that the outer diameter of the opening is the same as the interior diameter of the upper part of the cylinder. This construction is intended to decrease the friction between the sample and the cylinder Covering the inner surface with plastic film or a lubricant is also used to decrease friction.

Samples are taken by driving the cylinder evenly into the peat and turning it at the same time to improve the cutting. When the sampler is at the desired depth, a pneumatic piston (Figure 4:6 b, c) is attached to its upper part. The piston is pressed closely against the cylinder's interior surface, using air pressure. The sampler is then raised and the sample with it as a result of the friction and vacuum caused by the piston.

Good results have also been obtained by cutting samples of peat as columns with a long bladed power saw. The columns are cut at the bottom and raised with a special lifting board. Thus a prism-shaped profile sample, which is only very slightly disturbed, is obtained.

4.3 Water content

4.3.1 Gravimetric methods

The gravimetric method is the classic method generally used to calibrate also other methods. (Gardner 1965, Cope & Trickett 1965). Samples are taken and placed in tarred containers. These should be weighed as soon as possible, but careful scaling and cool storage will reduce errors to a minimum. The moisture content is determined by drying the samples at 105°C to a constant weight in a thermostatically controlled oven. Somewhat lower temperatures are used in drying peat samples. The weight of the water lost is expressed as a percentage of the dry soil weight. Sometimes the moisture content is expressed as a percentage of the colume of the original soil sample. The drying and weighing procedures are slow but they may be speeded up by using infra-red or vacuum drying techniques and an automatic balance. Apart from such expensive modifications, the method has the advantage of requiring simple equipment that is commonly available. It is valid for the sample used and, with adequate replication, for the site chosen. The chief disadvantages are those implicit in taking

and handling the samples, and the process is particularly tedious when correction must be made for the variable content of stones and gravel in the samples. The method often involves difficulties connected with following the moisture changes with time and in space. It demands much work and time. Complete drying requires about 24 hours. It is further known that some clay minerals can adsorptively retain water even at temperatures exceeding 105°C.

Other methods have been developed whereby even simpler pieces of apparatus have been used than oven drying and gravimetry in order to speed up operations. Of these, pyknometry and gravimetry based on drying by burning alcohol have been used to some extent. In the pyknometric method oven drying is eliminated by shaking a weighed sample in a flask to remove the air and then weighing the flask in water. The moisture content is calculated by assuming a mean value for the specific gravity of the soil, thus permitting simultaneous determination of the bulk density. On the other hand, the water content of the soil can be determined with an air pyknometer. In this method the soil sample is enclosed in a vessel of known size and the air volume of the sample determined by the combined use of pressure measurements and knowledge of the dry weight of the sample and the specific weight of the grains. Now the volume of water in the sample can be calculated and expressed on mass or volume basis. Water content can be determined with an air pyknometer in all types of soil, although the method is slightly less useful with solid clays, the pores of which are not easily penetrated by compressed air. The method is not very exact.

4.3.2. Nuclear radiation methods

Radiation consisting of neutron particles or gamma energy-quanta can be utilized for the determination of the water content of soil. The main elements required for such a determination are a radiation source and a detector that is sensitive to the radiation used. The flow of signals from the detector is determined with a counting device, i.e. a scaler or a rate meter, see Figure 4:7. A suitable voltage supply, a pulse amplifier and a pulse-height discriminator are other devices that are often needed. The necessary radiation shield and radiation monitoring must also be suitably arranged. An advantage of the radiometric methods

is that the measurement is performed without direct contact between the measuring probe and the soil. Radiometric gauges are relatively expensive but also fairly durable; spare parts and maintenance service are important requisites.

4. 3. 2. 1. Counting rate statistics

The number of pulses obtained with a detector in a certain time interval is a random quantity. When one repeats exactly the same measurement, the number of pulses obtained will vary. Let us assume that the activity of the radiating sources is constant; the random quantity, number of pulses is then Poisson-distributed. The number N of pulses for a certain measurement time deviates from its mean value by more than $2\sqrt{N}$, considering a probability of 5 %. The counting rate $R = N/t$ for the same probability has a value outside of error limits given by the expression:

$$\Delta R = \pm 2\sqrt{R/t}$$

where

$t = T$, when a scaler is used; T is the time of the measurement, and

$t = 2\tau$ when a rate meter is used; τ is the time constant of the meter.

4. 3. 2. 2. The neutron method

The neutron method is based on the exceptional ability of the hydrogen nucleus to slow down fast neutrons. Other elements existing in the soil merely hinder the outward diffusion of neutrons. Thus the density of the slow-neutron cloud around the fast neutron source mainly depends on the concentration of hydrogen nuclei. In many soils water is the only significant hydrogen compound, so that the concentration of slow neutrons that arise around the fast neutron source will be a function of the water content of the soil.

The radiation shield or some other hydrogenous body can serve as a standard medium on the basis of which a reference counting rate is measured. The ratio of the counting rate in the soil to the counting rate in the standard (or less preferably the counting rate in the soil alone) is related to the water content of soil by means of calibration. See Technical Reports from IAEA 1968-71 and Danfors & Skoglund 1971. Figure 4:7 illustrates a gauge (probe and indication unit) for subsurface measurement, and Figure 4:8 some calibration functions.

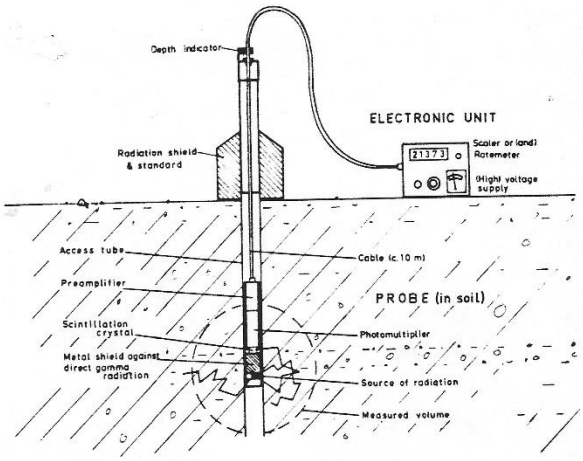


Figure 4:7 A typical subsurface gauge for neutron or gamma measurement using a scintillation detector. Some particle tracks are shown

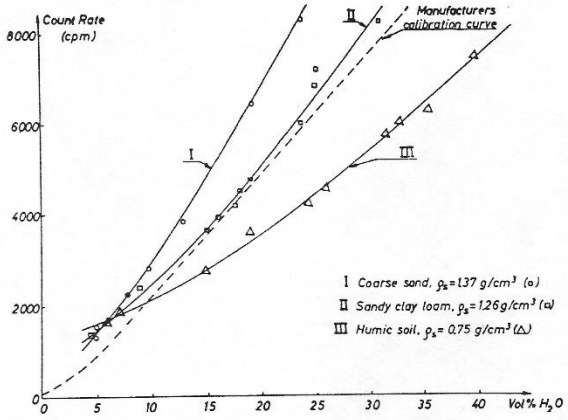


Figure 4:8 Measured counting rate versus moisture content curves (solid curves and experimental points) for three different Danish soils as compared with the gauge manufacturer's calibration curve (broken curve), from Ølgaard 1969

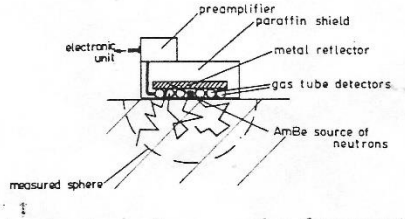


Figure 4:9 A typical surface probe for neutron measurement of moisture using ^{3}He- or $^{10}BF_3$-gas tube detectors. (The probe can include a high voltage supply and more electronic operations). Some neutron tracks are shown

4. 3. 2. 3. Different types of neutron gauges

For many hydrological investigations measurements of water content profiles in soil deposits are required. The subsurface neutron moisture gauge (Figure 4:7) is a reliable device for this purpose. Its disadvantages are poor resolution (4. 3. 2. 8), difficulties of making measurements near the soil surface (4. 3. 2. 9), deformation of the soil matrix and influence on the water profile caused by the access tube installation (4. 3. 2. 7), and its relatively high price. The surface neutron gauge (Figure 4:9) is deviced to be set directly on the surface of the soil.

Both the subsurface and surface neutron gauges have the property that the influence of the moisture content on gauge readings diminishes rapidly with distance from the probe, Kristensen 1971.

In one type of gauge the distance between a strong-activity source and a neutron detector is over 30 cm. The source and detector can then be placed in separate tubes, see IAEA Technical Report No 126.

4. 3. 2. 4. Neutron gauge components

Thorough tests of performance have been made on most of the commonly available commercial gauges, see IAEA Technical Report No 130. Danfors & Skoglund 1971 have described the design features of subsurface meters and their use in the Nordic countries.

The californium -252 spontaneous fission source, which, in spite of its short half life (2. 6 y), is an important future neutron source for moisture measurements because of its low mean energy (2. 35 MeV), and low (and decreasing) price, Corey et al 1970. Tritium-target deuterium bombarded neutron (14 MeV) generators are adequate for large-volume single or dual-tube measurements, IAEA Technical Report No 126. A non-operating generator poses no great hazard.

A proportional counter filled with helium-3 or boron-10-trifluoride gas, or a scintillation counter, are mostly used for detection. The Geiger-counter is cheapest, but the detector using a Geiger-counter can be too ineffective, IAEA Technical Report No 130. When the detector of thermal neutrons is completely covered by a thin cadmium foil, only epithermal neutrons are detected.

In a good gauge the repeated number of pulses (e. g. in the standard) varies according to the Poisson distribution (4. 3. 2. 1), Danfors & Skoglund 1971, Kristensen 1971; in a weak gauge it varies more.

The effect of temperature on the electronics of the gauge is significant in many devices and the instabilities of some devices under extreme temperature conditions can make the measurements futile, IAEA Technical Report No 130. Repeated counting may reveal such instabilities.

In recent years relatively light and small electronic units have been offered for sale. High voltage supply and many electronic operations have also been incorporated in the probe to improve field use, Danfors & Skoglund 1971.

The shield can serve as a standard, or another standard sufficiently large can, to insure the appropriate temperature conditions, be inserted in the soil near the measuring site.

4. 3. 2. 5. Soil matrix effects

For mineral soils especially, the following measurement aspects can be distinguished:

1) Since the effect of hydrogen in the soil matrix is similar to that of hydrogen in water, the hydrogen content of the dry soil matrix should be determined in the soil profile. This will improve calibration precision.

2) In many soils the effect of other elements, apart from hydrogen, can be summarized as the effect of dry density (Kasi 1971). Since the soil matrix can often be considered as stable, one measurement of the dry density profile combined with some control measurements is all that is required. A gamma gauge is generally used for the density measurement (see 4. 3. 2. 11). The dry density is determined by making simultaneous measurements of density by gamma radiation and of moisture by the neutron method.

3) Absorbers of thermal neutrons, elements such as boron, gadolin-

ium, samarium, etc. can strongly affect the measurement of thermal neutrons, Ølgaard 1969, Kasi 1971. Their effect is eliminated in epithermal measurements, IAEA Technical Report No 112, Kasi 1971.

All kinds of moisture measurements are affected by the heterogeneity of the soil medium (variety of matrix, stones, holes, etc).

4.3.2.6. Measurement of moisture changes

For the measurement of moisture changes the effects of factors such as bulk density, matrix hydrogen content, etc. can be neglected and it becomes sufficient for the calibration curve to have the form:

$$w = f(R) + B \qquad (1)$$

provided that the disturbances only appear in the value of the constant B, (and f(R) is a monotone function); w is the moisture content, and R is the counting rate. The range in which the calibration functions obey (1) has not been very thoroughly investigated. The form (1) may be violated especially by the occurence of low mineral densities or high organic matter densities in the soil matrix, as can be the case when measuring peat and snow (Figure 4:8), IAEA Technical Report No 91, Kasi 1973, or by the occurence of large concentrations of elements that strongly absorb thermal neutrons, Ølgaard 1969.

4.3.2.7. Access tube, probe lowering

For full instrumental sensitivity and accuracy, the access tube diameter and soil disturbance from the tube installation must be reduced to a minimum. The counting rate varies inversely with the diameter of the access tube and in cases in which the tube diameter is much wider than probe diameter the counting rate is also influenced by the position of the probe in the tube due to possible variability in the measurement geometry. Thin-walled aluminium tubes are ideal, but unfortunately lack sufficient strength and durability in many situations.

Stainless steel tubes and galvanized iron tubes are commonly used. (Corrosion of the iron tubes may be extensive and hence obstructive.) They are inserted into the soil by simultaneous augering, or knocked

into the soil with a vibration hammer machine. IAEA Technical Report No 126, Myhre et al 1969. The Danish manufacturer recommends the use of 44.5/42.0 mm aluminium tubes with a conical metal head, which are driven into an augered hole in the soil by means of a steel rod that fits into the access tube with a sleeve support at the open end. A motorized portable auger is used for making the hole prior to tube installation. Distortion effects on soil structure are probably greatest for the vibration hammer method, but on the other hand this method is fairly reproducible and the compression, etc. caused may not be so serious in the case of studies involving changes in soil moisture.

Some difficulties can be encountered in the field in defining the correct depth of measurement, partly due to the lack of distinctness in the reference plane (the soil surface has a complex microtopography) and partly due to the difficulties involved in adjusting the correct probe depth. The important point to remember here is not to overlook the reproducibility of the depth adjustment. A definite reference level should be assigned to each measurement station.

4.3.2.8. Measured volume and resolution ability

Haahr & Ølgaard (IAEA Technical Report No 112) have introduced the concept of the sphere of importance, which signifies the volume of soil required to give 95 % of the counting rate value obtained if the same soil is present in an infinite amount around the probe. The radius of the sphere of importance of the subsurface probe ranges from about 110 cm at zero water content to about 20 cm for 0.50 g H_2O/cm^3. The large measurement volume of the neutron probe naturally reduces its power of resolution - i.e. its ability to resolve changes in water content with depth. Experience has shown that layers thinner than 30 cm can hardly be distinguished correctly and that water content profiles cannot be obtained with a better accuracy than that given by measurements at intervals of 15 cm, IAEA Report No 112. However, although the water content profile obtained with the neutron probe is very much smoothed out, the integrated water content over the entire profile is fairly correctly indicated.

For surface measurement, the depth corresponding to the radius of the sphere of importance in the subsurface measurement is shorter than the latter because of neutron leakage into the air, IAEA Raport No 112.

4. 3. 2. 9. Measurements near the soil surface

For measurements of moisture just under the soil surface the surface probe has been developed. Measurements with the subsurface probe in the top 0-30 cm layer involves many difficulties due to the interference of the atmosphere. A reflector can be used to reduce this interference, IAEA Report No 112. Also a special calibration function can be derived for the uppermost soil layers, Kristensen 1971; in some cases soil sampling may be used in the top 0-20 cm.

Both surface and subsurface neutron measurement have a rather poor resolution ability. A gamma method is presented in 4. 3. 2. 13. which can achieve a resolution of 0. 5 cm.

4. 3. 2. 10. Calibration procedures

Factors which affect the counting rate v. water content relationship are as earlier discussed due to certain matrix effects, the nature of the access tube and the probe itself.

The best method to evaluate measurements from mineral soils is to use calibration curves for non-hydrogen soil. The water equivalent of the hydrogen content in the soil matrix is determined and subtracted from the measurement result to give the right moisture content, IAEA Report No 112, Kasi 1971.

Special calibrations are required, especially for organic soil matter, (e. g. humus, peat, etc) and for snow, Figure 4:8, Kasi 1973.

Commonly, users of the neutron probe arrive at adequate calibration functions on the basis of three experimental types of information:

a) the manufacturer´s calibration curve(s)
b) their own laboratory measurements in drums with known materials
c) their own field calibration, which involves soil sampling.

Computer programmes have been developed to give theoretically correct calibration functions for different soils, IAEA Report No 112, Kasi 1973. The input data for these theoretical calibrations include elemental composition, bulk density, probe characteristics, and access tube dimensions and material. However, some experimental results are needed for the absolute values of the counting rates. A relatively good establishment of an experimental calibration function is then necessary, whilst computer programmes can be used to present and to set down for consideration the effects of hydrogen content, bulk density, absorbing elements, etc. More details on the calibration procedures are found in IAEA Report No 112.

4.3.2.11. The gamma-ray method

Nuclear gamma radiation has long been used for measurement of bulk density and for density correction in the neutron moisture measurement. However, in many soils the bulk density changes are due to moisture changes, so that density gauges can be used for direct moisture measurement. The most usual gamma sources are given in Table 4:1.

Table 4:1. Some sources of gamma radiation.

Isotope	Main energies of gamma-quanta	Half life (years)	Coefficient L ($\frac{\text{rem m}^2}{\text{h Ci}}$)
^{60}Co	1.17, 1.33 MeV	5.26	1.35
^{137}Cs	662 keV	30	0.33
^{226}Ra		1620	0.83
^{241}Am	60 keV	458	0.0025

The detector is generally a Geiger-tube or a scintillator.

4. 3. 2. 12. The conventional type of single-well density gauge

This type of gauge has the same principle construction as the neutron gauge, Figure 4:7. It is not used much for moisture measurement, but is used more for determining the density correction in connection with neutron measurement of moisture content. This measurement has approximately the same resolution ability as the neutron measurement of moisture, 4. 3. 2. 8. The effect of the access tube on the calibration curves for mineral soils is presented in Figure 4:10. The character of the gamma measurement is very similar to that of neutron measurement in the determination of peat moisture, Kasi 1973.

4. 3. 2. 13. Dual-tube arrangement

An interesting and important device for measurement of water content profiles is a special type of meter based on the gamma-ray attenuation between two tubes, de Vries 1969, Giesel et al 1970, Figure 4:11. Cesium-137 is a suitable emitter of gamma radiation. The lower discriminating voltage level (L. D. L. in Figure 4:12) for pulses from the scintillation detector must be just below the voltage level of the ^{137}Cs single gamma-peak at the energy of 662 keV. Only gamma-rays are counted which have not been scattered or been very little changed in their direction via scattering(s). The collimators in Figure 4:11 are not always necessary, but they can improve the resolution ability, especially near the soil surface, de Vries 1969.

The counting rate produced by gamma radiation is given by:

$$R = (R_o e^{\rho \mu_\rho x}) e^{-w \mu_w x} \qquad (2)$$

where ρ is the dry bulk density, w is the water content in g/cm^3 and μ_ρ and μ_w are the corresponding mass attenuation coefficients dependent on the energies of gamma-rays and on the collimation-counting system used. R_o is the radiation intensity when there is no medium between the tubes. x is the distance between the tube walls. In order to obtain a good accuracy of measurement, x should be selected according to:

$$1 \leq (\rho \mu_\rho + w \mu_w) x \leq 3 \qquad (3)$$

The values of μ_ρ and μ_w are around 0.08 cm^2/g for gamma radiation of ^{137}Cs.

The accurate measurement of the water content profile presupposes that ρ remains constant, Giesel et al 1970 achieved an accuracy of approximately 0.0015 g/cm^3 by using a strong source of 50 mCi. A resolution of the order of 0.5 cm can be achieved. The tubes must be installed in the soil as parallel as possible, and the source and the detector must be lowered steadily to exactly the same depth. The serious source of errors in this measurement is the fluctuation and drift of the pulse amplitude caused by temperature variations, etc., Giesel et al 1970. This effect can be controlled with a standard measurement procedure, in which temperature conditions in the standard is made to correspond to those of the soil measurement. Reference measurements can also be made below the water table. Standard measurements slightly increase the approximate upper limit, 3, in formula (3). The temperature effects can also be corrected by means of an extra source of light or gamma radiation being used to directly affect the photocathode or the scintillation crystal, thereby achieving electronic compensation.

4.3.2.14. Measurements near the surface

The gamma-ray device described in 4.3.2.13. can be used for measurements just below the surface of the soil, especially when collimators are used, Figure 4:11. Another commercial transmission device has the source of gamma-rays at the end of a thin rod inserted in the soil and the detector placed at the surface of the soil. The rod can be inserted into the soil to different depths. Measurements can be made without much disturbance to the soil.

4.3.2.15. Safety

IAEA Reports No 112 and 126 include considerations of radiation safety. The dose is the dose rate multiplied by the time of exposure. IAEA Safety series No 9 gives maximum permissible doses for professional workers.

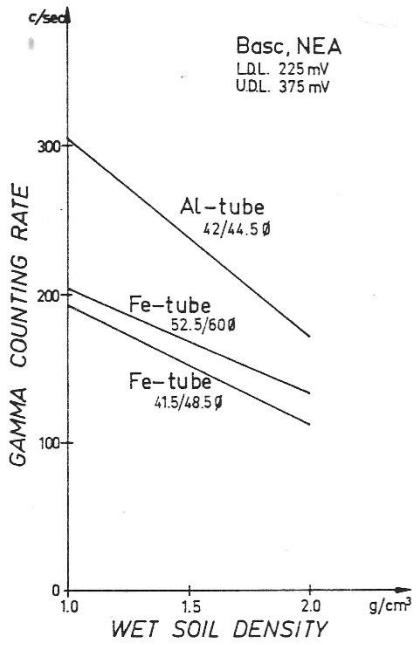


Figure 4:10 Some typical calibration curves of gamma backscatter as affected by the density of a mineral soil and by use of different aluminium and iron tubes

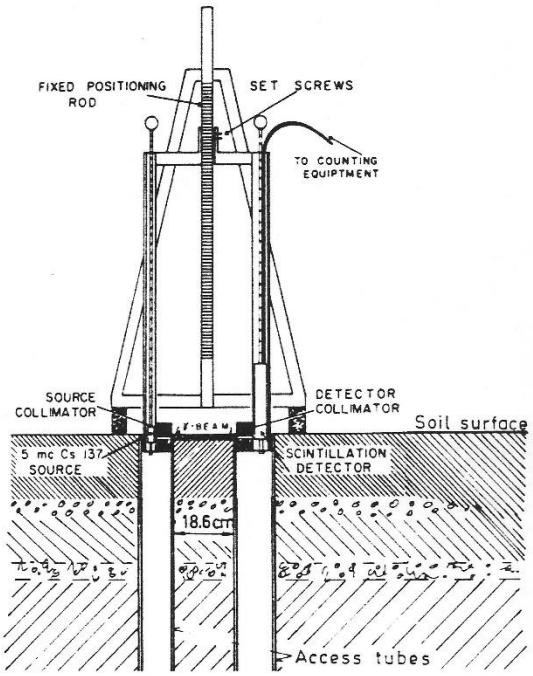


Figure 4:11 Dual-tube gamma transmission measurement. Field gamma beam positioning system and geometry of source, detector and their collimators with respect to undistrubed soil, from de Vries 1969

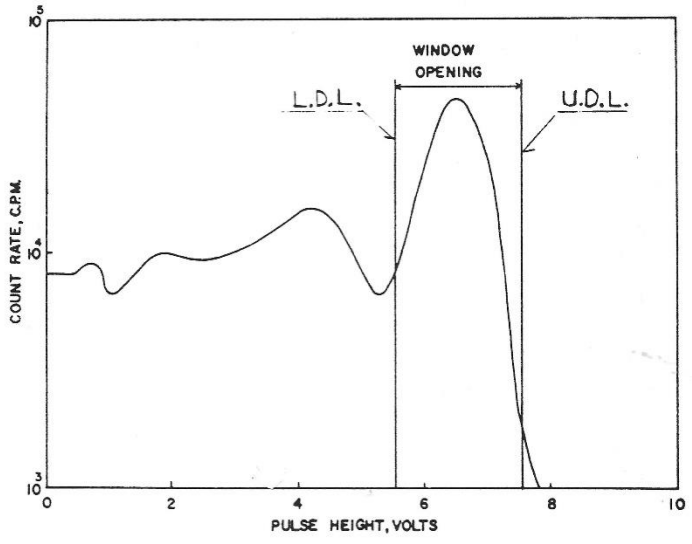


Figure 4:12 Pulse height spectrum of ^{137}Cs, from de Vries 1969

The gamma dose rate obtained in air from a point source is given by:

$$D_u = LA/r^2$$

where

D_u = gamma dose rate, (rem = 10^3 mrem = mr)

A = activity of gamma radiation source

r = distance from the source

L = coefficient for the isotope emitting gamma-rays, Table 4:1

The neutron dose rate D_n (mrem/h) from an isotope point source in air is correspondingly obtained from:

$$D_n = 1.15 \times 10^{-6} \; S/r^2 \qquad (5)$$

where S is the source strength (n/s), and r is the distance from the source (in units m).

The gamma and neutron doses from an Am-Be source are rather equal in air. The dose rate can be considerably diminished with a material shield, such as lead or other metal shielding against gamma radiation, and a hydrogenous material such as paraffin, wax, etc., against neutron radiation. As seen in the formulae above, a large distance from the source acts as a shield.

The manufacturer should give information on the maximum dose rate and the dose rate distribution on the surface of the meter, and of the attenuation of the dose rate. The operator of a gauge should be most careful when handling the probe, even when it is situated in the shield. The hazard is generally much below the permissible doses, when operations are carried out in a proper way.

4.3.3. Other methods

For certain purposes, penetration and chemical methods have been used to establish the water content of soil layers (Cope & Trickett 1965, Geary 1971). Many of these are rapid, single-structure methods, but their accuracy is fairly low and they have not been used extensively in hydrological studies.

4.4. Potential of soil water

4.4.1. Tensiometric methods

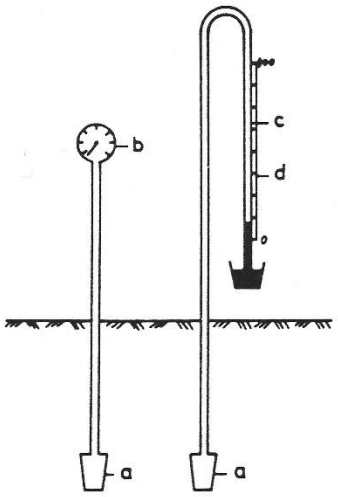
A tensiometer consists of a water-filled porous cup buried in the soil and connected to a manometer in a vacuum gauge, Figure 4:13. The water in the cup reaches pressure equilibrium with the soil, and this becomes a measure of the matric suction. Before equilibrium is reached, water in the tensiometer flows out into the surrounding soil and thus the column of mercury in the attached manometer sinks. The drier the soil, the stronger the resulting pressure reduction. With equilibrium, water no longer flows away from the tensiometer and the suction remains constant. Tensiometers can be used to measure a maximum suction corresponding to one atmosphere. If this value is exceeded air will enter the porous cup and the instrument can no longer be used. The tensiometer cannot detect osmotic potential as the cup is permeable to solutes. For most soils in the Nordic region osmotic potential can be neglected.

Fine-textured soils may clog the porous cup, but this can be delayed by setting the tensiometer in sand. Diurnal variations in temperature will affect exposed uninsulated parts. This can be remedied in different ways, e.g. by using plastic non-conducting materials, by installing the instruments completely below the soil surface or by reading each instrument at the same time each day.

Tensiometers are cheap and easy to construct, calibrate, and install and they permit adequate replication. Matric suction, which is a most useful measurement in field experiments, is recorded directly in situ and requires no mathematical transformations. The translation of matric suction into soil moisture content involves individual calibration for each soil and is not recommended.

4.4.2. Electrical methods

Electrical resistance units, see Figure 4:14, are used to measure the soil moisture status in situ, (Gardner 1965, Cope & Trickett 1965, Aslyng 1968, WMO 1968, Geary 1971). The resistance of absorbent blocks that are in moisture equilibrium with the soil is a



a. Porous clay cup
b. Dial gauge manometer
c. Mercury manometer
d. Scale

Figure 4:13 Principle of two types of soil moisture tensiometers, from Aslyng 1968

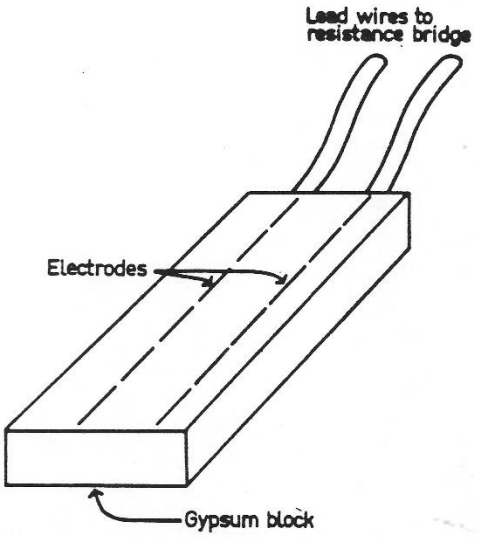


Figure 4:14 Electrical resistance method

function of the moisture content of the block, and can be used as a measure of also soil suction by means of suitable calibration.

The resistance of the units must be measured with an a. c. Wheatstone bridge (about 1000 cycles/second) because electrolysis and polarization occur if direct current is used. The resistance units are made of various materials, but usually consist of two carefully spaced electrodes surrounded by water-absorbent material. The materials most widely used are gypsum, nylon and fibreglass, either alone or in various combinations. Such units will measure suctions within the pF-range of 2 to 4.2. The measuring range of gypsum blocks alone, however, is considerably smaller, see Figure 4:15.

All resistance blocks must have very low geometric tolerance values and printed circuits have therefore been used; even so, individual calibration is necessary for each unit. Calibration for each soil type is also necessary and may be done in the field or in the laboratory. It is usually on the drying curve that blocks display marked hysteresis, and the resulting curves do not necessarily become stable with time. Changes due to possible dissolution of the calcium sulphate (applies to gypsum blocks) cannot be checked once the block is installed. However, this does give some degree of buffering against the effect of soluble salts - a major disadvantage of the method. Many blocks are temperature-sensitive, and corrections must be made either manually or from built-in thermocouples.

The resistance block method has a number of advantages for in situ measurements. Blocks are cheap, and a number can be installed in the field and read at intervals without disturbance to the site. The leads may be led to a central point, and the method lends itself to automatic recording. Blocks and measuring bridges for field use are commercially available. However, the method is still lacking in reliability and precision and will require considerable refinement in block-manufacture and in calibration techniques, before it receives wide acceptance.

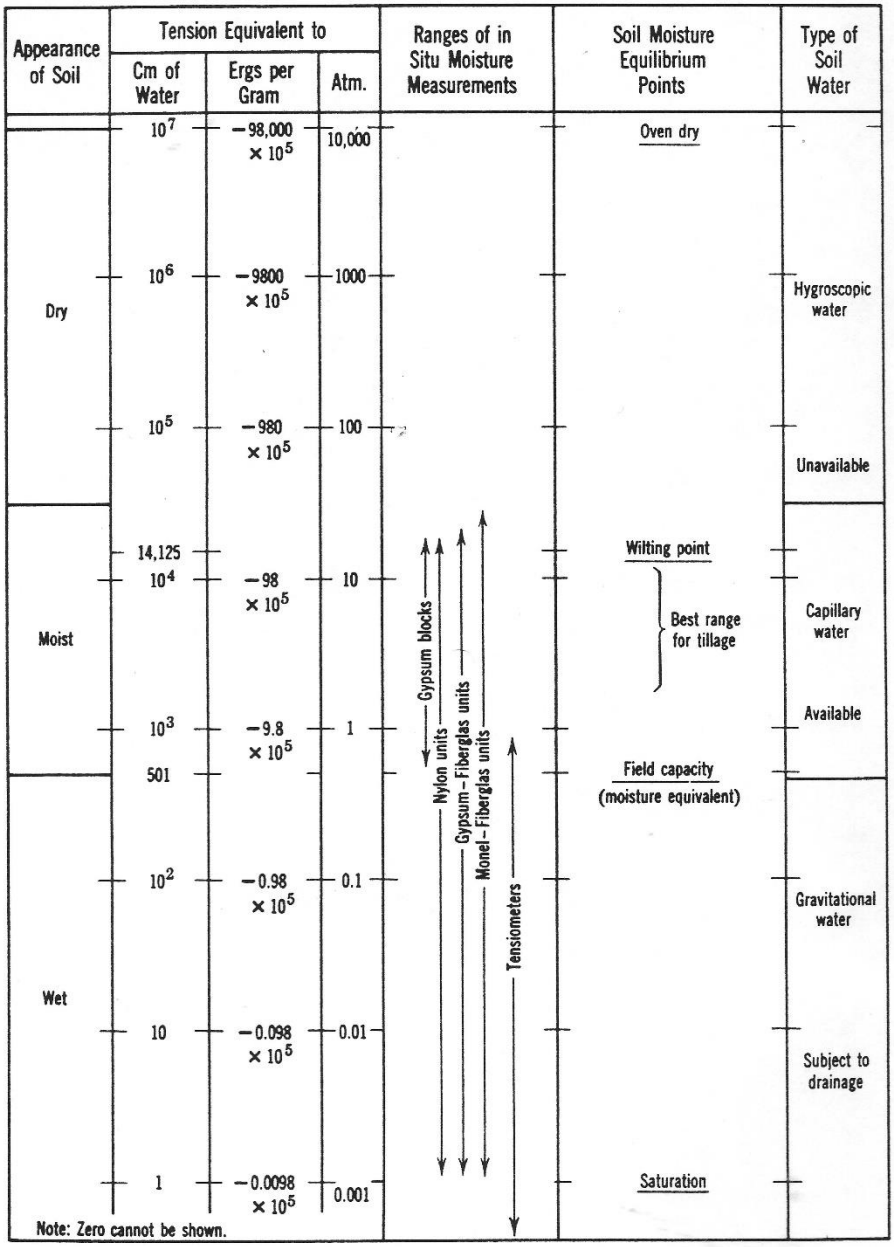


Figure 4:15 Possible uses for the tensiometer and certain gypsum blocks in different moisture ranges

For soil moisture determinations, the change in the capacitance of a condensor unit that is buried in the soil has also been tried,(Gardner 1965, Cope & Trickett 1965, Geary 1971). Multiple-sensing heads are needed with the capacitance method, as with the resistance block. The former is more expensive, since screened cables of stable shunt capacitance are needed. Temperature and hysteresis effects as well as power loss that occurs in a wet medium add to the complications involved.

A micro-wave meter, comprised of an oscillator, receiver, and a calibrated attentuator, is commercially available for determining the moisture content of samples, (Cope & Trickett 1965, Geary 1971). The sample is placed between the receiving and the transmitting antennae. The advantage of the method lies in the speed of the reading. The heterogenous nature of soils is the biggest limitation to in situ use of the micro- or radio-wave methods. One method based on the infrared absorption of water has the disadvantage that the penetration of the rays in the soil is shallow, but it is useful especially for aereal measurements of large tracts of bare soil.

4.4.3. Thermal methods

Attempts have been made to exploit the thermal conductivity of the soil or that of moisture absorbent thermal blocks in close contact with the soil to determine soil moisture in situ (Cope & Trickett 1965, Geary 1971). Thermal conductivity is independent of salt content and this gives the method an advantage over the resistance block method, particularly for saline soils. Direct measurements depend on very close contact between the soil and the probe, which is hard to achieve.

The heat source is an electrically heated wire in a needle-shaped probe 13 cm long. A thermo-junction near the centre of the heated wire gives a continuous measurement of the temperature change. Under laboratory conditions soil samples can be heated by a 300-watt lamp mounted above the samples. Measurements are made with a metal plate on top of the soil and thermo-couples located at various, relatively shallow depths.

The temperature dependence of resistance has also been used, e g one arm of a wheatstone bridge is made of enamelled copper wire wound around glass tubing that is set in the soil to follow moisture changes in sity. The other three bridge resistance units are made of manganin (temperature independent). In one method a mercury thermometer with half the bulb wound round with electrically heated wire is set in the soil. The time required to attain a constant temperature rise is said to be dependent on the soil moisture content.

4. 4. 4. Methods used in the laboratory

When soil water potential is measured in laboratory studies, pressure methods are usually used, most often the air-pressure membrane apparatus, but sometimes also vapour-pressure methods. These methods can be used to measure the uptake and release of moisture from samples of soil over a wide range of suction values. In addition temperature measurements of freezing-point depression have been used for determination of soil water potential (Aslyng 1968).

4. 5. Conclusions

In determining the soil moisture status, the goal is to get as undisturbed a sample as possible and also to keep the soil at the measuring spot as undisturbed as possible. In hydrology, especially, non-disturbance is considered important, because the soil water content is usually stated as volume percent water. Undisturbed samples can usually best be obtained from sampling holes or with various kinds of piston drills. When undisturbed samples cannot be obtained other sampling methods can be used, which means that the water content usually has to be expressed as percentage weights. Different kinds of sampling methods are treated more in detail in soil sampling guidebooks.

All the present methods of soil moisture measurement have different ranges of applicability.

1) Measurement of water content per volume unit

Gravimetric determination of moisture is the natural choice for small research tasks and for calibration of other methods, However, for large scale projects it often becomes more rational to invest in meth-

ods with greater measurement capacities, such as the neutron method. The neutron method is recommended for long term in situ measurements. The neutron method is the best nuclear method for mineral soils, but for pure peats gamma methods may be as applicable. With the dual tube gamma method a very good depth resolution is obtained and therefore also soil layers just below the soil surface can be measured as well. The single tube probe may be used for measurements below 15 cm depth.

2) Measurements of soil water potential

The measurement of soil water potential in the wet range will often supplement, but not replace, that of water content measurements. For in situ measurements the tensiometer, with adequate replication to overcome its lack of precision, is usually considered best suited for the purpose of measuring water potential.

Resistance and capacitance blocks provide rather imprecise measurements over a wide range, providing the site is not too wet or saline. Blocks are cheap, but not long-lived, and must be well replicated. These methods are also applicable for in situ measurements over the dry range in the topsoil. Figure 4:15 shows the possible uses of the tensiometer and certain gypsum blocks in different soil moisture ranges.

5. DESIGN OF MEASUREMENTS AND PROCESSING OF DATA

5.1 Purpose of soil water studies within the IHD-programme

According to resolutions and suggestions made by the Co-ordinating Council of the UNESCO IHD programme, soil water studies are considered important in many phases of the IHD. Studies on this reservoir parameter are expected to be concentrated within representative and experimental basins with objectives:

- to establish laws governing increases and decreases in soil water
- to determine its influence on changes in the water balance
- to produce data necessary for calculating runoff due to thaw and rain water
- to evaluate economic aspects of water available for crops and for establishing irrigation and drainage requirements, etc.

Suggestions have also been made concerning supplementary observations that should be made where applicable, such as: depth of water table, precipitation, freezing and thawing in the soil, evaporation, water equivalent of snow packs, type and stage of development of vegetation. These observations should be made at the same time and at the same location as routine soil water measurements are made for water balance purposes. Soil water values should be expressed in a form compatible with other hydrological data on precipitation, evaporation, etc, that is in mm or inches depth of water. Furthermore it is suggested that also the following soil hydrological properties be determined for each depth increment of soil that is studied:

- minimum moisture capacity (field capacity)
- capillary moisture capacity (the soil water content at various distances above the water table to the top of the capillary fringe. This will vary with changing depth of the water table in the soil)
- maximum water capacity (soil water content at different depths when the water table is at the ground surface)
- wilting point
- bulk density or volume weight of soil.

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