INTRODUCTION TO ENVIRONMENTAL SOIL PHYSICS

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state of water in the soil and the state of water being measured in the block. This effect, as well as the sensitivity of the block, may not be constant over the entire range of variation in soil wetness. Gypsum blocks are generally more responsive in the dry range, whereas porous nylon blocks, because of their larger pore sizes, are more sensitive in the wet range of soil-moisture variation.

The electrical conductivity of a porous block made of inert material is due primarily to the permeating fluid rather than to the block's solid matrix. Thus it depends on the electrolytic solutes present in the fluid as well as on the volume content of the fluid. Blocks made of such materials as fiberglass, for instance, are highly sensitive to even small variations in salinity of the soil solution. On the other hand, blocks made of plaster of Paris (gypsum) maintain a nearly constant electrolyte concentration corresponding primarily to that of a saturated solution of calcium sulfate. This tends to mask, or buffer, the effect of small or even moderate variations in the soil solution (such as those due to fertilization or low levels of salinity). However, an undesirable consequence of the solubility of gypsum is that these blocks eventually deteriorate in the soil. Hence the relationship between electrical resistance and moisture suction varies not only from block to block but also for each block over time, because the gradual dissolution of the gypsum changes the internal porosity.

For these and other reasons (e.g., temperature sensitivity), the evaluation of soil wetness by means of electrical resistance blocks is likely to be of limited accuracy. On the other hand, an advantage of such blocks is that they can be connected to a recorder to obtain a continuous indication of soil moisture changes in situ.

Neutron Scattering

This method has gained widespread acceptance as an efficient and reliable technique for monitoring soil moisture in the field. Its principal advantages over the gravimetric method are that it allows less laborious, more rapid, non-destructive (after initial installation), and periodically repeatable measurements, in the same locations and depths, of the volumetric wetness of a representative volume of soil. The method is practically independent of temperature and pressure. Its main disadvantages, however, are the high initial cost of the instrument, low degree of spatial resolution, difficulty of measuring moisture in the soil surface zone, and the health hazard associated with exposure to neutron and gamma radiation.

The instrument, known as a neutron moisture meter (Fig. 6.2), consists of two main components: (a) a probe (containing a source of fast neutrons and a detector of slow neutrons), which is lowered into an access tube inserted vertically into the soil, and (b) a scaler or rate meter (usually battery powered and portable) to monitor the flux of the slow neutrons that are scattered and attenuated in the soil.

The purpose of the access tube is both to maintain the borehole into which

![Fig. 6.2. Components of a portable neutron soil-moisture meter, including a probe (with a source of fast neutrons and a detector of slow neutrons) lowered from a shield containing hydrogenous material (e.g., paraffin, polyethylene) into the soil via an access tube. A scaler-rate meter is shown alongside the probe. Recent models incorporate the scaler into the shield body, and the integrated unit is lightweight for easy portability.](image)

A source of fast neutrons is generally obtained by mixing a radioactive emitter of alpha particles (helium nuclei) with beryllium. Frequently used is a 2- to 5-millicurie pelletized mixture of radium and beryllium. An Ra-Be source emits about 16,000 neutrons per second per milligram (or millicurie) of radium. The energies of the neutrons emitted by this source vary from 1 to 15 MeV (million electron volts), with a preponderant energy range of 2–4 MeV and an average speed of about 1600 km/sec. Hence, they are called fast neutrons. An alternative source of fast neutrons is a mixture of americium and beryllium. Both radium and americium incidentally also emit gamma radiation, but that of the americium is lower in energy and hence less hazardous than that of the radium. The source materials are chosen for their longevity (e.g., radium-beryllium has a half-life of about 1620 yr) so that they can be used for a number of years without appreciable change in radiation flux.

The fast neutrons are emitted radially into the soil, where they encounter and collide elastically (as do billiard balls) with various atomic nuclei. Through repeated collisions, the neutrons are deflected and "scattered," and they gradually lose some of their kinetic energy. As the speed of the initially fast neutrons diminishes, it approaches a speed that is characteristic for particles at the ambient temperature. For neutrons this is about 2.7 km/sec, equivalent to an energy of about 0.03 eV. Neutrons slowed to such a speed are said to be thermalized and are called slow neutrons. Such neutrons continue to interact with the soil and are eventually absorbed by the nuclei present.
encountered in the soil, the ones most nearly equal in mass to neutrons are the nuclei of hydrogen (protons), which are therefore the most effective moderators of fast neutrons in the soil. The average number of collisions required to slow a neutron from 2 MeV to thermal energies is 18 for hydrogen, 144 for carbon, 150 for oxygen, and 9N + 6 for nuclei of larger mass number N. If the soil contains an appreciable concentration of hydrogen, the emitted fast neutrons are thermalized within close proximity of the source.

The slow neutrons thus produced scatter randomly in the soil, quickly forming a swarm or cloud of constant density around the probe. The equilibrium density of the slow neutron cloud is determined by the rate of emission by the source and the rates of thermalization and absorption by the medium (i.e., soil) and is established within a small fraction of a second. Certain elements that might be present in the soil (e.g., boron, cadmium, and chlorine) exhibit a high absorption capacity for slow neutrons, and their presence in nonnegligible concentrations might tend to reduce the density of slow neutrons. By and large, however, the density of slow neutrons formed around the probe is nearly proportional to the concentration of hydrogen in the medium surrounding the probe and therefore is approximately proportional to the volume fraction of water present in the soil. Thus

\[ N_w = m\theta + b \quad \text{and} \quad N_w/N_i = y\theta \quad (6.7) \]

in which \( N_w \) is slow-neutron count rate in wet soil, \( N_i \) is the count rate in water or in a standard absorber (i.e., the shield of the probe), \( \theta \) is volumetric wetness, \( y \) is a constant, and \( m \) and \( b \) are the slope and intercept, respectively, of the line indicating \( N_w \) as a function of \( \theta \).

As the thermalized neutrons repeatedly collide and bounce about randomly, a number of them (proportional to the density of neutrons thus thermalized and scattered and, therefore, approximately linearly related to the concentration of soil moisture) return to the probe. Here they are counted by the detector of slow neutrons. The detector cell is usually filled with BF\(_3\) gas. When a thermalized neutron encounters a \(^{10}\)B nucleus and is absorbed, an alpha particle is emitted, creating an electrical pulse on a charged wire. The number of pulses over a measured time interval is counted by a scaler or indicated by a rate meter (Hignett and Evett, 2002).

The effective volume of soil in which the water content is measured depends on the energy of emitted neutrons as well as on the concentration of hydrogen nuclei; that is, for a given source and soil, it tracks the volume concentration of soil moisture. If the soil is relatively dry, the cloud of slow neutrons surrounding the probe will be less dense and extend farther from the source, and vice versa for wet soil. With commonly used radium-beryllium and americium-beryllium sources, the so-called sphere of influence, or effective volume of measurement, varies with a radius of less than 0.10 m in a wet soil to 0.25 m or more in a dry soil. The low and variable degree of spatial resolution makes the neutron moisture meter unsuitable for the detection of moisture profile discontinuities (e.g., wetting fronts or boundaries between layers). Measurements made within 0.20 m of the surface are unreliable because of the possible

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**Sample Problem**

 Calibration of a neutron probe shows that when a soil's volumetric wetness is 45%, we get a reading of 24,000 cpm (counts per minute), and at a wetness of 40% we get 40,000 cpm. Find the equation of the straight line defining the calibration \( Y' = mX + b \), where \( Y' \) is counts per minute, \( X \) is volumetric wetness, \( m \) is the slope of the line, and \( b \) is the intercept on the \( Y' \) axis. Using the equation derived, find the wetness value corresponding to a count-rate of 90,000 cpm.

We first obtain the slope \( m \):

\[ m = \frac{(24,000 - 40,000)/(45 - 40)}{600 \text{ cpm per 1% wetness}} = 800 \text{ cpm per 1% wetness} \]

We next obtain the \( Y' \) intercept \( b \):

\[ b = Y' - 800X = 44,000 - 800 \times 40 = 12,000 \text{ cpm} \]

The complete equation is therefore

\[ Y' = 800X + 12,000 \]

Now, to find the wetness value corresponding to 90,000 cpm, we set

\[ 90,000 = 800X + 12,000 \]

\[ X = (30,000 - 12,000)/800 = 22.5\% \]

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**Gamma-Ray Absorption**

The gamma-ray scanner for measuring soil moisture generally consists of two spatially separated units, or probes: (1) a source, usually containing a pellet of radioactive cesium (\(^{137}\)Cs emitting gamma radiation with an energy of 0.661 MeV), and (2) a detector, normally consisting of a scintillation counter (e.g., a sodium iodide crystal or a synthetic scintillator) connected to a photomultiplier and preamplifier. If the emission of radiation is monoenergetic and radial and if the space between the source and the detector is empty and the two units
material, a fraction of the original radiation that would otherwise be detected will be absorbed, depending on the interposing mass, that is, on the thickness and density of the intervening material. In the event the material placed between source and detector is a body of soil of constant bulk density, the intensity of the transmitted radiation will vary only with changes in water content. In fact, it will be an exponential function of soil wetness, as follows (Gurr, 1962; Ferguson and Gardner, 1962):

$$\frac{N_w}{N_d} = \exp(-\theta_m \mu_w x)$$  \hspace{1cm} (6.8)

where $\frac{N_w}{N_d}$ is the ratio of the monoenergetic radiation flux transmitted through wet soil ($N_w$) to that transmitted through dry soil ($N_d$), $\mu_w$ is the mass attenuation coefficient for water, $x$ is the thickness of the transmitting soil, and $\theta_m$ is the water mass per unit bulk volume of soil. Equation (6.8) can be transformed to give wetness as a function of the relative transmission rate:

$$\theta_m = \frac{\ln(N_w/N_d)}{\mu_w x} = -\frac{\log_{10}(N_w/N_d)}{0.4343 \mu_w x}$$  \hspace{1cm} (6.9)

where $\ln(N_w/N_d)$ is the natural logarithm of the count ratio for wet to dry soil and $\log_{10}$ is the common logarithm for the same ratio.

The gamma-ray absorption method is used mostly in the laboratory, where the dimensions and density of the soil sample as well as the ambient temperature can be precisely controlled. A high degree of spatial resolution (e.g., 2 mm or so) can be obtained by collimation of the radiation. This is done by drilling a narrow hole or slot into the lead (Pb) wall shielding the source (as well, perhaps, as into a second shield placed in front of the detector), thus allowing passage of only a very narrow beam.

Since the absorption of radiation depends on the entire mass between source and detector, the readings can be related uniquely to soil moisture only if soil bulk density is constant or if its change is monitored simultaneously. To permit concurrent measurement of soil bulk density and moisture changes in swelling or shrinking soils, dual-source scanners have been developed, in which both cesium 137 and americium 241 are used. Analysis of the concurrent transmission of the two beams can allow separation of the change in attenuating mass between that due to bulk density and that due to soil wetness (Gardner, 1986).

The double-probe gamma-ray method has also been adapted to field use (Fig. 6.3). In principle, this technique offers several advantages over the neutron moisture meter, in that it allows better depth resolution in the measurement of soil-moisture profiles (i.e., about 1 cm in effective measurement width), sufficient to detect discontinuities between profile layers as well as movement of wetting fronts and conditions near the soil surface. However, the field device is still too cumbersome for general usage. Not the least of the problems is the accurate installation and alignment of two access tubes that must be strictly parallel along with the accurate determination of soil bulk density, which might vary in depth and time.

The health hazard associated with use of gamma-ray equipment is similar

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**Time-Domain Reflectometry (TDR)**

This is a relatively new method of measuring soil wetness, based on the unusually high dielectric constant of water. A dielectric, in general, is a non-conductor of electricity, that is, a substance that, when placed between two charged surfaces (a capacitor), allows no net flow of electric charge but only a displacement of charge. (The simplest form of a capacitor consists of two parallel metal plates separated by a layer of air or some other insulating material, such as mica.) The dielectric constant, also called relative permittivity (or specific inductive capacity), is defined as the ratio of the capacitance of a capacitor with the given substance as dielectric to the capacitance of the same capacitor with air (or a vacuum) as the dielectric.

The value of the dielectric constant ($\varepsilon_r$) depends on the nature of the material. The value for dry air is usually taken to be 1, for paraffin wax 2.0–2.5, for rubber 2.8–3.0, for porcelain and mica 6.0–8.0. The value for dry soil is roughly 4 (Jackson and Schmugge, 1989). In contrast, the value for water is about 80. Hence the water content of a soil determines its dielectric constant.

In the TDR technique (Topp and Davis, 1985), a pair of parallel metal rods connected to a signal receiver is inserted into the soil. The rods serve as one