SOIL MOISTURE METERS

by the

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A summary of the literature overviews listed in the References section of this report is made on the various methods of measuring soil water content. Only those methods regarded as being useful by researchers are described in detail. Techniques which may become useful with further development are also mentioned.

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INTRODUCTION

Most physical and chemical properties of soil vary with moisture content. Measurement of soil water content is needed in every type of soil study. Hydrology, agrology, plant science and civil engineering all require soil moisture data.

Soil moisture content is normally given as a dimensionless ratio of two masses or two volumes. When soil moisture content, given as a dimensionless ratio, is multiplied by 100, the value becomes a percentage on a mass or volume basis. Where no indication of mass or volume is given, soil moisture content is normally on a mass basis. Determination of soil moisture on a volume basis involves finding mass basis figures first. Once mass basis figures are found, volume basis figures are determined using bulk density. Considering the variance in soil, some error is nearly always involved in determining bulk density. The amount of water in soil can also be given as a depth as if it were accumulated in a layer. A depth of water is typically used in irrigation. Specification of a depth of accumulated water is usually accompanied by a modifier such as, "in the rooting zone."

Numerous methods of obtaining soil moisture are available and include direct, indirect and remote soil moisture measurement. Direct measurements of soil water content involve removing water from a soil sample by evaporation, leaching or chemical reaction. The soil moisture content is calculated from the mass of water removed and the mass of the dry soil. Indirect methods involve measurement of some property of the soil that is affected by soil water content. Indirect methods can also measure a property of some object placed in the soil. The object placed in the soil is normally a porous absorber which comes to water equilibrium with the soil. Unfortunately, the relationships between chemical and physical soil properties and soil water content are not all well understood. The need for indirect methods for obtaining water content or indices of water content is evident when the time and labour involved in direct sampling is considered. Remote measurements include both non-contact methods and measurement from a great distance. Remote sensing of soil moisture depends on the measurement of electromagnetic energy that has either been reflected or emitted from the soil surface. The variation in intensity of electromagnetic radiation with soil moisture depends on either the dielectric properties (index of refraction), soil temperature or a combination of both. The property that is important depends on the wavelength region that is being considered. Soil moisture measurements from a great distance normally involve satellite systems measuring the spectral reflectance of the soil surface.

1. GRAVIMETRIC TECHNIQUES

1.1 OVERVIEW

Gravimetric measurement of soil water content is based on removal of water from the sample. Sample water is removed by evaporation, leaching or chemical reaction. Once sample water is removed, the amount of water removed from the sample is determined and used to calculate soil moisture content. Determination of water content removed is done using several methods. The simplest method to determine water content removed is by measurement of loss of weight of the sample. Sample water content can also be determined by collection of the water through distillation or absorption in a desiccant. Extraction of substances which replace sample water and measurement of a physical or chemical property of the extracting material that is affected by water content is another method. Finally, sample water content can be determined by quantitative measurement of reaction products displaced from a sample. In each of these methods the water and soil are separated and the amount of water removed is measured or inferred.

Oven drying is the most widely used of all gravimetric methods. The oven dry method is the standard for the calibration of all other soil moisture determination techniques.

1.2 PRINCIPLE

Apparatus required for gravimetric water content measurements comes in many different forms and so exact specifications are not needed. For the oven drying method, apparatus normally includes a soil sampling device such as an auger or sampling tube. In addition, soil containers with tight-fitting lids, an oven with means for controlling the temperature, a desiccator with active desiccant and a balance for weighing samples are typical of the oven drying method. Both convective and forced-draft ovens are used. For precise work a vacuum oven can be of benefit. Balances used range from analytical balances to rough platform scales. The balance used is dependent on the size of the sample used and the precision of measurement desired. If soil samples are taken under conditions where evaporation losses may affect the accuracy of measurement, equipment for weighing the samples immediately or reducing evaporative loss are used.

1.3 METHODOLOGY

For the oven drying method, moisture content is determined by measuring the weight of water removed. Drying the moist soil to a constant weight in a drying oven is controlled at 230° ± 9° F (110° ± 5° C). Temperature of the drying oven is checked frequently to ensure adequate temperature is maintained. The time necessary to reach constant weight will depend upon the type of oven used, the size or depth of the sample and the nature of the soil. If a forced draft oven is used, samples should be dried for at least 24 hours. Precautions should also be taken to avoid adding wet samples during the last half of the drying period. Additional time should be added if the oven is loaded heavily. The weight of soil remaining after oven drying is used as the weight of soil solids. Moisture content expressed as a percent is equal to the weight of water divided by weight of soil solids all times 100. An alternative method may be used for drying soil. Radiation drying can be used for soil water content measurements where low precision is adequate. Radiation drying uses an infrared or ordinary heat lamp. The variable drying temperature makes radiation-drying less accurate than those methods using closely controlled, constant temperature drying ovens. However, the radiation drying method is rapid, requiring only a few minutes to dry the soil.

Water content for stony or gravely soils, both on a mass and volume basis, can be grossly misleading. A large rock can occupy a large volume of a soil sample. Since rocks contribute to the mass and not the water capacity of the soil, errors arise. For near surface soil moisture measurement, gravimetric techniques are reliable, destructive and tedious. Rapid moisture changes imply frequent sampling and interference with the surface by repeated sampling could be a severe drawback in some studies. In addition to requiring a waiting time for oven drying, direct sampling methods are destructive and disturb measurement areas.

Moisture content is computed as:

$$\text{Percent Moisture Content, Dry Basis} = 100 \times \frac{Wt - Ws}{Ws}$$

Where: Wt = weight of soil and water

Ws = Dry soil weight (weight of soil solids)

In order to avoid possible organic matter decomposition by heat, a material may be dried using a desiccant. A material may be dried by placing a weighed portion of the material in a closed container with a relatively large quantity of desiccant. The moisture is gradually vaporized and then absorbed into the desiccant. The time required for this process is too great for the method to be of widespread practical importance. Despite the limitations, desiccant drying may be very accurate and useful for some low moisture content materials.

There are several distillation methods which may be used for moisture determination. They involve removing the moisture from the material, heating it in oil or some other non-aqueous liquid and measuring either the weight loss or the volume of water distilled from the material.

OVEN DRYING SUMMARY

Accuracy

- Oven drying is considered the standard method for obtaining soil moisture content.

Surface Accuracy

- Obtaining a representative moisture value of the surface is difficult because of reduced resolution.

Equipment

- Equipment includes a sampler, scale, and oven.
- Very simple equipment requirements.

Ease of Sampling

- Sampling is a very tedious and time consuming job.
- Measurement in frozen soil conditions is difficult.

Time of Sampling

- Time to dry sample is approximately 24 hours, which will drastically reduce sample rate.
- Soil moisture content is easily calculated on mass basis.

Disturbance of Site

- If sampling is required over long periods, direct methods can be very destructive to the site.

Calibrations

- No specific site calibrations are required.

Resolution

- Obtaining representative soil moisture values in a heterogeneous soil profile is difficult.

- It is difficult to determine moisture content at specific depths.

Health Risk

- No health risks associated with method.

Expense

- Sample acquisition is inexpensive compared to other methods.

2. NEUTRON SCATTERING

2.1 OVERVIEW

The neutron scattering method is an indirect way of determining soil moisture content. This method measures the moisture content of the soil by measuring the thermal or slow neutron density.

2.2 PRINCIPLE

Average energy loss or thermalization is much greater when neutrons collide with atoms of low atomic weight than from collisions with heavier atoms. In soils, low atomic weight atoms are primarily hydrogen. As a result, hydrogen can decelerate fast neutrons much more effectively than any other element present in the soil or vapour state. Since water is the largest source of hydrogen atoms in soil, a relationship between water content and neutron thermalization exists.

When fast neutrons of high energy are emitted by a radioactive source into a soil and are slowed by elastic collisions with nuclei of atoms they become thermalized. As fast neutrons move into moist soil, they become surrounded by a cloud of thermal neutrons. The density of this cloud represents an equilibrium between the rate of emission of fast neutrons and their thermalization by nuclei. Each neutron travels a specific distance from the source before making a sufficient number of collisions to become thermalized. The distance each neutron has to travel is determined by the capture cross-section and concentration of hydrogen nuclei. The farther the neutron travels from the source, the larger the volume which will be occupied by thermal neutrons and the lower their density. With the number of neutrons involved, the absorption capacity of the soil for neutron capture is essentially infinite. Since the rate of neutron capture depends upon the thermal neutron concentration and the combined capture cross section of the elements in the soil, hydrogen concentration can be determined. If the capture cross section remains constant, the thermal neutron density may be calibrated against water concentration on a volume basis. Soil moisture is determined from the slow neutron count and calibration curves of counts versus volumetric water content.

The nature of neutron scattering and the thermalization process imposes important restrictions on the resolution of water content measurements. The volume of soil involved in the measurement will depend upon the concentration of scattering nuclei and thus, largely upon water content. The volume of soil involved is also dependent on the energies o f the mitted fast neutrons. Experimental work indicates that the practical resolution ranges from about a 16 cm radius at saturation to 70 cm at near zero water content. Lack of high resolution makes it difficult to accurately detect any discontinuity or sharp change in water content gradient in a soil profile. In particular, measurements close to the surface are unreliable because of the discontinuity at the interface between soil and air.

2.3 METHODOLOGY

Neutron moisture probes consist of a source of fast neutrons, a thermalized neutron detector and a protective shield. Probes may also contain a scaler for registration of counts or a meter for direct display of water content. Some neutron probes come with a built-in computer for mathematic computation. The protective shield is used for neutron absorption and is normally composed of lead with polyethylene or paraffin serving as a reference standard. The neutron source usually is a small capsule of Americium-241/ Beryllium located on the side of the detector cylinder or an annular ring placed around the detector. Units are available with several different neutron source strengths and arrangements. Separate gamma ray density units for back scattering bulk density measurements or a density probe combined with a moisture probe also are available commercially. A separate neutron moisture meter for use on surface soil also is available.

The fast neutron source is placed in the soil with an auger. A soil auger slightly smaller than the access tubing is used to assure a tight fit. In loose soil no air space in the vicinity of the access hole should exist. An air space will influence the thermalized neutron distribution and, consequently, the neutron count. To make a measurement the probe unit is placed over the access tube. Several sizes of tubing are available. The size of tubing should be consistent with the probe size. Consistent tube sizes will reduce errors associated with an air gap which may be created between the probe and the tubing wall. Select an appropriate counting time and make several standard counts while the probe is in the shield. The measurement used will be the ratio of the count taken at the particular position of the probe to the average of counts taken in the standard. This will correct for any electronic changes in the counting circuit. The calibration curve is then used to reduce count ratios to volumetric water content, or read water content directly if the equipment has a computer.

For many practical applications manufacturers' calibrations are accurate enough. However, calibrations may be required if a soil has unusual neutron absorption characteristics. In addition, calibrations are required if the access tubing is a different size or material from that in which the probe was calibrated. Manufacturers claim that calibration curves for neutron count and volume of soil water are linear and apply to all soil types. In addition, manufacturers claim that calibration curves are unaffected by density, temperature, and other parameters. Manufacturers' claims may not be completely valid. However, if changes in moisture content are the concern, reliable data can be obtained using the manufacturer's calibration curve. Field calibration should only be used to detect large differences in calibration due to unusual soil conditions. However, field calibration should not be relied upon for precision work. Field calibration can cause inaccuracies associated with the determination of the volume basis water content values required.

Measurements are not usually made with well type equipment any closer than about 18 cm from the surface. Surface probes are used to obtain surface soil moisture measurements where well type units are inadequate. Surface probes use a slow neutron detector laid horizontally on the surface of the soil with a fast neutron source beside it. Most surface probes use a moderator rich in hydrogen (paraffin or polyethylene) over the source and detector to compensate for the discontinuity at the interface between soil and air. While soil probes measure surface soil moisture content, surface probes are considerably less accurate than well type equipment. Experimental work indicates that surface units have a sensitivity depth of 15 to 35 cm. Where water content is not uniform or the soil surface is rough, precision falls off drastically.

There are two major disadvantages of neutron probes for near surface soil moisture measurement. The volume sampled varies in shape and size with moisture content distribution. There is also difficulty in measuring moisture near the surface. Surface measurement is difficult because a large and unpredictable proportion of the fast neutrons escape into the atmosphere. Numerous solutions to eliminate neutrons escaping have been suggested. However, none of the solutions have alleviated the problem of a changing large sample volume. In addition, steep gradients of moisture content in the surface layer can also cause errors. Gradient errors in moisture content measurement are similar to errors associated with abrupt changes in soil properties in a layered soil.

NEUTRON SCATTERING SUMMARY

Accuracy

- Accuracy of greater than 0.1% can be achieved with some commercial instruments.
- The moisture measurement depends on many physical and chemical properties of the soil, which are, in themselves, difficult to measure.

Surface Accuracy

- The sphere of influence of the depth probe does not allow accurate measurements of soil water at or near the soil surface.

Equipment

- The method is portable and commercial units are simple to use. However, a permit for radioactive material is required.

Ease of Sampling

- Moisture can be measured regardless of physical state.
- The system can be interfaced to a data logger to accommodate automatic readings.

- Temporal soil moisture changes can be easily monitored.
- The ability to record moisture as percentage by volume.

Time of Sampling

- Rapid changes in soil moisture can be detected.
- Relatively rapid in obtaining soil moisture data (1 to 5 minutes per moisture value)
- Can be set up as an automatic recording system.

Disturbance of Site

- Measurements can be made repeatedly at the same site.
- Once an access tube is located there is no further disruption of the soil. Moisture readings can then be taken frequently and with minor inconvenience to the operator.

Calibrations

- Readings are directly related to soil moisture.
- Calibration in site specific soils can be difficult.

Resolution

- Inadequate depth resolution makes measurement of absolute moisture content difficult. Absolute moisture measurement is difficult due to large, unpredictable proportions of fast neutrons escaping into the atmosphere.
- Interpretation of results can be difficult because the actual sampling volume which neutron moderation is gauged by the detector is never known precisely. Volume varies inversely with water content and water nearer the source has a greater effect on the shape of the volume.

Health Risk

- Care must be taken to minimize health risks.

Expense

- High equipment cost and radioactive material license is required.

3. GAMMA RAY ATTENUATION

3.1 OVERVIEW

The gamma ray attenuation method is a radioactive technique that can be used to determine soil moisture content within a 1 to 2 cm soil layer.

3.2 PRINCIPLE

Principles of absorption by matter of gamma rays is well known. The amount a beam of monoenergetic gamma rays is attenuated or reduced in intensity in soil depends upon the soil's constituent elements and the density of the soil column. Gamma ray attenuation assumes that scattering and absorption of gamma rays is related to the density of matter in their path. Gamma ray attenuation also assumes that the specific gravity of a soil remains relatively constant as the wet density changes with moisture content. Changes in wet density are measured by the gamma transmission technique and the moisture content determined from this density change. Simply, if soil constituents and bulk density without water remain constant, then changes in gamma ray attenuation represent changes in water content.

If measurements are made at two different gamma ray energies, attenuation equations may be solved simultaneously to provide both water content and soil bulk density. Bulk density often changes with the wetting and drying of a soil. By using the dual gamma technique the accuracy of water content measurements improves compared to when bulk density must be assumed to remain constant.

3.3 METHODOLOGY

Basic equipment includes a gamma ray source surrounded by a collimator, a detector with a collimator, and a scaler. Cesium-137, which emits gamma rays at 0.662 MeV and Americium at 0.060 MeV are well suited for water content measurements. The size of the gamma ray source depends upon the use of the equipment. Sources of 20 to 25 mCi have been satisfactorily used. However, where rapidly changing water content is to be followed, counting times of only a few seconds are required, or where resolution of the order of a millimetre or less is required, much larger sources are desirable. Sources from 100 to 500 mCi have proven satisfactory under more stringent conditions. Gamma ray sources are housed in lead shields with suitable collimating holes or slits. With protective plugs for collimating slits, shields serve also as storage containers.

Gamma rays may be collimated to a narrow beam, which permits a representative reading to be obtained at any position in the soil. The precision of gamma ray methods for measuring water content varies with several soil properties. Bulk density measurements vary with thickness and density of the soil column, the absorption characteristics of the soil, and the size of the gamma count in a moist and dry soil column. Since attenuation of gamma rays is independent of the state of the water in the material tested, the measurement of attenuation is unaffected by the transition of liquid water to ice. Therefore, the use of gamma attenuation has an advantage in that measurements of dry bulk density and total water content (including ice) can be made simultaneously.

GAMMA RAY SUMMARY

Accuracy

- Large variations in bulk density and moisture content can occur in highly stratified soil and limit spatial resolution.
- Inability to measure in situ water condition when the soil is freezing, thawing, or frozen.

Surface Accuracy

- Surface accuracy is normally the same as subsurface accuracy.

Equipment

- Field instrumentation is costly and difficult to use.

Ease of Sampling

- The system can be interfaced to accommodate automatic readings.
- Temporal soil moisture changes can be easily monitored.

Time of Sampling

- Sampling time is relatively short, 10 seconds.

Disturbance of Site

- The measurement is non destructive.

Calibrations

- Calibrations may be required for specific sites.

Resolution

- Data can be obtained over very small horizontal or vertical distances.
- Average moisture content can be determined with depth.

Health Risk

- Extreme care must be taken to ensure that radioactive source in not a health hazard.

Expense

- Equipment can be relatively expensive.

4. ELECTROMAGNETIC TECHNIQUE INCLUDING POROUS BLOCKS

4.1 OVERVIEW

Electromagnetic techniques include methods which depend upon moisture effects on the electrical properties of soil. The dependence of dielectric properties of soil on moisture content can be used for either in situ or remote sensors. A variety of implanted sensors have been constructed which are responsive either to resistivity, polarization, or both. Directly implanted methods appear very promising for near surface measurements. Unfortunately, non near surface measurements made directly in soil have not resulted in unique correlations with water content. While some problems remain, considerable progress with direct sensors has been reported in the last few years. While the probes are very simple, the bridge circuitry to interrogate them has been costly.

4.2 PRINCIPLE

The magnetic permeability of soil is close to that of free space. By using electromagnetic techniques, the moisture dependence of the soil's dielectric properties can be used to determine soil moisture. Dielectric properties of moist soil may be characterized by a frequency dependant complex dielectric response function. The function is a measure of the energy dissipation rate in the medium. Viewed as a function of frequency, and starting from low wavelengths, the response function rises to a peak and then decreases. The behaviour is due to permanent dipoles in the soil medium.

The resistivity of soils depends on moisture content and can thus serve as the basis for a sensor. Unfortunately, soil heterogeneity prevents uniform flow of current in soil and is an obstacle to successful use of direct electrical resistance methods. In addition, since resistivity depends on ion concentration as well as on moisture concentration direct measurements are difficult.

Many of the problems involved in measurement of electrical and thermal conductivity and capacitance in soil are avoided by use of porous blocks. Porous blocks use resistivity measured indirectly from a material in equilibrium with the soil. When these blocks reach equilibrium with the surrounding soil, their electric or thermal properties are often regarded as an index of soil water content. Porous blocks contain imbedded electrodes sensitive to polarization which in essence measure capacitance. Capacitance is the electrical quantity that most directly indicates moisture concentration.

The relationship between moisture and the dielectric response function is linear. Since the equilibrium is a matric potential and not a water content equilibrium, associated soil water content must be obtained from a calibration curve. The calibration curve is made using soil from the site under investigation. In addition, the electrical conductivity of porous block depends upon the electrolyte concentration of the conducting fluid and the cross section of this fluid content. In a porous block made from an inert material, the electrolytes that carry the current come from the soil solution. Even a small change in electrolyte concentration will influence the resistance.

There is difficultly in specifying an expected precision for water content measurements using electrical conductivity blocks. The difficulty arises because of the many sources of error involved. The key problem in water content determination in porous materials has to do with the definition of dry state. The relationship is such that the sensitivity, low for wet soil, increases rapidly as the soil dries. Due to the porosity of the sensors, there is a time lag before a true reading is obtained after a sudden change in soil moisture. The lag is influenced by the density and dimensions of the sensor. In addition, for near surface soil moisture measurement, rapid fluctuations from wet to dry conditions and vice versa cause precision problems. The fluctuations occur since blocks have an appreciable time lag before a true reading is obtained. Precision better than ± 2% water content should not be expected and errors as great as 100% easily are possible. Hysteresis enters into the problem of inferring water content from measurements made on porous blocks. Even though a calibration curve for a particular soil is available, the water content of both soil and block depends in part upon the soil's wetting history. Ideally, two calibration curves are needed, one for drying and one for wetting. Unfortunately, since it is difficult to wet a soil only part way, a wetting curve is usually not made.

4.3 METHODOLOGY

Porous blocks are the most widely used for moisture measurement and are available in a variety of porous materials ranging from nylon cloth and fibreglass to casting plasters. The most common porous block is a form of gypsum. Several different electrode systems are in common use. Common electrode systems are imbedded 1 or 2 cm apart in a rectangular porous block roughly 1 by 3 by 5 cm. Each block is calibrated in soil and soil density typical of the site the block is to be used in.

The water content of a porous block coming to water equilibrium with a soil depends on the energy status of the water rather than the water content of the soil. Soils with fine pores will contain more water than soil with coarse pores at equal matric potential. Hence, if porous blocks are to provide an indirect measure of soil water content, calibration is necessary. Calibration against the water content of a sample of soil in which the block is to be used is required. In addition, some indication of the wetting history of the soil is of value.

In calibration as well as under field conditions, true water content equilibria is rarely reached, particularly in the dry range. However, the uncertainty of the water content inference, at best, does not justify an elaborate and time consuming calibration. Under practical conditions, when the resistance reading approaches a constant value equilibrium may be assumed consistent. In the wet range, for most porous blocks the resistance change with changing water content is small and the precision is low. Precision is also affected by changes in the calibration curve over successive wetting and drying cycles.

POROUS BLOCK SUMMARY

Accuracy

- With calibration, they are capable, in principle, of providing absolute values for soil moisture.
- The precision of both the resistive and capacitive sensors is high. Resistive sensors are also relatively accurate when other parameters are adequately controlled and the capacitive sensors have relatively high intrinsic accuracy that is more nearly independent of parameters other than moisture.
- Inability of the sensor to measure very tightly bound water. This is especially true in high clay content soil/water systems.

Surface Accuracy

- Difficulty of calibration and drying and wetting cycles can cause large errors on surface.

Equipment

- Relatively simple. Blocks must be placed in the soil and remain there over the sampling period.

Ease of Sampling

- Simple, once block has reached equilibrium.

Time of Sampling

- Quit sampling once blocks have reached equilibrium.

Disturbance of Site

- The moisture sensor must be implanted properly to minimize disturbance to the soil.

Calibration

- These are questions of long-term reliability and maintenance of the calibration, especially if the ionic concentration in the soil water changes.

Resolution

- They can be implanted at any depth, thus moisture profile data can be obtained by this method.

- A variety of sensor configurations varying from very small to large are possible, and hence there is some control over the sensor volume of influence.

Health Risk

- No health risks are involved.

Expense

- Cost of readout devices and interfaces with remote collection platforms can be high.

5. TENSIOMETRIC TECHNIQUES

5.1 OVERVIEW

The most widely known method for measuring the capillary or moisture potential is based upon the so-called suction force of the soil for water. These types of systems are capable of monitoring soil tension changes occurring in infiltration, irrigation, groundwater recharge and evapotranspiration studies. The term tensiometer is an unambiguous reference to the porous cup and vacuum gage combination. Tensiometer is regarded as a method for measuring capillary tension or the energy with which water is held by the soil.

5.2 PRINCIPLE

The energy with which water is held by the soil can be defined as the common log of the height of a water column in centimetres equivalent to the soil moisture tension. The energy with which water is held by the soil can also be defined as a suction (negative pressure) or a potential (energy per unit mass). Matric suction is the pressure difference across a boundary permeable only to water. Where the boundary solute separates bulk water and soil water in hydraulic, chemical, and thermal equilibrium. Dissolved salts or chemicals in the soil water contribute to solute suction.

Tensiometers are used to measure suction and consist of a liquid-filled porous ceramic cup connected by a continuous liquid column to a manometer or vacuum gage. The ceramic cup is porous to water and solute but not to air. From changes in water flow, changes in soil water conditions or moisture content can be determined. As the soil water increases, it is held at a lower tension. When the tensiometer reads zero, the soil is saturated, and water tension is zero. The highest tension reading that can be obtained with a tensiometer is about 1 bar. This means that the moisture content range over which the tensiometer can be used is limited. In contrast, at quite high soil water potential under very dry conditions tensiometers break down.

5.3 METHODOLOGY

Many techniques have been used to design tensiometers. In most cases tensiometers are constructed by using a ceramic cup about 20 mm in diameter on the end of rigid plastic tubing. A perforation is made in the plastic tube a few centimetres below the top, and the top is covered with a rubber stopper. A vacuum gauge or manometer can be inserted at the perforation to measure the soil water tension.

One technique is to make an oversized hole in the soil to a depth about 8 cm above the point at which the soil moisture content or tension data are required. Another soil probe is then inserted, which produces a hole 8 cm deep and of the same diameter as the ceramic cup. The tensiometer is then inserted into the hole. The essential steps in the technique include eliminating air from the water or solution in the tensiometer, placing the tensiometer system in the soil, and allowing it to come to equilibrium with the soil water. Soil water conditions or the change in soil moisture can then be determined. As soil water content increases, water is held at a lower tension. The highest tension reading that can be obtained with a tensiometer is around 1 bar. Therefore, the moisture content range over which the tensiometer may cover more than 90% of the available moisture content range.

TENSIOMETER SUMMARY

Accuracy

- Tensiometers provide direct measurement of soil water suction, but only indirect measurement of soil moisture content. To understand the relationship between suction and moisture content requires knowledge of the moisture characteristics for the soil.

- Field installations using pressure transducers drift electronically.
- The technique covers only a limited range at the moist end of the scale running from pF 1 - 2.7. Above pF 2.7 tensiometers ceases to be accurate and soon breaks down completely, requiring recharging with air free water. If the pores in the tensiometer are very small, ranges can be extended slightly. However, response time for fluctuations in soil potential becomes excessive.
- The range of information obtainable is limited to 0 - 800 cm of water tension.

Surface Accuracy

- Direct surface measurement is not possible.

Equipment

- Systems are easy to design and construct.
- Systems can operate over long periods if properly maintained.

Ease of Sampling

- Different types of liquids, like ethylene glycol solution, can be used to obtain data during freezing and thawing conditions. When soils are frozen, the tension of the unfrozen water is greater than 800 cm and the system fails.
- Tensiometers can be broken easily during installation.

Time of Sampling

- Information can be obtained on moisture distributions under saturated and unsaturated conditions in near real time.
- With the tensiometer/transducer system the response time is very rapid.

Disturbance of Site

- Tensiometers can usually be placed in soil easily and usually with minimal disturbance.

Calibration

- Understanding of soil suction in different soils is required.

Resolution

- Systems can be used with positive or negative reading tensiometers. With positive and negative systems both water table evaluation and soil moisture tension, depending on soil water status, can be read.

Health Risks

- No health risks are involved in the system.

Expense

- Systems cost relatively little.

6. MICROWAVE METHODS

6.1 OVERVIEW

Water is unique in that it is near the extremes in its thermal and dielectric properties. The dielectric properties of a soil are strong functions of moisture content. One dielectric property of a soil is thermal emission. Thermal emission from a soil surface in the microwave region may be detected remotely by the use of microwave radiometry. The parameter which is effectively measured is the brightness temperature. Brightness temperature is the product of the temperature and emissivity of the surface. Thermal microwave emission in the surface layers (fractions of a wavelength) is moderated by the dielectric gradients in the soil which in turn are dependant on soil moisture content.

Dielectric properties of a medium determine the propagation characteristics for electromagnetic waves in the medium. Therefore, dielectric properties will affect the emissive and reflective properties at the soil surface. As a result, the emissive and reflective properties at the soil surface depend on the soil moisture content. Soil moisture content can therefore be measured in the microwave region of the spectrum by radiometric (passive) and radar (active) techniques. The physical relationship between the microwave response and soil moisture, and the ability of the microwave sensors to penetrate clouds, makes them very attractive for use as soil moisture sensors.

6.2 PRINCIPLE

PASSIVE MICROWAVE

A microwave radiometer measures the thermal emission from the surface. At microwave wavelengths the intensity of the observed emission is essential proportional to the product of the temperature and emissivity of the surface. The product of temperature and emissivity is commonly referred to as brightness temperature.

Thermal microwave emission from soils is normally within the soil volume. The amount of energy generated at any point within the volume depends on the soil dielectric properties and the soil temperature at that point. As energy propagates upward through the soil volume from its point of origin, it is affected by the dielectric gradients along the path of propagation. In addition, as energy crosses the surface boundary, it is reduced by the effective transmission coefficient (emissivity). The transmission coefficient (emissivity) is determined by the dielectric characteristics of the soil near the surface.

Effective sampling depths have been shown to be in the order of only a few tenths of a wavelength (Wilheit 1978). Thus for a 21 cm wavelength radiometer this depth is about 2-5 cm.

The resolution of a passive system is limited by the size of the antenna, and this for practical reasons will be limited to 5-10 km.

ACTIVE MICROWAVE

The backscattering from an extended target, such as a soil medium, is characterized by the target's scattering coefficient. The scattering coefficient represents the link between the target properties and the scatterometer responses. For a given set of sensor parameters (wavelength, polarization, and incidence angle about 0), the scattering coefficient of bare soil is a function of the soil moisture, surface roughness, and dielectric properties. Dielectric properties depend on the soil's moisture content.

The presence of a vegetative canopy over the soil surface reduces the sensitivity of the radar backscatter to soil moisture by attenuating the signal as it travels through the canopy down to the soil and back and contributing a backscatter component of its own. The effect of vegetative cover on the radar response to soil moisture is to reduce the sensitivity by about 40% compared with responses from bare soil when the two responses are compared as a function of field capacity in the top 5 cm.

The limiting factor is the ability of the system to measure soil moisture in only the top 5-10 cm layer. The sampling depth for active microwave sensors also is limited to the surface few centimetres of the soil for some wavelengths.

6.3 METHODOLOGY

Remote sensing with microwave offers rapid data collection over large areas on a repetitive basis. Several questions still need to be answered concerning the dependence of sensor observation on soil moisture and other parameters, like vegetation. The major problems related to remote sensing seem to be the spatial resolution, depth of penetration, and cost.

SUMMARY OF ACTIVE MICROWAVE

Accuracy

- The area of interest is relatively large.
- Somewhat susceptible to surface roughness and vegetation.
- Not as accurate as direct methods and limited to the top layer of the soil surface.

Surface Accuracy

- The accuracy is normally limited to the top layer of the soil surface but is dependant on frequency and moisture content.

Equipment

- Very complex equipment normally involving satellites.

Ease of Sampling

- Can be mounted on board aircraft and satellites.

Time of Sampling

- Sampling can be done whenever satellite systems are in the correct position.

Disturbance of Site

- No disturbance.

Calibrations

- No calibrations are required.

Resolution

- Able to penetrate the layer below the surface although the depth of penetration is dependent on frequency and moisture content.

Health Risk

- No health risk involved with the systems.

Expense

- Very expensive method involving the use of satellite systems in most cases.

7. NUCLEAR MAGNETIC RESONANCE

7.1 OVERVIEW

The use of nuclear magnetic resonance (NMR) to monitor moisture is due to the ability of NMR to identify the concentration of hydrogen atoms and thus, moisture in the soil. NMR has similar disadvantages to the neutron method such as being sensitive to organic matter. However, NMR has the advantage of being able to analyze between hydrogen atoms and water molecules in different binding states. Water molecules can be tightly bound hydrated water, loosely bound absorbed water and mobile free water.

In this technique, use is made of the resonance induced by a radio frequency electric field on certain atomic nuclei precessing in a strong magnetic field. Careful selection of radio frequency in relation to magnetic field strength can make this device specific for hydrogen, which means that small soil samples can be processed rapidly for determination of hydrogen and thus, soil moisture.

7.2 PRINCIPLE

Placement of a soil/water mixture in a fixed magnetic field and varying the magnetic field results in an increased absorption of energy at a specific frequency of the varying magnetic field. This is called nuclear magnetic resonance (NMR). Nuclear magnetic resonance uses resonance induced by a radio frequency electric field on certain atomic nuclei precessing in a strong magnetic field. The varying nuclear magnetization is converted into a voltage. Conversion is done by using either the single coil absorption technique or the quadrature coil induction technique. Careful selection of the radio frequency used in relation to magnetic field strength can make the device specific for hydrogen. Making the device specific to hydrogen allows the NMR spectrum to be directly related to water content of the soil. In addition, if the device is specific for hydrogen, small soil samples can be processed rapidly for determination of hydrogen and thus, soil moisture.

Pulsed NMR techniques offer several advantages over wide-line NMR absorption procedures. The analyzer contains electronics required to provide radio frequency pulses, signal detection and signal averaging. The system is tuned to analyze hydrogen (protons) in the sample. The protons accept energy from the radio frequency field when in a strong, fixed magnetic field. The protons then release this energy and return to equilibrium through a series of relaxation processes which can be easily measured. The measured difference in the relaxation processes is related to physical and chemical soil properties associated with the hydrogen in liquid and solid states.

7.3 METHODOLOGY

The NMR technique does appear to have potential for non-contact rapid measurement of moisture content. However, a reduction in size and cost is necessary for practical field applications.

SUMMARY OF NUCLEAR MAGNETIC RESONANCE

Accuracy

- Can be sensitive to organic matter content.
- Resolution causes precise depth measurements to be difficult.

Surface Accuracy

- Resolution causes precise depth measurements to be difficult.

Equipment

- A reduction in size and cost is necessary for practical field applications.

Ease of Sampling

- Sampling can be difficult because of the size of equipment.

Time of Sampling

- Rapid.

Disturbance of Site

- Nondestructive.

Calibration

- Site specific calibration is not required.

Resolution

- The type of moisture, as well as the amount can be identified
- Very small soil samples can be analyzed.

Health Risk

- Care must be taken to minimize health risks.

Expense

- Very expensive.

8. THERMAL METHODS

8.1 OVERVIEW

As thermal inertia of a porous medium depends on moisture content, soil surface temperature can be used as an indication of moisture content.

8.2 PRINCIPLE

The amplitude of the diurnal range of soil surface temperature is a function of both internal and external factors. The internal factors are thermal conductivity and heat capacity or thermal inertia. The external factors are primarily meteorological: solar radiation, air temperature, relative humidity, cloudiness and wind. The combined effect of these external factors is that of the driving function of the diurnal variation of surface temperature. Thermal inertia is an indication of the soil's resistance to this driving force. Since both heat capacity and thermal conductivity of a soil increase with an increase of soil moisture, the resulting thermal inertia increases.

A complicating factor is the effect of surface evaporation in reducing the net energy input to the soil from the sun. Evaporation compliments the other effects of water in soil by reducing the amplitude of the surface diurnal temperature cycle. As a result, the day-night temperature difference is an indicator of some combination of soil moisture and surface evaporation.

Numerous tests show that for particular soils, the diurnal range of surface temperature is a good measure of the moisture content in the surface (0-4 cm) layer. In addition, for a given set of diurnal meterological conditions, there is a wide range of temperature amplitude-water content relationships for different soils. However, when soil water content was transformed into pressure potential, a single relationship was found for the different soil types investigated. This is the basis for expressing moisture values as a percent of field capacity, where field capacity is the moisture content of the -1/3 bar pressure potential.

8.3 METHODOLOGY

This technique is not applicable to fields with a vegetative canopy. However, the difference between canopy temperature and ambient air temperature has long been known to be an indicator of crop stress.

SUMMARY OF THERMAL METHODS

Accuracy

- Not applicable to fields with surface cover.
- Dependant on numerous soil and environmental conditions.
- Limited to surface measurement of soil moisture in most cases.

Surface Accuracy

- Dependant on numerous soil and environmental conditions.

Equipment

- Portable surface heat sensors are normally employed.

Ease of Sampling

- Relatively simple sampling procedure.

Time of Sampling

- Limited to calibration environment.

Disturbance of Site

- No disturbance to site.

Calibration

- Required for site specific conditions. General trends of moisture content can be determined in some instances.

Resolution

- Dependant and mechanism used to transport thermal sensor.

Health Risk

- No health risk associated with systems.

Expense

- Expenses can vary with transport systems.

9. TIME DOMAIN REFLECTOMETRY (TDR)

9.1 OVERVIEW

Time domain reflectometry has been one of the more recent advances in determination of soil moisture content. Therefore, little research literature is available on the subject.

9.2 PRINCIPLE

In time domain reflectometry (TDR), a pulse of radio frequency energy is injected into a transmission line. The pulse's propagation velocity is then measured by detecting the reflected pulse from the end of the line. A delay time between transmitted and reflected pulses is then used to determine the velocity of the pulses. The velocity depends on the dielectric constant, loss of the transmission line dielectric and frequency. Where the loss is small relative to the dielectric constant, the velocity, may be approximated by v = c/ square root (E) where c is the velocity in free space. Tests done determined that moisture content determined by TDR correlated with gravimetric moisture content at r >0.9, but there was considerable scatter. Experimental results indicated that an accuracy of 2% volumetric moisture content can be achieved with TDR.

9.2 METHODOLOGY

Two probes or wave guides are placed in the soil using an installation tube. The depth of the moisture content reading is dependant on the length of the probe placed in the soil.

SUMMARY OF TIME DOMAIN REFLECTOMETRY

Accuracy

- Experimental results indicate accuracies of 2% can be achieved. Volumetric measurement of soil moisture content is made.

Surface Accuracy

- Guide lengths are usually greater than 6 inches.

Equipment

- Very complex.

Ease of Sampling

- Can be used very simply.

Time of Sampling

- Sampling can be done in less than 5 seconds. Long term sampling can be done with data loggers.

Disturbance of Site

- Little or no disturbance to test site.

Calibration

- No site specific calibrations required.

Resolution

- Very precise depth measurements are possible.

Health Risk

- No health risks involved.

Expense

- Very expensive.

10. HYGROMETRIC TECHNIQUES

10.1 OVERVIEW

The relationship between moisture content in porous materials and the relative humidity of the immediate atmosphere is reasonably well known. Therefore several relatively simple sensors for measuring RH have been designed. Sensors can be classified into seven types of hygrometers: electrical resistance, capacitance, piezoelectric sorption, infrared absorption, transmission, dimensionally varying element, dew point, and psychometric. Electrical resistance hygrometers utilize chemical salts and acids, aluminum oxide, electrolysis, thermal, and white hydrocal to measure RH. The measured resistance of the resistive element is a function of RH. The main use of the technology is in applications where RH in the material is directly related to other properties, an example would be drying and shrinking of cements.

White Hydrocal Method: The various types of electrical resistance hygrometers include chemical salts and acids, aluminum oxide, electrolysis, and thermal and white hydrocal. The measured resistance of the resistive element is a function of the relative humidity. Casting of the stainless steel electrodes in white hydrocal leads to greater accuracy. Casting in white hydrocal gives greater accuracy because the cement sets hard, is pure, contains no salts, and has a low solubility.

Capacitance Method: Two types of capacitance hygrometers are capacitive transducer and microwave refractometers. A typical capacitive transducer is constructed with a thin plastic film on acetyl resin. Acetyl resin is a crystalline form of the highly polymerized formaldehyde. The capacitor plates are formed with evaporated gold electrodes thin enough to be pervious to water vapour and still be conductive. Sensors of this type can be used in the range of 10-100% RH over a temperature range of 35-80C. The disadvantage to the sensor is the relatively small change in capacitance of the sensor related to the change in humidity.

Dew or Frost Point Method: This technique depends on the measurement of temperatures and is relatively simple and inexpensive. Systems have been designed which are very small.

Psychrometric Method: An advantage of the psychrometer is its simplicity. Two thermometers, one covered with a moist wick, are what is required. The thermometers are then placed in ambient air which has a velocity of more than 3 m/s. Miniature thermocouples psychrometers are also commonly used for measuring water potential in soil systems. Problems occur in the field since procedure calls for controlling the temperature of the psychrometer chamber. In some cases, chamber temperature must be constant to within 0.001 C. The time required for the chamber to reach temperature and humidity equilibrium may not allow such a small temperature fluctuation.

The primary advantages in using the aforementioned hygrometers are the simplicity of the apparatus and the low cost. The basic disadvantages in using the method include deterioration effects of the soil components on the sensing element and the requirements for special calibration for each material to be tested.

Calibration of thermocouple psychrometers is temperature dependant and diurnal soil temperature changes prevent in situ operation within about 300 mm of the surface.

11. ELECTROLYSIS METHOD

11.1 OVERVIEW

Electrolysis systems employ a continuous flow of gas mixture over a thin layer of partially hydrated phosphorus pentoxide (p205). The moisture in the gas is absorbed by the phosphorus pentoxide. A sensor can be built with two platinum wires placed helically inside an insulating tube. The tube is then coated with P205. A dc voltage is applied across the two wires, dissociating the water molecules into gaseous hydrogen and oxygen.

At equilibrium, the measured current is proportional to the moisture absorbed. The dc voltage must be larger than the polarization voltage (2v). The sensitivity of the measurement can be up to 1 ppm. However, the need for constant mass flow and constant temperature can cause problems with accuracy.

The response time for the measurement is relatively short.

The cost of the system is very high.

12. OPTICAL METHODS

12.1 OVERVIEW

Polarized Light

Optical methods are based on the principle that the presence of moisture at a surface of reflection tends to cause polarization in the reflected beam. An achromatic light source is directed at the soil surface. The reflected light passes through a polarizer onto a photocell. The polarizer can be rotated so horizontal and vertical polarization signals can be determined by the photocell. The percentage of polarized visible light is determined from these two measurements and has been found to relate to moisture content. However, calibration is also affected by soil type and the roughness of the surface. The source and detectors are contained in a light proof enclosure which is placed on the soil surface.

Near Infrared Methods

There are several water absorption bands in the near infrared (NIR), the strongest being at 1450, 1940, and 2950 nm, near infrared techniques may be used for monitoring soil moisture content. Such methods depend on molecular absorption at distinct wavelengths by water in the surface layers and are therefore not applicable where the moisture distribution is very non-homogeneous. The published literature on near infrared reflectance of soils indicates that the method has potential as a non-contact rapid moisture sensing technique, but with the apparent disadvantage of dependence on surface roughness, indication of surface moisture only and non-linear effects due to water filled pores at the surface.

13. MODELS

13.1 OVERVIEW

Recent developments of soil water models based on column mass balance provide an alternative to directly or indirectly measuring soil moisture in the field. Published soil moisture models vary in the level of detail they use in representing the physical system and temporal variations of the driving forces. Some of the important differences between models are:

- Method used for computing potential evapotranspiration.
- Method used for computing infiltration and runoff.
- Temporal definition of evaporative demand and precipitation.
- Consideration of saturated and unsaturated levels.
- Number of soil layers used.
- Method used for computing soil evaporation and plant transpiration.
- Consideration of the thermal properties of the soil system.

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