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Soil Moisture Sensors[1]

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INTRODUCTION

This bulletin is a survey and classification of the general methods for determining soil moisture. The techniques reviewed here involve the use of gravimetric, nuclear, electromagnetic, tensiometric, hygrometric, and remote sensing processes. Other miscellaneous methods are grouped under the heading Other Related Papers. Each of the soil moisture measuring methods is presented by means of (1) simple description, (2) measured parameter, (3) estimated response time, (4) disadvantages, (5) advantages, and (6) related papers.

GRAVIMETRIC TECHNIQUES

1. Description:

The oven-drying technique is probably the most widely used of all gravimetric methods for measuring soil moisture and is the standard for the calibration of all other soil moisture determination techniques. This method involves removing a soil sample from the field and determining the mass of water content in relation to the mass of dry soil. Although the use of this technique ensures accurate measurements, it also has a number of disadvantages: laboratory equipment, sampling tools, and 24 hours of drying time are required. In addition, it is a destructive test in that it requires sample removal. This makes it impossible to measure soil moisture at exactly the same point at a later date. Eventually, measurements will become inaccurate because of field variability from one site to another.

2. Measured Parameter:

Mass water content (percentage of dry vs. wet soil weight)

3. Response Time: ≈ 24 hours

4. Disadvantages:

- Destructive test
- Time consuming
- Inapplicable to automatic control
- Must know dry bulk density and transform data to volume moisture content

5. Advantages:

- Ensures accurate measurements
- Not dependent on salinity and soil type
- Easy to calculate

6. Related Literature:

Erbach, D.C. 1983. Measurement of soil moisture and bulk density. ASAE Paper No. 83-1553.

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Gardner, W.H. 1986. Water content. In: Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods (Klute, A., ed). Agronomy Series No. 9. Am. Soc. Agronomy, 2nd edition, pp. 493-544.

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Taylor, S.A. 1955. Field determinations of soil moisture. Ag. Engineering. 26:654-659.

NUCLEAR TECHNIQUES

Neutron Scattering

1. Description:

Neutron scattering is widely used for estimating volumetric water content. With this method, fast neutrons emitted from a radioactive source are thermalized or slowed down by hydrogen atoms in the soil. Since most hydrogen atoms in the soil are components of water molecules, the proportion of thermalized neutrons is related to soil water content. This method offers the advantage of measuring a large soil volume, and also the possibility of scanning at several depths to obtain a profile of moisture distribution. However, it also has a number of disadvantages: the high cost of the instrument, radiation hazard, insensitivity near the soil surface, insensitivity to small variations in moisture content at different points within a 30 to 40 cm radius, and variation in readings due to soil density variations, which may cause an error rate of up to 15 percent (Phene, 1988).

2. Measured Parameter:

Volumetric water content (percentage of volume)

3. Response Time: 1 to 2 min.

4. Disadvantages:

- Costly
- Dependent on dry bulk density and salinity
- Radiation hazard
- Must calibrate for different types of soils
- Access tubes must be installed and removed
- Depth resolution questionable
- Measurement partially dependent on physical and chemical soil properties
- Depth probe cannot measure soil water near soil surface
- Subject to electrical drift and failure

5. Advantages:

- Nondestructive
- Possible to obtain profile of water content in soil
- Water can be measured in any phase
- Can be automated for one site to monitor spatial and temporal soil water
- Measurement directly related to soil water content

6. Related Literature:

Augustin, B.J. and G.H. Snyder. 1984. Moisture sensor-controlled irrigation for maintaining bermudagrass turf. Agron. J., 76:848-850.

Bavel, C.H.M., D.R. Nielsen and J.M. Davidson. 1961. Calibration and characteristics of two neutron moisture probes. Soil Sci. Soc. Am. Proc., Vol. 25. pp. 329-333.

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Goodspees, M.J. 1981. Neutron moisture meter theory. Soil Water Assessment by The Neutron Method. Gsiro, Australia.

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Stafford, J.V. 1988. Remote, non-contact and in-situ measurement of soil moisture content: a review. J. Agric. Eng. Res. 41:151-172.

Taylor, S.A. 1955. Field determinations of soil moisture. Ag. Engineering. 26:654-659.

Tollner, E.W. and R.B. Noss. 1988. Neutron probe vs. tensiometer vs. gypsum blocks for monitoring soil moisture status. Sensors and Techniques for Irrigation Management. Center for Irrigation Technology, California State Univ., Fresno, CA 93740-0018. pp. 95-112.

Tyler, S.W. 1987. Application of neutron moisture meters in large diameter boreholes. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 41-44.

Gamma Attenuation

1. Description:

The gamma ray attenuation method is a radioactive technique that can be used to determine soil moisture content. This method assumes that the scattering and absorption of gamma rays are related to the density of matter in their path and that the specific gravity of a soil remains relatively constant as the wet density changes with increases or decreases in moisture. Changes in wet density are measured by the gamma transmission technique and the moisture content is determined from this density change.

2. Measured Parameter: Volumetric water content

3. Response Time: < 1 min.

4. Disadvantages:

- Restricted to soil thickness of 1 inch or less, but with high resolution
- Affected by soil bulk density changes
- Costly and difficult to use
- Large errors possible when used in highly stratified soils

5. Advantages:

- Can determine mean water content with depth
- Can be automated for automatic measurements and recording
- Can measure temporal changes in soil water
- Nondestructive measurement

6. Related Literature:

Gardner, W.H., G.S. Campbell and C. Calissendorff. 1972. Systematic and random errors in dual gamma energy soil bulk density and water content measurements. Soil Sci. Soc. Am. Proc. 36:393-398.

Gardner, W.H. 1986. Water content. In: Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods (Klute, A., ed). Agronomy Series No. 9. Am. Soc. Agronomy, 2nd edition, pp. 493-544.

Gurr, C.C. 1959. Use of gamma rays in measuring water content and permeability in unsaturated columns of soil. Soil Sci. pp. 224-229.

Mckim, H.L., J.E. Walsh and D.N. Arion. 1980. Review of techniques for measuring soil moisture in situ. United States Army Corps of Engineers, Cold Regions Research and Engineering Lab., Special Report 80-31.

Nofziger, D.L. 1978. Errors in Gamma-ray measurements of water content and bulk density in nonuniform soils. Soil Sci. Soc. Am. Proc., Vol. 42. pp. 845-850.

Nuclear Magnetic Resonance

1. Description:

With this technique, water in the soil is subjected to both a static and an oscillating magnetic field at right angles to each other. A radio frequency detection coil, turning capacitor, and electromagnet coil are used as sensors to measure the spin echo and free induction decays. Nuclear magnetic resonance imaging can discriminate between bound and free water in the soil.

2. Measured Parameter: Volumetric water content

3. Response Time: < 1 min.

4. Disadvantages: Same as for neutron scattering

5. Advantages: Same as for neutron scattering

6. Related Literature:

Anderson, S.H. and C.J. Gantzer. 1987. Determination of soil water content by X-ray computed tomography and NMR imaging. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 239-246.

Paetzold, R.F., A.D. Santos and G.A. Matzkanin. 1987. Pulsed nuclear magnetic resonance instrument for soil-water content measurement: sensor configurations. Soil Sci. Am. J. 51:287-290.

Stafford, J.V. 1988. Remote, non-contact and in-situ measurement of soil moisture content: a review. J. Ag. Eng. Res. 41:151-172.

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ELECTROMAGNETIC TECHNIQUES

Resistive Sensor (General)

1. Description:

Electromagnetic techniques include methods that depend upon the effect of moisture on the electrical properties of soil. Soil resistivity depends on moisture content; hence it can serve as the basis for a sensor. It is possible either to measure the resistivity between electrodes in a soil or to measure the resistivity of a material in equilibrium with the soil. The difficulty with resistive sensors is that the absolute value of soil resistivity depends on ion concentration as well as on moisture concentration. Therefore, careful calibration is required for these techniques.

2. Measured Parameter:

Soil water potential aided by electrical resistance measurements

3. Response Time: Instantaneous

4. Disadvantages:

- Calibration not stable with time and affected by ionic concentration
- Cost of equipment to generate signal and readout system is high but could decrease with new solid-state technology

5. Advantages:

- Theoretically, can provide absolute soil water content
- Can determine water content at any depth
- Sensor configuration can vary in size so sphere of influence or measurement is adjustable
- Relatively high level of precision when ionic concentration of the soil does not change
- Can be read by remote methods

Resistive Sensor (Gypsum)

1. Description:

One of the most common methods of estimating matric potential is with gypsum or porous blocks. The device consists of a porous block containing two electrodes connected to a wire lead. The porous block is made of gypsum or fiberglass. When the device is buried in the soil, water will move in or out of the block until the matric potential of the block and the soil are the same. The electrical conductivity of the block is then read with an alternating current bridge. A calibration curve is made to relate electrical conductivity to the matric potential for any particular soil. Using a porous electrical resistance block system offers the advantage of low cost and the possibility of measuring the same location in the field throughout the season. The blocks function over the entire range of soil water availability. The disadvantage of the porous block system is that each block has somewhat different characteristics and must be individually calibrated. The main disadvantage of the gypsum block is that the calibration changes gradually with time, limiting the life of the block (Phene, 1988).

2. **Measured Parameter:** Soil moisture tension

3. **Response Time:** 2 to 3 hours

4. **Disadvantages:**

- Each block requires individual calibration
- Calibration changes with time
- Life of device limited
- Provides inaccurate measurements

5. **Advantages:** Inexpensive

6. **Related Literature:**

Armstrong, C. Fletcher, J.T. Ligon and M.F. Mcleod. 1987. Automated system for detailed measurement of soil water potential profiles using watermark brand sensors. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 201-206.

Bloodworth, M.E. and J.B. Page. 1957. Use of thermistor for the measurement of soil moisture and temperature. Soil Sci. Soc. Am. Proc., Vol. 21. pp. 11-15.

Bouyoucos, G.J. and A.H. Mick. 1948. A comparison of electric resistance units for making a continuous measurement of soil moisture under field conditions. Plant Physiology. pp. 532-543.

Bouyoucos, G.J. and R.L. Cook. 1961. Humidity sensor: permanent electric hygrometer for continuous measurement of the relative humidity of the air. Soil Sci., Vol. 100. pp.63-67.

Carlson, T.N. and J.E. Salem. 1987. Measurement of soil moisture using gypsum blocks. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 193-200.

Cary, J.W. and H.D. Fisher. 1983. Irrigation decisions simplified with electronics and soil water sensors. Soil Sci. Soc. Am. J., 47:1219-1223.

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Rose, M.A. and J.M. Russo. 1987. Integrated system for evaluating performance of soil moisture units in field capacity conditions. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 207-214.

Taylor, S.A. 1955. Field determinations of soil moisture. Agr. Engineering. 26:654-659.

Thomson, S.J. and C.F. Armstrong. 1987. Calibration of the watermark model 200 soil moisture sensor. Applied Eng. in Agr. Vol. 3. pp. 186-189.

Tollner, E.W. and R.B. Noss. 1988. Neutron probe vs. tensiometers vs. gypsum blocks for monitoring soil moisture status. Sensors and Techniques for

Irrigation Management. Center for Irrigation Technology, California State Univ., Fresno, CA 93740-0018. pp. 95-112.

Wheeler, P.A. and G.L. Duncan. 1984. Electromagnetic detection of soil moisture. ASAE Paper No. 84-2078.

Capacitive Sensor

1. Description:

Soil moisture content may be determined via its effect on dielectric constant by measuring the capacitance between two electrodes implanted in the soil. Where soil moisture is predominantly in the form of free water (e.g., in sandy soils), the dielectric constant is directly proportional to the moisture content. The probe is normally given a frequency excitation to permit measurement of the dielectric constant. The readout from the probe is not linear with water content and is influenced by soil type and soil temperature. Therefore, careful calibration is required and long-term stability of the calibration is questionable.

2. Measured Parameter:

Volumetric soil water content

3. Response Time: Instantaneous

4. Disadvantages:

- Long-term stability questionable
- Costly

5. Advantages:

- Theoretically, can provide absolute soil water content
- Water content can be determined at any depth
- Sensor configuration can vary in size so sphere of influence or measurement is adjustable
- Relatively high level of precision when ionic concentration of soil does not change
- Can be read by remote methods

6. Related Literature:

Bell, J.P., T.J. Dean and A.J.B. Baty. 1987. Soil moisture measurement by an improved capacitance technique, Part II. Field techniques, evaluation and calibration. J. of Hydrology. 93:79-90.

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Halbertsma, J., C. Przybyla and A. Jacobs. 1987. Application and accuracy of a dielectric soil water content meter. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 11-16.

Malicki, M.A., E.C. Campbell and R.J. Hanks. 1987. Investigation on power factor of the soil electrical impedance as related to moisture, salinity and bulk density. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 233-238.

Malicki, M.A. and R.J. Hanks. 1989. Interfacial contribution to two-electrode soil moisture sensors reading. Irrig. Sci., 10:41-54.

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Varallyay, G. and K. Rajkal. 1987. Soil moisture content and moisture potential measuring techniques in Hungarian soil survey. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 183-184.

Time-Domain Reflectometer (TDR)

1. Description:

Time-domain reflectometer (TDR) determinations involve measuring the propagation of electromagnetic (EM) waves or signals. Propagation constants for EM waves in soil, such as velocity and attenuation, depend on soil properties, especially water content and electrical conductivity. The propagation of electrical signals in soil is influenced by soil water content and electrical conductivity. The dielectric constant, measured by TDR, provides a good measurement of this soil water content. This water content determination is essentially independent of soil texture, temperature, and salt content.

2. Measured Parameter:

Volumetric water content aided by propagation of electromagnetic wave measurements.

3. Response Time: ≈ 28 sec.

4. Disadvantages: Costly

5. Advantages:

- Independent of soil texture, temperature, and salt content
- Possible to perform long-term *in situ* measurements
- Can be automated

6. Related Literature:

Baker, J.M. and R.R. Allmaras. 1990. System for automating and multiplexing soil moisture measurement by time-domain reflectometry. J. Soil Sci. Soc. Am., 54(1):1-6.

Dalton, F.N. 1987. Measurement of soil water content and electrical conductivity using time-domain reflectometry. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 95-98.

Dasberg, S. and F.N. Dalton. 1985. Time domain reflectometry field measurements of soil water content and electrical conductivity. Soil Sci. Soc. Am. J., 49:293-297.

Dasberg, S. and A. Nadler. 1987. Field sampling of soil water content and electrical conductivity with time domain reflectometry. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 99-102.

Drungil, C.E.C., K. Abt and T.J. Gish. 1989. Soil moisture determination in gravelly soils with time domain reflectometry. Transaction of ASAE, Vol. 32(1), pp. 177-180.

Heimovaara, T.J. and W. Bouten. 1990. A computer-controlled 36-channel time domain reflectometry system for monitoring soil water contents. Water Resource Research, Vol. 26, pp. 2311-2316.

Herkelrath, W.N., S.P. Hamburg and Fred Murry. 1991. Automatic, real-time monitoring of soil moisture in a remote field area with time domain reflectometry. Water Resour. Res., Vol. 27, pp. 857-864.

Reeves, T.L. and S.M. Elgezawi. 1992. Time domain reflectometry for measuring volumetric water content in processed oil shale waste. Water Resource Research, 28:769-776.

Simpson, J.R. and J.J. Meyer. 1987. Water content measurements comparing a TDR array to neutron scattering. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 111-114.

Stein, J. and D.L. Kane. 1983. Monitoring the unfrozen water-content of soil and snow using time domain reflectometry. Water Resour. Res., 19:1573-1584.

Topp, G.C. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resources Research, 16:574-582.

Topp, G.C., J.L. Davis and A.P. Annan. 1982. Electromagnetic determination of soil water content using TDR: I. Application to wetting fronts and steep gradients. Soil Sci. Am. J., Vol. 46, pp. 672-677.

Topp, G.C. and J.L. Davis. 1985. Measurement of soil water content using time-domain reflectometry (TDR): A field evaluation. Soil Sci. Soc. Am. J., 49:19-24.

Topp, G.C. 1987. The application of time-domain reflectometry (TDR) to soil water content measurement. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 85-94.

TENSIOMETRIC TECHNIQUES

1. Description:

The primary method for measuring matric potential (capillaric tension) in soil involves the use of the tensiometer, which directly measures matric potential. Tensiometers are commercially available from several different sources and in numerous configurations. The main disadvantage of the tensiometer is that it functions only from zero to about -0.8 bar, which represents a small part of the entire range of available water. The lower moisture limit for the good growth of most crops is beyond the tensiometer range. It is apparent, therefore, that the use of the tensiometer to schedule irrigation can cause overirrigation, unless tensiometer readings are combined with information on soil water content (Phene, 1988).

2. Measured Parameter:

Soil water potential (capillary potential)

3. Response Time: 2 to 3 hours

4. Disadvantages:

- Limit range of 0 to -0.8 bar not adequate for sandy soil
- Difficult to translate data to volume water content
- Hystersis
- Requires regular (weekly or daily) maintenance, depending on range of measurements
- Subject to breakage during installation and cultural practices
- Automated systems costly and not electronically stable
- Disturbs soil above measurement point and can allow infiltration of irrigation water or rainfall along its stem

5. Advantages:

- Recommendation for irrigation policy developed with the aid of tensiometers
- Inexpensive and easily constructed
- Works well in the saturated range
- Easy to install and maintain
- Operates for long periods if properly maintained
- Can be adapted to automatic measurement with pressure transducers
- Can be operated in frozen soil with ethylene glycol
- Can be used with positive or negative gauge to read water table elevation and/or soil water tension

6. Related Literature:

Augustin, B.J. and G.H. Snyder. 1984. Moisture sensor-controlled irrigation for maintaining bermudagrass turf. Agron. J., 76:848-850.

Cassell, D.K. and A. Klute. 1986. Water potential: tensiometry, Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods (Klute, A., ed.). 2nd edition, Madison, Wisconsin.

Erbach, D.C. 1983. Measurement of soil moisture and bulk density. ASAE Paper No. 83-1553.

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Marvil. J.D., A.L. Flint and W.J. Davies. 1987. Tensiometer-transducer system: calibration and testing. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 151-155.

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Rogers, E.P. 1988. Care and Checking of Tensiometers. Sensors and Techniques for Irrigation Management. Center for Irrigation Technology, California State Univ., Fresno, CA 93740-0018, pp. 111-112.

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Taylor, S.A. 1955. Field determinations of soil moisture. Ag. Engineering. 26:654-659.

Tollner, E.W. and R.B. Moss. 1988. Neutron probe vs. tensiometers vs. gypsum blocks for monitoring soil moisture status. Sensors and Techniques for Irrigation Management. Center for Irrigation Technology, California State Univ., Fresno, CA 93740-0018, pp. 95-112.

Wierenga, P.J., J.L. Fowler and D.D. Davis. 1987. Use of tensiometer for scheduling drip-irrigated cotton. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 157-161.

HYGROMETRIC TECHNIQUES

1. Description:

The relationship between moisture content in porous materials and the relative humidity (RH) of the immediate atmosphere is reasonably well known. Since thermal inertia of a porous medium depends on moisture content, soil surface temperature can be used as an indication of moisture content. Electrical resistance hygrometers utilize chemical salts and acids, aluminum oxide, electrolysis, thermal principles, and white hydrosol to measure RH. The measured resistance of the resistive element is a function of RH. The main application for this technology seems to be in materials where RH is directly related to other properties.

2. Measured Parameter: Soil water potential

3. Response Time: < 3 min.

4. Disadvantages:

- Sensing element deteriorates through interaction with soil components
- Each material to be tested requires special calibration

5. Advantages:

- Wide soil matric potential range
- Low maintenance
- Well suited for automated measurements and control of irrigation systems

6. Related Literature:

Brown, R.W. and J.C. Chambers. 1987. Measurements of in situ water potential with thermocouple psychrometer: a critical evaluation. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 125-136.

Campbell, G.S. and W.H. Gardner. 1971. Psychometric measurement of soil water potential: temperature and bulk density effects. Soil Sci. Soc. Am. Proc., Vol. 35. pp. 8-11.

Campbell, G.S. 1979. Improved thermocouple psychrometers for measurement of soil water potential in a temperature gradient. J. Physics. E: Sci. Instr., 12:739-743.

Mckim, H.L., J.E. Walsh and D.N. Arion. 1980. Review of techniques for measuring soil moisture in situ. United States Army Corps of Engineers, Cold Regions Research and Engineering Lab., Special Report 80-31.

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Phene, C.J., G.J. Hoffman and R.S. Austin. 1973. Controlling automated irrigation with soil matric potential sensor. Trans. of ASAE, Paper No. 71-230.

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Savage, M.J., J.T. Ritchie and I.N. Khuvutlu. 1987. Soil hygrometers for obtaining water potential. International Conference on Measurement of Soil and Plant Water Status. Centennial of Utah State Univ., pp. 119-124.

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REMOTE SENSING TECHNIQUES

1. Description:

This method includes satellite, radar (microwaves), and other non-contact techniques. The remote sensing of soil moisture depends on the measurement of electromagnetic energy that has been either reflected or emitted from the soil surface. The intensity of this radiation with soil moisture may vary depending on dielectric properties, soil temperature, or some combination of both. For active radar, the attenuation of microwave energy may be used to indicate the moisture content of porous media because of the effect of moisture content on the dielectric constant. Thermal infrared wavelengths are commonly used for this measurement.

2. Measured Parameter:

Soil surface moisture, through the measurement of electromagnetic energy

3. Response Time: Instantaneous

4. Disadvantages:

- System large and complex
- Costly
- Usually used for surface soil

5. Advantages:

- Method allows remote measurements to be taken
- Enables measurements to be taken over a large area

6. Related Literature:

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OPTICAL METHODS

1. Description:

Optical methods rely on changes in the characteristics of light due to soil characteristics. These methods involve the use of polarized light, fibre optic sensors, and near-infrared sensors. Polarized light is based on the principle that the presence of moisture at a surface of reflection tends to cause polarization in the reflected beam. Using this device, an achromatic light source is directed at the soil surface. Fibre optic sensors are based on a section of unclad fibre embedded in the soil. Light attenuation in the fibre varies with the amount of soil water in contact with the fibre because of its effect on the refractive index and thus on the critical angle of internal reflection. Near-infrared methods depend on molecular absorption at distinct wavelengths by water in the surface layers; therefore, they are not applicable where the moisture distribution is very nonhomogeneous.

2. **Measured Parameter:** Soil water content

3. **Response Time:** Instantaneous

4. **Disadvantages and Advantages:**

These methods are still in developmental and experimental stages.

5. **Related Literature:**

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