

THE NEUTRON METHOD FOR MEASURING SOIL MOISTURE CONTENT—A REVIEW

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Introduction

THE various methods of measuring the soil moisture content and its variations in space and time have been reviewed by many authors (Taylor, 1955; Marshall, 1959; Todd, 1960; Ballard and Gardner, 1965; Cope and Trickett, 1965). The moisture content is either measured directly, as in the gravimetric method, or it is estimated by determining its relationship to some other property of the soil as in the electric resistance, tensiometer and neutron scattering methods. The neutron scattering method estimates the moisture content of the soil by measurement of its hydrogen content.

This paper summarizes the theoretical and practical aspects of the method and provides a bibliography which includes references to papers published more recently than those provided by Sweeny (1962), Ballard and Gardner (1965), and the Commonwealth Bureau of Soils (1968).

The theoretical basis

Belcher *et al.* (1950) initiated the development of the neutron probe, while Gardner and Kirkham (1952) stated the principles on which the method is based. When fast neutrons with energy of a million electron volts or more, are injected into the soil from a suitable radioactive source, they are slowed by elastic collision with nuclei of hydrogen atoms and eventually become thermalized. The average energy loss is much greater in neutron collisions with atoms of low atomic weight than in collisions involving heavier atoms. As it is the only element of low atomic weight in ordinary soils in appreciable amounts, hydrogen slows fast neutrons more effectively than any other common element present in the soil. Hydrogen in the soil is present almost entirely in the form of water and hence the density of the resultant cloud of slow neutrons (100 eV or less) is a function of the soil moisture content whether this be in the solid, liquid, or vapour state. The soil moisture content is measured in terms of the number of slow neutrons counted per unit of time averaged over a volume of soil, expressed often as a ratio of the neutron counts in the medium of measurement to the count over the same period of time in a primary standard.

The field method

Most writers and manuals of operation describe the field method to be adopted. The probe is positioned on the soil surface (or within access tubes for subsurface measurements) and the number of slow neutrons counted per unit of time is noted. The access tubes are driven into slightly undersized auger holes to ensure a snug fit. The access tubes,

closed at the bottom, vary in size and material; both properties affect the resultant neutron density (Stolzy and Cahoon, 1957). Use has also been made of polythene tubing (Holmes and Turner, 1958) but the general choice appears to be aluminium. The probe with the fast neutron source and slow neutron counter is lowered into the access tube by means of a cable. For surface measurement the probe is placed on the surface under a hydrogenous shield (Van Bavel, 1961) or used as in subsurface measurements with a fibreglass container of soil fitted over the access tube (Institute of Hydrology, 1968).

There has been much discussion on the advantages of preset time over preset counts (Bell and Eeles, 1967; Bell and McCulloch, 1969; Merriam and Knoerr, 1961) and the counting time necessary. In general preset time is preferred to preset count. The time should be constant and small so that the maximum number of access tubes can be read in a day (Bell and McCulloch, 1969). For most purposes a counting time of a minute is sufficient while thirty seconds is ample for very moist soil. The sampling network should also be carefully planned to ensure that each access tube is located outside the range of influence of all the others.

Calibration

The accuracy of the neutron method depends on the derivation of a regression whereby neutron counts can be accurately converted to moisture content (expressed as moisture volume fraction, MVF). The moisture content is determined by various procedures. Laboratory calibration consists of determining the count rate for fixed moisture contents, while in field calibration the moisture content is determined by some other means, usually the gravimetric method. Finally a theoretical calibration curve can be calculated using the neutron transport theory (Holmes, 1955; Phillips *et al.*, 1960), which is based on the assumption that soil constituents other than soil moisture are negligible in the slowing of fast neutrons (Gardner and Kirkham, 1952).

The experimental procedures require the location of the centre of sensitivity of the probe. Bell and McCulloch (1969) when comparing different models of neutron meters found a vertical displacement of the curves due to inexact location of this centre. The sensitive point can be taken to be at the source position only when the latter is centrally placed (McHenry, 1963; Zuber and Cameron, 1966); even then, in a heterogeneous medium, distortion of the neutron flux distribution alters its location. Various methods have been suggested (Cohen, 1964; Burn, 1961; Stewart and Taylor, 1957), Schulz (1964) gave a regression method for correlating the depth readings of two probes in reference to each other.

In experimental calibration the volume of soil used should be large enough to be considered effectively infinite relative to the neutron flux. As the value for moisture content is averaged over a volume of soil, in calibration the latter should be of homogeneous structure, density, and moisture content. In laboratory calibration this condition is easily satisfied with the use of sufficiently large containers of sieved oven dry soil of known density, well mixed with the required quantity of water

(Belcher *et al.*, 1950; Douglass, 1962b; Van Bavel *et al.*, 1954). Alternatively, various concentrations of neutron-absorbing material could be used. In field calibration only data from homogeneous layers of sufficient thickness to include the neutron flux should be used (Lawless *et al.*, 1963). The field calibration undertaken by Stewart and Taylor (1957) produced a considerable scatter of points. This was partly due to the difficulties of obtaining undisturbed soil samples, besides the effect of soil heterogeneity, especially since the volume of soil sampled varies with the moisture content and the moisture gradient.

Various writers favour different methods of calibration. Van Bavel *et al.* (1961) asserted that field calibration is inadequate for maximum efficiency. However, with laboratory calibration, practical difficulties are involved in constructing reliable primary standards with the same chemistry, density, and moisture range as field soils. Horonjeff and Javete (1954) found a greater deviation between gravimetric and neutron probe results using laboratory calibration than when using field calibration. Cotecchia *et al.* (1968) found very good agreement between laboratory and field calibrations and theoretical curves for the same soil. While field operators seem to prefer laboratory calibration, those with laboratory experience tend to think that field calibration would be more suitable. Ideally it is best to include both field and laboratory results (Bell and McCulloch, 1969).

All equipment is liable to drift, important factors include the ageing of components and their replacement or repair. Hence primary standards should be set up to permit periodic checks to detect changes in the response of the moisture meter. A calibration based on count ratio would be independent of source strength and the characteristics of the electronics (Holmes, 1966). This also facilitates intercalibration between probes of identical design. Operators have used paraffin standards (Belcher *et al.*, 1950; Stone *et al.*, 1960), an infinite drum of water (Carlton *et al.*, 1953; Stewart and Taylor, 1957), polyethylene cylinders (Ursic, 1967), cadmium (Bowman and King, 1965), and solutions of chemical neutron absorbers, or other suitable hydrogenous moderating material like plastic (Bell, 1969). Ideally the standards must be permanent, of fixed dimensions and hydrogen content, easily stored, portable, reproducible, and not too expensive.

Other factors which influence the neutron count

Although the neutron count is primarily a function of soil moisture content, recent theoretical and experimental research indicated that, unless corrected for, properties pertaining to the instrument itself and the soil may introduce errors.

I. Instrumental properties

The type and dimension of the source and detector and their relative positions on the probe affect the slope and shape of the calibration curve (Marais and Smit, 1960; Zuber and Cameron, 1966). Merriam (1960) found that the calibration curve was essentially a straight line through the range of soil moisture most commonly encountered. Short and long

counters give concave and convex calibration curves while a counter 10 to 15 cm long results in one that is nearly linear (Van Bavel *et al.*, 1963). Again the curve becomes convex at low moisture content for a probe with the source placed at the end of the detector instead of the centre. The error of moisture determination is less when the sensitivity, the slope of the calibration curve, is greater.

II. *Soil properties*

Various soil properties other than soil moisture interact to produce a cumulative effect on the count rate; these are soil hydrogen in forms other than free water, neutron-absorbing elements, soil density, soil texture, and temperature.

1. *Hydrogen in other forms*

a. *Bound water* in the mineral fraction does not affect the calibration greatly as the amount is relatively constant during wetting and drying (Gardner and Kirkham, 1952) and because of a fortuitous correlation between bound water content and the concentration of neutron absorbing elements, especially in the clay minerals (Zuber and Cameron, 1966).

b. *Hydrogen in humus*. Belcher *et al.* (1950) concluded that the influence of organic matter is negligible as readings from a highly organic topsoil containing 75 per cent moisture were on the calibration curve. The hydrogen content of humus is approximately 5 per cent of its weight (Waksman, 1938) and as the hydrogen content of water is 11 per cent of its weight, the amount of hydrogen in organic matter may be an appreciable part of total hydrogen. However, Knight and Wright (1954) found that a 96 per cent increase in organic content increased the count rate by only 25 per cent and as the organic content of most mineral soil is only 5 to 10 per cent the effect is negligible.

2. *Neutron-absorbing elements*

While the presence of hydrogen in other forms overestimates the moisture content, a concentration of neutron-absorbing elements, e.g. magnesium and potassium in lowland or arid soils, decreases the count and thus causes an underestimation of the moisture content. Such possibilities also arise when fertilizers are added to the soil or when evaporation changes the salt concentration. Holmes (1958) suggests that neutron absorption might explain the family of curves derived for different soils. The calibration curve expresses the change of count rate when water content is varied and all other soil constituents are held constant; Holmes and Jenkinson (1959) assumed that the difference in count rate at a given water content expresses the effect of slow neutron absorption by soil solids. They found that boron reduces the count rate by a factor independent of the magnitude of the water content; a boron content within 2 to 100 ppm could result in a maximum error of 10 per cent in changes of water content if it were computed from a single calibration curve. A similar effect was produced by 0.74 per cent of chlorine as sodium chloride. Burn (1966) found a large discrepancy between laboratory and field calibration due to an absorption effect which reduced

the neutron activity at every moisture content by 11 per cent; 9 per cent of this was produced by an iron content of 7 per cent by weight. Carbon, on the contrary, having a low absorption capacity keeps neutrons in circulation longer; and with hydrogen it keeps neutrons in the vicinity of the detector longer, increasing the thermal neutron density (Ballard and Gardner, 1965).

3. *Soil density*

Apparent moisture content increases with increasing bulk density owing to the impedance of neutron transport (Olgaard and Haahr, 1968); the error being greatest at higher moisture content. Holmes and Jenkinson (1959) found that the effect of soil density was less pronounced than that of neutron-absorbing elements. A change in soil density from 1.4 to 1.6 g/cc of dry soil caused a 2.4 per cent change in the slope of the calibration curve (Holmes and Jenkinson, 1959). Marais and Smit (1962) emphasized that the linearity of the calibration curve over the range of moisture of practical interest was primarily due to a constant bulk density; and that the form of the calibration curve can be varied by changing the bulk density of the medium. Holmes (1966), as well as Marais and Smit, gave methods for correcting for bulk density. However, changes in bulk density merely cause a shift in the calibration curve and this does not affect the operation of the neutron probe if changes in moisture content are required only at a bulk density which is constant between measurements.

4. *Soil texture*

It is difficult to isolate the effect of textural differences as total hydrogen, neutron absorbers, and soil density are closely related to soil texture. It is fortuitous that early research did not indicate any systematic difference between different materials used, for a single curve could be fitted through all the results (Belcher *et al.*, 1950; Church and Smith, 1955; Knight and Wright, 1954; Merriam, 1959; Van Bavel *et al.*, 1961).

This could be due to the fact that clay minerals which retain large amounts of water at oven-drying temperatures also contain an abundance of neutron-absorbing elements compared with sand and light-textured soil. A positive correlation between the neutron absorbers and the amount of loss-on-ignition water in soils could cancel their respective influence on the calibration curve. This would be especially so when the values for moisture content for the calibration were determined on oven-dry weight (Holmes and Jenkinson, 1959).

However, the effects of these properties are different. While the hydrogen content of the loss-on-ignition water overestimates the moisture content, this is a constant error producing a parallel shift of the calibration curve. Mortier *et al.* (1960) found separate curves for clay and for loam and sand, while Burn (1964) found that the count rates in clay and inert soil substances differed. Holmes (1966) found a 40 per cent flatter curve for clay compared with loam and Cohen (1964) found that the calibration curves for Israel soils varied so greatly that they could not be combined in one calibration, linear or curvilinear. The

effect is greatest in dry soil as the volume integrated is then at a maximum (Long and French, 1967). Hence, different soils may require different calibrations.

5. *Soil temperature*

An increase in temperature decreases neutron density in the vicinity of the source (Zuber and Cameron, 1966); the temperature effect is more significant at higher than at lower moisture content.

III. *Other factors*

Zuber and Cameron point out some other factors that cause erroneous readings during measurement.

1. *Access tube characteristics*

a. A greater diameter and wall thickness reduce the efficiency of the probe, affecting the shape of the calibration curve.

b. Stolzy and Cahoon (1957) compared the performance of access tubes made of different material. Aluminium tubes gave approximately the same readings as uncased holes while steel and plastic (polyvinyl chloride) decreased the readings, the latter by at least 15 per cent.

c. Compaction of the surrounding soil during installation and the presence of water in the borehole into which the access tube is inserted increase the apparent moisture content, while loose backfill around the access tube when dry reduces the neutron count owing to a rapid escape of neutrons (Holmes, 1956). These effects are less pronounced at lower moisture content owing to the larger volume of soil sampled.

2. *Ignition noise*

Extraneous engine ignition causes a definite increase in the count rate when the cable was within three feet of a motor, as indicated by Stone *et al.* (1967). A similar effect was observed at an experimental site in the Catchwater Drain Catchment when a lawn mower was in operation.

Although the instrumental components can be standardized, a single laboratory calibration is not usually adequate for field applications. Recent research (Cotecchia *et al.*, 1968) with different rocks indicated the diversity of moderating, diffusing, and capture properties of the various components. Sartz and Curtis (1961) found that the calibration curve furnished by the manufacturers coincided with their own only at 21 per cent moisture content; progressively overestimating it at the higher moisture levels. With the largely unpredictable changes in soil properties and existing variations in instrument properties it is hardly surprising that published calibration curves vary so widely. A universal curve with theoretical corrections for these factors would be of little value (Long and French, 1967). Even the average curve supplied by manufacturers for each instrument should be checked by gravimetric sampling or a theoretical calibration should be produced and normalized to satisfy one or more experimental points for a given soil and probe parameters.

The sphere of importance and depth resolution

Neutron scattering takes place over a volume of soil, such that the resulting data represent the moisture content averaged over this volume, which itself depends on the moisture content. The volume over which the average is taken is greater at low than at higher moisture content.

Two concepts have been advanced. The 'sphere of influence' (Van Bavel *et al.*, 1956; Glasstone and Edlund, 1957), defined as the sphere around the source that contains 95 per cent of all thermal neutrons, has been criticized (Mortier *et al.*, 1960; Olgaard, 1965). The 'sphere of importance' defined by the sphere around the source which, if all the soil and water outside the sphere were removed, would yield a neutron flux at the source that is 95 per cent of the flux obtained in an infinite medium, has been suggested instead. Based on five soils of different density and composition the following relationship was developed (Olgaard, 1965):

$$R_1 = \frac{100}{1.4 + 10m} \text{ (cm)}$$

R_1 , the radius of the sphere of importance, varies from 70 cm when m (moisture content) = 0 g/cc, to 22 cm when $m = 0.35$ g/cc. The estimate agrees within ± 2 cm with the experimental results for moisture content within the stated range.

The above concept delimits the minimum dimensions for calibration drums in the laboratory and for the spacing of access tubes in the field, based on the minimum values of moisture content expected. This feature of sampling moisture over an extended volume of soil, while mitigating the effects of lateral irregularities, both natural and produced by the installation of access tubes, limits the vertical resolving power of the probe.

The vertical or depth resolution of the neutron probe is its ability to distinguish changes in moisture content with depth. As the moisture flux in a non-homogeneous medium is difficult to calculate theoretically, resolution can only be estimated or measured empirically. The diameter of the sphere of importance itself cannot be easily related to resolution as the latter may be asymmetric in shape due to the non-homogeneity of the medium and moisture content and also because the thermal neutron density decreases with distance from the neutron source.

Good vertical resolution is very important when trying to detect interfaces between wet and dry layers such as in layered soils or at the soil surface. Many authors find the resolution insufficient for this purpose. Allied to this is the tendency for the total moisture content of the profile to be underestimated although the wet and dry layers on either side of the interface are underestimated and overestimated respectively. One experiment demonstrated that a sharp transition from wet to dry soil during infiltration could be indicated only as a boundary layer, approximately 30 cm deep. When the probe was placed at the interface the estimate was less than average moisture content for the two regions (Van Bavel *et al.*, 1961). The limited resolution thus smooths out large

gradients in the moisture profile (Belcher *et al.*, 1950; Holmes and Jenkinson, 1959; Perrier and Johnston, 1962).

As varying soil properties and moisture content make it difficult to maintain soil moisture boundaries that are not textural ones, McHenry (1963) simulated various combinations of wet and dry soil layers within a container by surrounding an access tube with a cadmium shield to approximate an extremely dry layer. A wet or dry layer of 2.5 cm would be detected using 2.5 cm spacings of readings but, in order to derive the actual moisture content of the layer, a minimum thickness of 30 to 35 cm was required. A spacing of less than 10 cm between two 2.5 cm layers did not distinguish the two layers but only revealed the existence of an area of lower hydrogen content.

The underestimation of total moisture content in layered soils increased with decreasing thickness of the moist layer and moisture content. According to Long and French (1967) the difference between measured and actual moisture content decreased as the discrepancy between the water content of the two layers decreased. Van Bavel (1961) found that the stratification of moisture in the top 6 cm resulted in an inaccurate estimate of moisture content for the top 15 cm of the soil, owing to the effect of the top 2.5 cm of soil predominating over the next 2.5 cm layer and so on. A superficial wet layer had a relatively greater effect than a superficial dry layer; the error being less when the moisture gradient is gradual as in the case of a drying soil, than when abrupt changes occur as when a small amount of rain falls on dry soil.

Hence, owing to poor resolution the method is suitable only for measuring net changes in soil moisture over a period of time as the errors in sequential profiles cancel out. Douglass (1962*a*) found that the variance for total moisture content was large, particularly where soils varied considerably in texture. He suggested that an analysis of the change in moisture content with time reduced experimental error, as it removed the constant effect of textural differences.

The limited depth resolution creates problems in the measurement of surface soil moisture. For when 'the sphere of importance' is intersected by the soil surface there is a rapid escape of neutrons from the soil mass giving readings which indicate a lower than actual moisture content. Without a surface shield Long and French (1967) indicate an underestimation of moisture content by 5 per cent of the actual value, using the ratio of observed counts to the number of counts in water at the same depth below an air interface. The influence of the surface extends to greater depths in dry than in wet soils; but different authors found differing values for the extent of surface influence (Stolzy and Cahoon, 1957; Van Bavel, 1958).

Resolution can be improved by surrounding the source with a paraffin or a Perspex mantle of suitable dimensions and thus deliberately slowing down fast neutrons before they enter the soil layer (Mortier *et al.*, 1960). This has the effect of reducing the count rate and thus the efficiency and sensitivity besides contracting the 'sphere of importance'.

Various methods have been suggested to overcome the effect of the surface interface. The simplest method consists of applying correction

factors (Cole and Green, 1966). Other methods can be divided into two types: those where the probe is retained in the access tube and those where it is taken out and placed horizontally upon the ground surface. The latter method was suggested very early on in the development of the neutron method (Belcher *et al.*, 1952). The probe is then surrounded by a suitable hydrogenous shield, e.g. paraffin or polyethylene, which scatters the neutrons back in a constant manner. Variations in the counts can thus be attributed to changes in soil moisture (Underwood *et al.*, 1954). Various neutron meters were designed and adapted specially for surface work (Zuber and Cameron, 1966) but now many probes can be used for either method with the changes necessary. A separate calibration is required when a probe is used as a surface moisture meter and estimate so derived must be treated cautiously when there is a stratification of moisture in the top 6 cm of soil. Errors are also introduced if the probe is not placed flush against a smooth surface (Van Bavel, 1961).

When the probe is retained within the access tube, a surface shield can be placed above it so that the 'sphere of importance' is not subject to an air interface. Ideally this shield should be constructed of stable material having the same hydrogen content as the soil layer to make the count rate representative. Pierpoint (1966) found that the use of a surface shield reduced the extent of surface effects from 19 to 15 cm. Black and Mitchell (1968) used the method of shielding out part of the sphere of importance by placing cadmium around the top of the detector tube in conjunction with a surface shield; the method was found to give reliable readings at 10 cm depth in a dry medium and at less than 5 cm in a wet medium. Recently, the Institute of Hydrology (1968) devised fibreglass surface extension units to contain soil similar in composition to the surface soil; these are subject to the same weather conditions and when placed above the access tubes, enable readings to be taken with the probe centred at 10 cm depth.

Evaluation of the neutron method

The neutron method possesses some obvious advantages over the other methods of measuring soil moisture. It measures moisture regardless of its physical state and enables observations to be made at any depth limited only by the length of the access tube. Moreover it lends itself to continuous and automatic recording (Belcher *et al.*, 1950). More important, it allows continuing observations of the same soil throughout cyclic seasonal changes. Thus any difference in readings through time at a location may be attributed to moisture changes and not to possible soil variations as with the gravimetric method. The possibility of measurements at short time intervals enables the detection of rapid changes in moisture, especially since the method is free of hysteresis which reduce the efficiency of resistance blocks and tensiometers.

It is thus argued that its accuracy exceeds that of standard procedures. Stone *et al.* (1960) estimate the method to be more precise than the gravimetric but Stewart and Taylor (1957) take it to be slightly inferior.

The neutron method would be more accurate than the gravimetric when moisture sampling extends below a perched water body, as moisture would drain into the auger hole in the latter method. The access tubes in the neutron method are inserted into slightly undersized holes to check the tendency for vertical drainage down the tube wall from seepage planes. This involves minimum disturbance of adjacent soil, especially when compared with the electric resistance and tensiometer methods which require adequate excavation, disturbing the drainage properties of the soil. Also, as moisture is sampled over a larger volume, the standard error is much smaller with the neutron method (Van Bavel *et al.*, 1954). This probably explains the discrepancy between the gravimetric and neutron readings being greater at high than at low moisture content (Stewart and Taylor, 1957).

The neutron meter is also held to be quicker (Phillips *et al.*, 1960). Letey *et al.* (1961) discuss the advantages of the meter over infiltrometers in infiltration experiments.

However, the method does suffer from inherent limitations, especially in the measurement of absolute moisture content owing to the inadequate depth resolution and to factors other than moisture content that affect the calibration. This introduces problems in the study of surface and layered soil. An increase in the resolving power of the probe, however, involves a greater sampling error owing to a reduction of the sampled volume of soil, which besides reducing the sensitivity increases the effect of heterogeneity especially in the disturbed portion near the tube. The poor resolution diminishes the potential for determining the exact moisture profile in the study of evaporation, infiltration, percolation and of the phreatic surface, also because such investigations require a knowledge of the moisture stress in layered soil besides the moisture content by volume.

Operators should look for stable, portable, durable models with stable electronic and power components compatible with other available equipment (Bell, 1969; Bell and McCulloch, 1966 and 1969; Long and French, 1967; Merriam and Copeland, 1963; Zuber and Cameron, 1966). With unstable electronics only glaring errors are detectable while minor deviations may be misinterpreted hydrologically. With simple precautions the method is without hazard to health.

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