Methods of Measuring Soil Moisture in the Field

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By A. I. JOHNSON

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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Evaluates methods for measuring soil moisture and describes the equipment used

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By A. I. Johnson

ABSTRACT

For centuries, the amount of moisture in the soil has been of interest in agriculture. The subject of soil moisture is also of great importance to the hydrologist, forester, and soils engineer.

Much equipment and many methods have been developed to measure soil moisture under field conditions. This report discusses and evaluates the various methods for measurement of soil moisture and describes the equipment needed for each method. The advantages and disadvantages of each method are discussed and an extensive list of references is provided for those desiring to study the subject in more detail.

The gravimetric method is concluded to be the most satisfactory method for most problems requiring onetime moisture-content data. The radioactive method is normally best for obtaining repeated measurements of soil moisture in place. It is concluded that all methods have some limitations and that the ideal method for measurement of soil moisture under field conditions has yet to be perfected.

INTRODUCTION

The subject of soil moisture has long been of interest in agriculture. For centuries the farmer has picked up and felt a handful of soil to determine the best time to plow his fields. The amount of moisture in the soil is also of great importance in hydrology, forestry, and soil-mechanics engineering. Consequently, much effort has been expended in the last 50 years in developing methods and equipment for measuring soil moisture under field conditions.

Determination of soil moisture is one of the most difficult measurements required in the field of hydrology. Measurement of soil moisture ranges from the method of feeling the soil to the use of complicated electronic equipment using radioactive substances. The development of equipment has been directed primarily toward instruments that continuously measure changes in moisture content at a single sampling point.

METHODS

GRAVIMETRIC

The gravimetric method involves collecting a soil sample, weighing the sample before and after drying it, and calculating its original moisture content. The gravimetric method is the oldest (other than the ancient method of feeling the soil) but still continues to be the most widely used method for obtaining data on soil moisture. Because it is the only direct way of measuring soil moisture, it is required for calibrating the equipment used in the other methods.

Russell (H, 1950) [1] reporting on work completed in 1843 and Whitney (A, 1894), describe some of the first scientific investigations of soil moisture using gravimetric methods. The King tube, for collecting drive-core samples, was developed in 1890 and was modified and improved by Veihmeyer (A, 1929). Since that time many types of sampling equipment, as well as special drying ovens and balances, have been developed for use with the gravimetric method.

The disadvantage of the gravimetric method is the time and effort required to obtain data. It is time-consuming work to collect the samples, especially from depths greater than a few feet, and to oven dry and weigh the many samples required for most projects. For many problems, such as the study of evapotranspiration by grasses, the sampling procedure alters the area of experiment owing to trampling of the vegetation or the making of numerous holes. Under these conditions, the sampling may have to be done from platforms, and the holes may have to be refilled and packed. Soils are normally variable within an experimental area and, as two samples cannot be collected from the same point, slight variations of moisture content may be noticed.

SAMPLE COLLECTION

For the best samples, the soil should be homogeneous, just moist enough to permit easy cutting by the sampling equipment, and free from roots, organic matter, and stones. Seldom are all these conditions met.

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

[1] Letters refer to the center heads in "Selected References," as follows: A, Gravimetric method; B, Electrical-resistance method; C, Heat-diffusion method; D, Absorption method; E, Tensiometric method; F, Penetration method; G, Radioactive method; H, General method.

from running down the hole into the drier material. If there is free water in the soil, the moisture content as measured probably will be less than the correct value because some water will drip off as the sample is removed from the ground, or some may be squeezed out by compaction during sampling.

When dry hard fine-textured sediments are encountered, 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 the end of the core barrel or auger as it is withdrawn. Stony soils are very difficult to sample, especially volumetrically, owing to the danger of hitting a stone with the cutting edges of the equipment and because representative samples must be large. Soils that contain a considerable amount of roots and organic matter also present difficulty.

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 samplers, may be overcome if all equipment is kept clean—that is, free of moisture, oil, rust, and dirt.

SAMPLING AUGERS

The simplest equipment for soil-moisture sampling is the hand auger. Hand augers, with shaft extensions of aluminum pipe, have been used in sampling to depths as great as 55 feet.

One of the most useful types of hand augers is the Orchard auger (fig. 1). It consists of a cylinder 3 inches in diameter and 9 inches

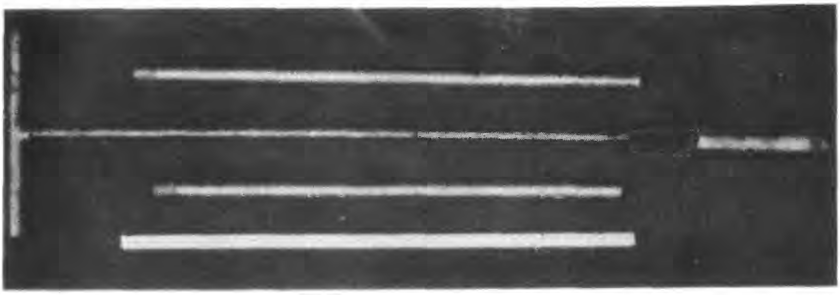


FIGURE 1.—Orchard auger.

long having a 4½-foot extension pipe on the top and two curved cutting teeth on the bottom. Because the barrel is a solid cylinder, the sample is not as likely to become contaminated from the side of the test hole as with the Iowan or the posthole auger. Thus, a good representative, but disturbed, sample is obtained by use of this equipment. For ease in sampling at depths greater than 5 feet, 3-foot extensions of ¾-inch aluminum pipe are added as needed.

To obtain a sample by the hand-auger method, the auger is turned by its handle and forced downward into the material to be sampled. Usually about 3 inches of the material may be penetrated before the cylinder barrel is filled. The auger is then raised to the surface, and the sample is jarred loose from the auger barrel by hitting the barrel with a rubber hammer.

SAMPLING TUBES OR CORE BARRELS

A soil-sampling tube, core barrel, or drive sampler of some type offers an advantage in soil-moisture sampling because volumetric samples can be obtained for calculating moisture content by volume. The King tube was developed in 1890, and Veihmeyer developed modified soil tubes in 1929. Since that time many people, including the writer, have developed variations of this type of sampling equipment. (See Hvorslev, A, 1949.)

Core samplers provide uncontaminated samples if the equipment is kept clean. Oil should never be used on the samplers, and they should be kept free of dirt, rust, and moisture. A two-man crew is normally recommended for deep sampling. Depths to 65 feet may be sampled.

PORTER PISTON SAMPLER

The Porter piston sampler (fig. 2) is one type of sampling equip-

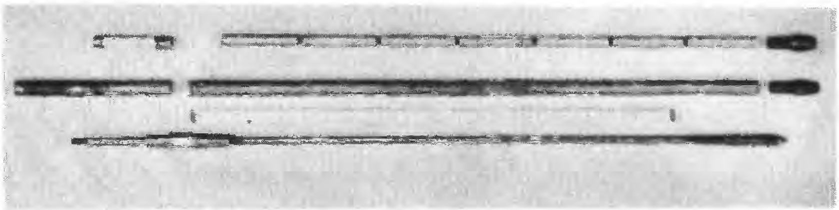


FIGURE 2.—Porter piston sampler.

ment that has been very useful, especially for sampling through loose or wet materials that tend to slough into the hole. This sampler is the retractable-piston drive-sampler type. By means of a hand-operated 25-pound drop hammer, a plugged sample section may be driven to the required depth by the addition of 5-foot extension rods. The plug is then retracted, the sampler is driven a maximum of 2 feet, and the soil core is retained in brass insert liners contained in the 4-foot sample section. Further retraction of the plug helps retain the sample by forming a partial vacuum above it. After extraction, the liners with the soil cores are removed from the sample tube and capped and sealed for laboratory testing. The liners are brass cylinders, 1 inch in diameter and 6 inches in length. Two types of hardened-steel cutting points are available for use in different soils.

This sampler is made from high-strength steel and is rugged and dependable. However, reasonable care must be taken in its use and storage to insure efficient operation and long life.

POMONA OPEN-DRIVE SAMPLER

The Pomona open-drive sampler (fig. 3) consists of a core barrel 2

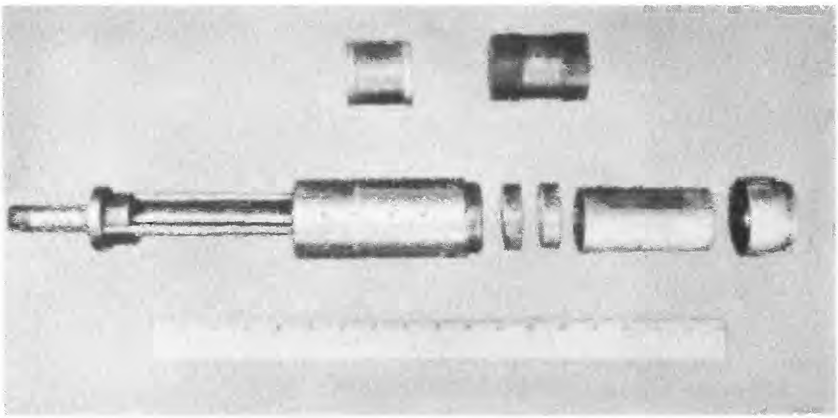


FIGURE 3.—Pomona open-drive sampler.

inches in inside diameter and 4 inches long, with extension tubes 1 inch in diameter and 5 feet long for sampling at depth. Brass cylinder liners, 2 inches in length, are used to retain the "undisturbed" core samples. The samples are removed from the core barrel by pushing a plunger.

A light drill rod or 1-inch pipe may be used for extensions. The cores are collected by use of a 25-pound drop hammer as described for the Porter sampler.

JOHNSON OPEN-DRIVE SAMPLER

A simple and economical sampler for obtaining volumetric core samples from shallow depths was designed by the writer in 1952. The sampler is easily constructed, and consists of a thin-walled brass tube 2 inches in diameter and 6 inches long mounted on the end of a 3-foot T-handle of ¾-inch pipe (fig. 4). Samples are collected by a downward thrust on the handle and are then pushed out of the core barrel by the central plunger. Because the inside diameter and area of the core barrel are known, volumetric samples may be easily obtained by cutting off a predetermined length of the core as it is removed from the sampler.

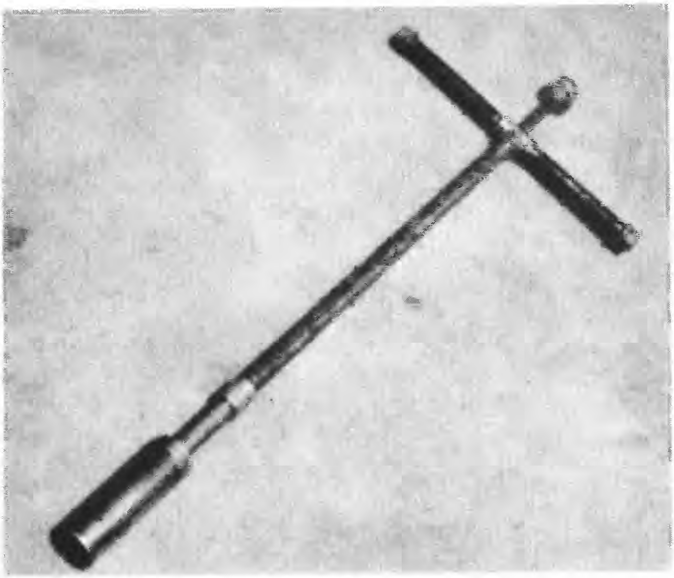


FIGURE 4.—Johnson open-drive sampler.

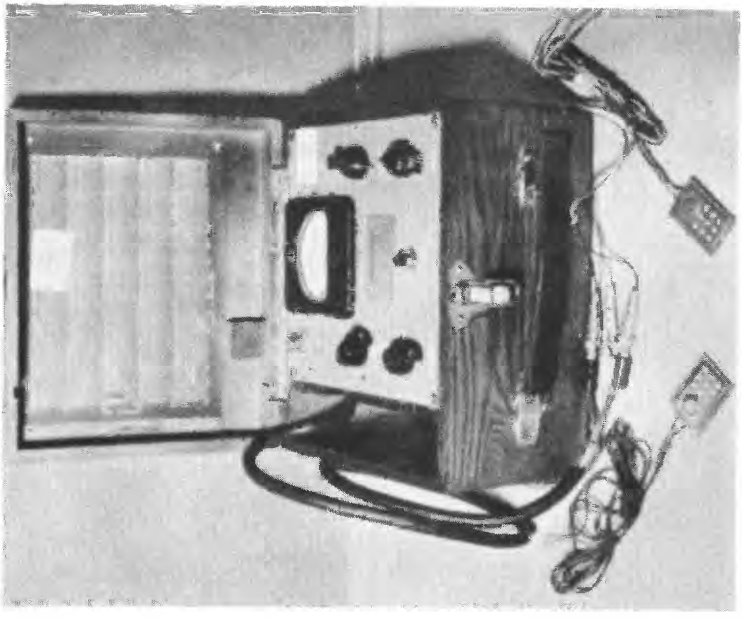
ELECTRICAL-RESISTANCE

The principle of electrical measurement of soil moisture was first reported by Whitney and others (B, 1897). However, many years passed before truly successful electrical units were developed by Bouyoucos and Mick (B, 1940a), Colman (B, 1946), Bouyoucos (B, 1949), and Youker and Dreibelbis (B, 1951).

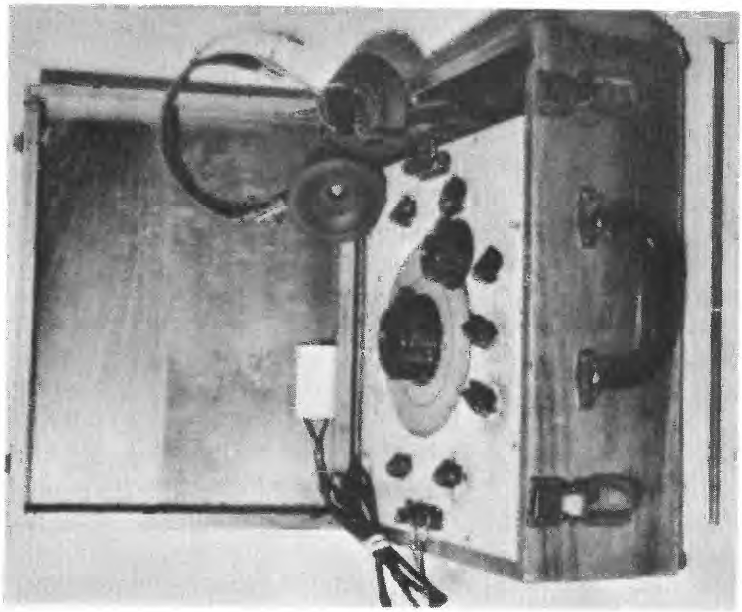
The electrical-resistance "blocks" developed by those named above operate on the principle that resistance to the passage of an electrical current between two electrodes buried in the soil will depend upon the moisture content of the soil. Nylon or Fiberglas fabric or plaster of paris surrounding the electrodes permits uniform contact with the soil moisture. When buried in the soil, the porous material of the block readily absorbs moisture or gives it up so that the moisture content of the block tends to stay in equilibrium with the moisture content of the soil. These moisture-content changes cause changes in electrical resistance which are measured by a meter at the surface. The resistance read on the meter is converted to moisture-content values by means of a calibration chart. The calibration chart is prepared by correlation, either in the field or in the laboratory, of gravimetric moisture-content values and resistance readings for the soil in which the blocks are buried. Laboratory calibration consists of drying and intermittently weighing soil cores in which blocks have been inserted. Field calibration consists of taking gravimetric samples as close as possible to blocks that have been buried in the field, and relating the moisture content of the sample to the measured resistance.

Two main types of blocks are in current use, the Fiberglas unit developed by Colman and Hendrix (B, 1949) and the plaster-of-paris or gypsum-block unit developed by Bouyoucos and Mick (B, 1940a). The Colman Fiberglas block is also available with an integrally installed thermistor so that soil temperatures may be measured, and resistance can be corrected to a common temperature. (Corrections for temperature are necessary for resistance blocks if accurate results are required.) Two general types of meters are used for reading the resistance values of the moisture blocks—the Colman meter (fig. 5*A*) and the Bouyoucos bridge (fig. 5*B*). The blocks may also be wired to a recorder for obtaining a continuous record (Korty and Kohnke, B, 1953).

The accuracy claimed by the developers of soil-moisture blocks is at best 1 percent by weight. All the types of blocks respond with equal rapidity to changes in soil moisture. Soil-moisture blocks are generally considered most dependable in the low-moisture-content range, below field capacity. Under these conditions, the Fiberglas blocks normally have a greater range of operation than the gypsum blocks. At higher moisture contents, between field capacity and saturation, the change in resistance per unit change in moisture content is small, thus reducing the sensitivity of the units. However, some of the apparent inaccuracies at the higher moisture contents may be due also to the loss of free water in sampling during the calibration.



A. Colman meter and Fiberglas block.



B. Bouyoucos bridge and gypsum block.

FIGURE 5.—ELECTRICAL-RESISTANCE SOIL-MOISTURE BLOCKS AND METERS.

The salt concentration in the soil moisture will materially affect results obtained by use of soil-moisture blocks. A drop in resistance correlates with an increase in salt concentration, but the changes in salt concentration at any single site are generally negligible under most conditions.

Blocks require relatively little effort to install and can be speedily read. The Fiberglas blocks are easier to install because they are thinner and thus may be inserted into the soil without disturbing it much. The speed of taking readings is greatest with the Colman meter. In well-drained soils the blocks are fairly durable, and have a life of 3 to 4 years.

HEAT-DIFFUSION

The basic theory of heat-diffusion blocks or cells was reported by Patten (C, 1909). The design for a cell was suggested by Shaw and Baver (C, 1939a). Kersten (C, 1948), Momin (C, 1947), and Aldous, Lawton, and Mainfort (C, 1952) tested several modifications of the design suggested by Shaw and Baver.

The heat-diffusion method is based upon the principle that the heat conductivity of a soil varies with its moisture content. The temperature rise caused by an electrically activated heat source installed in the soil is measured by a sensitive temperature-measuring device and is correlated with moisture content. Wet soil will conduct heat rapidly away from the heat source in the cell and will thus have a smaller temperature rise than dry soil.

To date, three general types of heat-diffusion cells have been developed. These are described by Aldous, Lawton, and Mainfort (C, 1952) as a porous-block type in which the electrical elements are imbedded in a porous medium, a direct-contact type in which the electrical elements are directly in contact with the soil, and a modified direct-contact type (thermal-conductivity cell) in which the heater and the temperature-measuring elements are in contact with, but separated by, a portion of the soil being tested.

Use of heat-diffusion cells has indicated that the blocks are sensitive to minor variations in construction. The cells are unsatisfactory when used in soils at moisture contents above field capacity; in high-shrinkage soils, intimate contact between the cell and the soil is lost as the moisture content decreases and erratic results are obtained until the shrinkage limit is reached. The porous-block type of cell has been reported as entirely unsatisfactory because consistent correlation between soil moisture and cell measurements could not be obtained under different soil conditions. The thermal-conductivity cell has been the most satisfactory of the three types but needs further development.

Heat-diffusion cells require calibration for different soils and densities, but Shaw and Baver (C, 1939b) noted that salt concentrations from 100 to 10,000 ppm did not affect the readings. None of the types of cells can be easily installed at depths of more than 5 feet or in undisturbed soil. These cells have not received widespread use and are not presently available from commercial sources.

ABSORPTION

Livingston and Koketsu (D, 1920) developed porous points or blocks that would absorb moisture from the adjacent area when installed in the soil. The soil moisture was then estimated from the change in weight of the points or blocks. Wilson (D, 1927) and Stoeckeler (D, 1937) did additional work on the use of absorption blocks. Davis and Slater (D, 1942) used an absorption block consisting of a porous chamber that contained a close-fitting plug that could be removed for weighing. The plug overcame the disadvantage of having to disturb the installations in the soil each time the blocks were to be weighed. Dimbleby (D, 1954) developed a pencil-type absorption block which is stuck into the soil; the moisture contents are estimated from the color changes of the "pencil."

This method is more qualitative than quantitative and has considerable inherent error; it has never been used extensively.

TENSIOMETRIC

A tensiometer consists of a porous point or cup (usually ceramic) connected through a tube to a pressure-measuring device. The system is filled with water and the water in the point or cup comes into equilibrium with the moisture in the surrounding soil. Water flows out of the point as the soil dries and creates greater tension, or back into the point as the soil becomes wetter and has less tension. These changes in pressure, or tension, are indicated on a measuring device, usually a Bourdon-tube vacuum gage or a mercury manometer. (See fig. 6.) The tensiometer may also be attached to a pressure recorder (Richards and Gardner, E, 1936) or to an electonic pressure transducer to maintain a continuous record of tension changes. Tensiometers are available in lengths of 6 inches to 4 feet, but probably could be manufactured in longer lengths if desired. Specially constructed tensiometers have been installed to depths of 15 feet (Richards, L. A., E, 1942). Multiple tensiometers, for determining tension data at several depths by use of a single probe, were developed by L. A. Richards (E, 1954).

Tensiometers were probably most fully developed by L. A. Richards (E, 1942). They are most useful for measuring moisture content

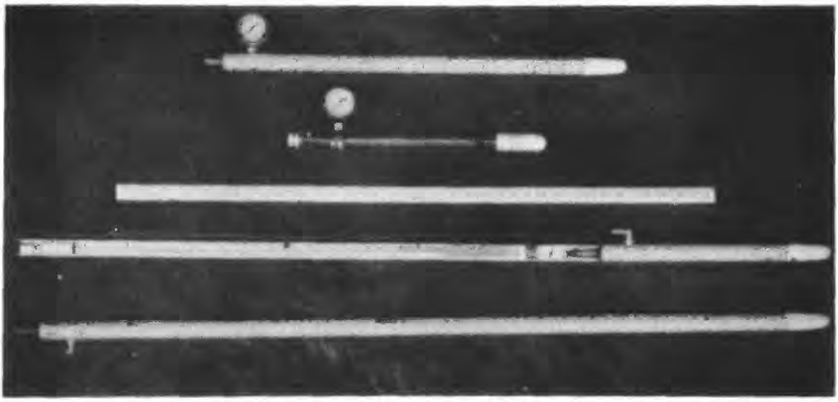


FIGURE 6.—Tensiometers. Top, vacuum-gage type. Bottom, mercury-manometer type.

of tensions below approximately 0.9 atmosphere. Such tensions will, on the average, correspond to a range in moisture content from slightly below field capacity to saturation. At the higher tensions found in drier soils, tensiometers become inoperative because air enters the system through the porous point. To determine the moisture content with a tensiometer, the relation between moisture tension and moisture content must be known. This relation may be found in the laboratory from a moisture-tension curve constructed by means of a pressure-membrane or porous-plate apparatus or by collecting soil samples in the area surrounding a tensiometer installation and relating the moisture content of the samples to the tensiometer reading obtained concurrently. L. A. Richards (E, 1949) noted that the vacuum-gage type of instrument will generally provide an accuracy within 2 percent, and the mercury-manometer type is even more accurate.

Tensiometers are affected by temperature. The temperature gradients between the porous point of the tensiometer and the soil may cause variations in the tension readings.

The salt concentration in the soil or in the pore water seems to affect tensiometric methods less than electrical methods. S. J. Richards (E, 1938) pointed out that tensiometers exhibit considerable hysteresis effect; they tend to give a higher soil-moisture tension during soil drying than during soil wetting. In 1949, L. A. Richards noted that this effect is not too serious a disadvantage because the wetting cycle is usually rather short in comparison with the drying cycle. Ewart and Baver (B, 1950) reported a serious disadvantage because of the timelag in response to soil-moisture changes. Tensiometers have exhibited lags of half an hour to many hours in indicating changes in tension caused by changes in moisture content. Recent studies by the hydrologic laboratory of the U.S. Geological Survey, Denver, Colo., showed that semipermeable plastic points provide much faster response than ceramic points.

The tensiometer is probably the easiest to install and the most rapidly read of all soil-moisture measuring equipment. However, at present, tensiometers are not suitable for installation at depths greater than about 20 feet.

PENETRATION

Moisture content may be estimated by relating it to the force required to push an instrument through the soil. Allyn and Work (F, 1941a) developed an instrument they called the "availameter" that measured the force required to drive a pair of needles into a soil core. Allyn (F, 1942) reported a newly developed soil probe with which he found moisture-content estimation possible within 0.5 percent. Many others, especially in the Netherlands, have developed equipment for measuring penetration resistance (Hvorslev, F, 1949).

Penetration equipment must be calibrated for each type of soil to obtain the relation between penetration resistance and moisture content. The method is very fast, although the equipment is difficult to use in gravelly or stony soils.

Penetration equipment designed by the Waterways Experiment Station, Corps of Engineers, Vicksburg, Miss., consists of a pipe with a point at the bottom and a T-handle containing a pressure-indicating device at the top. Depth of penetration is limited by the amount of force available.

RADIOACTIVE

Belcher, Cuykendall, and Sack (G, 1950) apparently introduced the radioactive method of measuring soil moisture in 1950. This method is based on the principle of measuring the slowing of neutrons emitted into the soil from a fast-neutron source. The energy loss is much greater in neutron collisions with atoms of low atomic weight and is proportional to the number of such atoms present in the soil. The effect of such collisions is to change a fast neutron to a slow neutron. Hydrogen, which is the principal element of low atomic weight found in the soil, is largely contained in the molecules of the water in the soil. The number of slow neutrons detected by a counter tube after emission of fast neutrons from a radioactive source tube is electronically indicated on a scaler.

The radioactive method indicates the amount of water per unit volume of soil. The dry density of the soil must be determined if moisture content in percent by weight is desired. The U.S. Corps of Engineers (G, 1955b) stated that the soil volume measured by this method is bulb shaped and has a radius of 6 to 15 inches, according to the moisture content and density of the soil.

One type of equipment presently available is shown in figure 7.

FIGURE 7.—Radioactive soil-moisture meter.

It consists of: a portable battery-powered scaler having five glow-tube decade counters that can accumulate as much as 99,999 counts, and a spring-wound timer that has a time-counting range of ½ to 5 minutes and weighs approximately 35 pounds; and a depth moisture probe having a 5-millicurie fast-neutron source of radium 226 and finely ground beryllium (half-life, 1,620 years) within a probe 15 inches in length and 1½ inches in diameter and having a weight of 45 pounds when complete with a lead and paraffin shield 6 inches in diameter and 8 inches long. These meters have been used with as much as 200 feet of cable.

Most investigators have reported an accuracy within 1 to 2 percent by volume. However, to obtain this accuracy, it is recommended that the probe be calibrated in the type of soil to be tested and the type of casing into which the probe is to be lowered.

Salt concentration in the soil moisture does not materially affect the data obtained by the radioactive method. Temperature usually has been considered ineffective in the radioactive method, but there is some evidence of a temperature effect. Readings close to the surface are affected by the position of the probe with respect to the air-soil interface; proximity of the interface causes lower counts than are characteristic for a particular moisture content at greater depth. Timing errors may be kept to a minimum by using a standard-count timing cycle of 2 minutes. Access tubes must be kept free of excess moisture, or erroneous readings will result. One must remember that the type and size of casing and the method of installation of the access tubes have a considerable effect on the readings, and new calibration curves should be obtained for each type of installation. Calibration may be done by means of gravimetric sampling in the area surrounding an access tube, by using large samples in the laboratory, and by use of boric-acid solutions of various concentrations.

There is some radioactive hazard from use of this equipment. The danger from exposure is proportional to the distance between the source and the operator and to the length of time of exposure. Thus, most of the danger can be minimized by proper handling of the equipment.

The radioactive method is time consuming, especially if the time required for calibration is considered. The equipment is heavy and delicate and equipment failures are likely. Considerable time is lost in repairs and in the recalibration needed after most repairs. The repair of the scaler may require the services of an electronics specialist.

SUMMARY

Of the methods described, only the gravimetric, electrical-resistance, tensiometric, and radioactive methods are used commonly. All methods have their disadvantages, as well as advantages, and the ideal method that will give accurate, reliable, and rapid measurements in place has yet to be developed.

The gravimetric method is considered the best for most soil-moisture-measurement problems requiring one-time moisture-content data. Because the gravimetric method provides data directly, the effort and possibility of error associated with the conversion of indirect readings (electrical-resistance, radioactive, and tensiometric) to moisture content are avoided. The gravimetric method requires less experience than the indirect methods, but also requires more effort under many conditions. Considerable gravimetric sampling is required for calibration even if one of the indirect methods is used. Some indirect method may have to be used if continuous or frequent moisture-content readings are necessary.

Radioactive methods are probably the best for obtaining repeated measurements of soil moisture in the field. Because of the delicate equipment and the work of calibration, this method requires sufficient effort and expense that one must consider seriously whether gravimetric sampling would not be a satisfactory substitute.

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