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## **SOIL MOISTURE MEASUREMENT BY AN IMPROVED CAPACITANCE TECHNIQUE, PART II. FIELD TECHNIQUES, EVALUATION AND CALIBRATION**

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### **ABSTRACT**

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Part I of this paper describes the design principles, mechanical design and instrumental performance of a soil moisture probe which utilises the principle of measuring the dielectric constant of the soil, and hence its water content, by the capacitance method. This paper discusses the comparison of the capacitance method with established methods of defining and determining water content using the neutron probe and the gravimetric technique.

The relationship between the capacitance probe readout and water content is not linear and is influenced by the type of soil. Emphasis is placed on field rather than laboratory calibrations, however, and a linear approximation is adequate for the restricted ranges of water content experienced in practice in many soils.

Access tubes must be installed with greater care than for the neutron probe and a technique has been developed that combines installation with collection of relevant samples for gravimetric determination.

### **INTRODUCTION**

The capacitance probe developed by the Institute of Hydrology operates within a plastic access tube installed vertically in the soil. The mechanical design gives ease and flexibility of use for measurements to be made in the upper 2 m of the soil, based on the premise that 95% of potential applications are in this zone. There is no reason, however, why alternative versions should not be constructed to operate to greater depths, although the maximum operational depth will be limited by the ability to install the access tube to the precise criteria necessary with the capacitance probe. Alternative versions of the probe could be used as static sensors set semipermanently in the soil to log soil moisture continuously or to act as sensors for irrigation control or flood warning systems.

The current design produces a soil moisture profile in a similar way to the neutron probe, over which it has the following advantages: (1) the output is easily recorded by automatic logger; (2) the instrument is much cheaper; (3) the

reading is obtained almost instantly and there is no random counting error; readings are repeatable to better than 0.005 moisture volume fraction (MVF); (4) the method is fast: a profile of (say) 25 reading depths can be determined within 2 or 3 min; (5) there is no nuclear radiation hazard and therefore no legal constraint; and (6) the depth resolution is more precise than that of the neutron probe. Disadvantages are: (1) The calibration is less linear and hence less simple to determine and to apply. (2) Because the "sphere of influence" is small, the presence of gaps, cavities, stones or roots in proximity to the access tube can create anomalous results. Access tubes must be installed with exceptional care and experimental rigour to avoid the introduction of errors. (3) Small scale heterogeneity of soil moisture is more significant than for the neutron probe and more measurements are required to represent the mean moisture content of a soil body to the same precision.

The design and physical principles of operation of this probe have been described in detail in Part I of this paper.

## PRINCIPLES

The probe is 44 mm in diameter and 290 mm in length and is connected directly to a rigid plastic tube, of the same diameter, which acts as a handle. The probe is inserted by means of the handle into a 50 mm diameter PVC access tube, where it can be located precisely at 2 cm depth intervals by means of a "click-stop" device, fitted over the top of the access tube. The handle is sectional and sections are screwed together to provide sufficient length to permit the probe to be inserted to the full length of the access tube. The signal is fed to a hand held frequency meter by means of a fibre optic cable within the handle. An electrical field is generated between two annular electrodes within the probe; this penetrates into the surrounding soil and the oscillator frequency of the system changes with volumetric soil water content.

## THE DEFINITION OF SOIL WATER

The term "calibration" implies the establishment of a precise relationship between a new system of measurement and one which is long established and accepted as a standard method for measuring the same variable. The difficulty here is that it has not been shown that the definition of "soil water" as measured by the capacitance probe conforms with that of any other established method (Gardner, 1965). Theoretical considerations (Part I) suggest that the probe may respond to only part of the total water content of the soil, presumably that which is least strongly held by surface absorption forces and surface tension, and hence there may be no direct general relationship between frequency and water content as determined by the standard gravimetric method.

The gravimetric method of defining water content of a soil expresses the weight or volume of water expelled by oven-drying at 105°C, per unit weight or volume. Water in unsaturated soil is held by surface tension forces within a wide range of different pore sizes and shapes. It is also held as thin films on

particle surfaces (particularly of clay minerals). Most of this water is expelled by oven-drying at 105°C, together with water of crystallisation of some minerals (e.g. that of calcium sulphate minerals), volatile organic materials, water which is held in association with hydrated oxides, etc. Only the first of these categories of "water" expelled by oven-drying (i.e. water held in pores by surface tension) is likely to contribute to the frequency response of the capacitance probe, which depends mainly on the number of water molecules which are free to relax as their dipoles respond to the field reversals.

It is therefore likely that a calibration more independent of soil type might be obtained by a less extreme drying procedure than oven-drying at 105°C. This aspect of the development of new calibration procedures requires further investigation, because the apparent diversity of calibration curves for different soils may arise largely from this. If an independent means of determining and defining soil water content appropriate to the capacitance probe can be found the possibility of a universal calibration curve is evident; it is unlikely that this could be achieved for the neutron probe.

Notwithstanding the caveats mentioned above however, in the experimental work described in this paper the capacitance probe has been calibrated against the gravimetric method. This is adequate for evaluation purposes and, if the user is prepared to accept the need for calibrating each soil, is also satisfactory for operational use.

This problem is not unique to the capacitance probe. A different but analogous problem arises with the neutron probe, but here it is generally accepted as one of the penalties of the method that every soil, in principle, requires calibrating. The neutron probe operates on entirely different principles from the capacitance probe but, as with the latter, the "water" it responds to is not entirely the same as the "water content" determined by the gravimetric method (Bell, 1976; Greacen, 1981). All forms of hydrogen in the soil (organic compounds, water of crystallisation, hydroxide molecules, etc) cause the neutron probe to respond as if they were the equivalent amount of water, but a significant proportion of these may not be expelled by oven-drying at 105°C. Because the neutron probe and capacitance probe operate on entirely different physical principles, direct comparison of soil water profiles determined by the two methods is unrealistic and potentially misleading. Examples have occurred where one system indicates total water content of a soil profile increasing upward while the other shows the opposite! Comparison of water content changes is less risky, but even here problems in detail arise from the different depth resolution characteristics of the two systems. In this paper therefore neutron probe profiles are shown only for the purpose of permitting comparison of the general forms of the profiles.

#### THE RELATIONSHIP BETWEEN FREQUENCY AND WATER CONTENT

Figure 1 shows calibration data for four soils; water contents have been determined by oven-drying at 105°C on samples taken as described below.

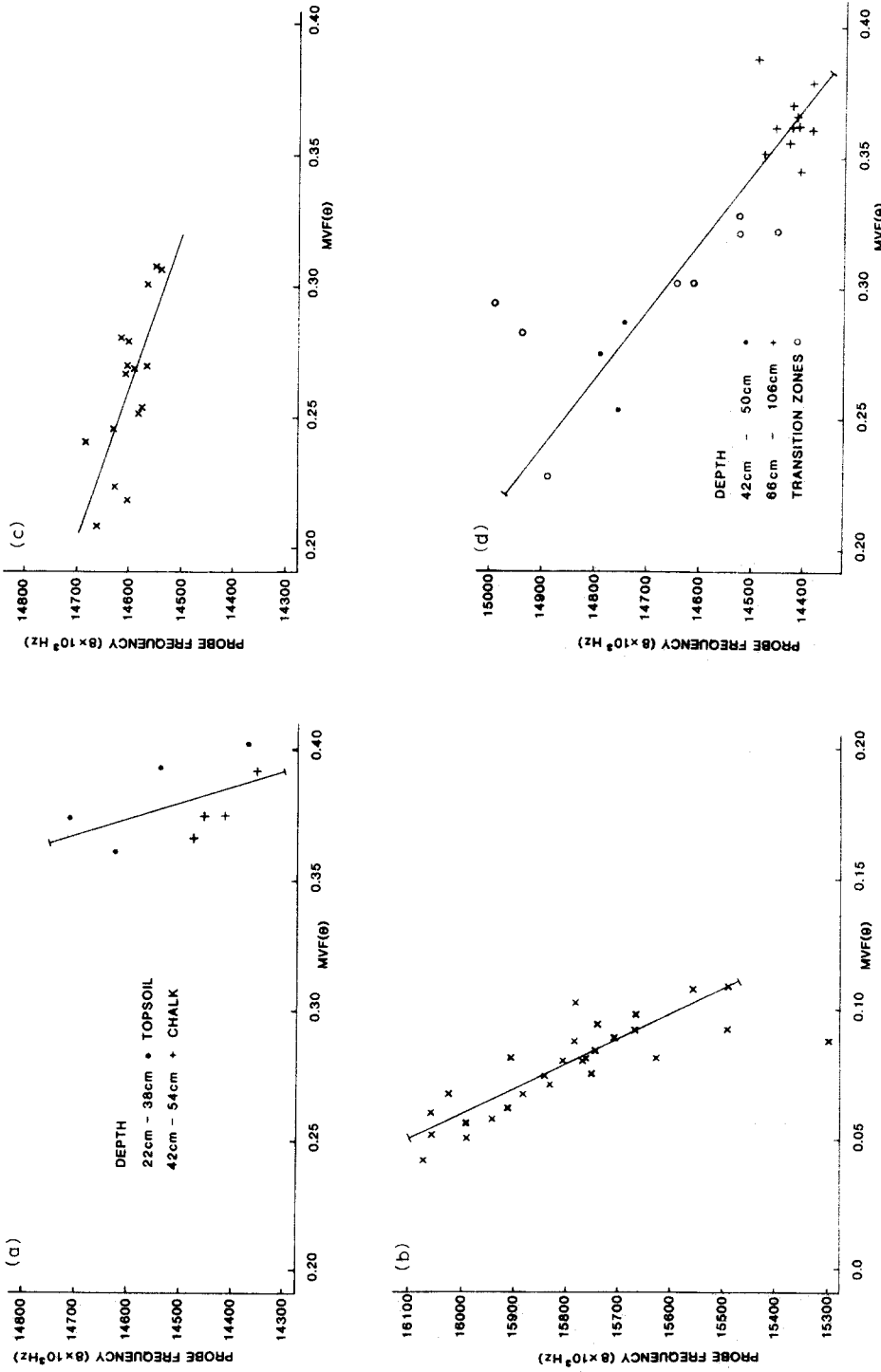


Fig. 1. Calibration data for four soils, with fitted linear regressions: (a) soil a = chalk overlain by topsoil; (b) soil b = medium-fine sand overlying Jurassic sandstone; (c) soil c = sandy clay drift overlying Lower Greensand; and (d) soil d = chalky silt overlying poorly sorted fine gravel (repacked within a lysimeter).

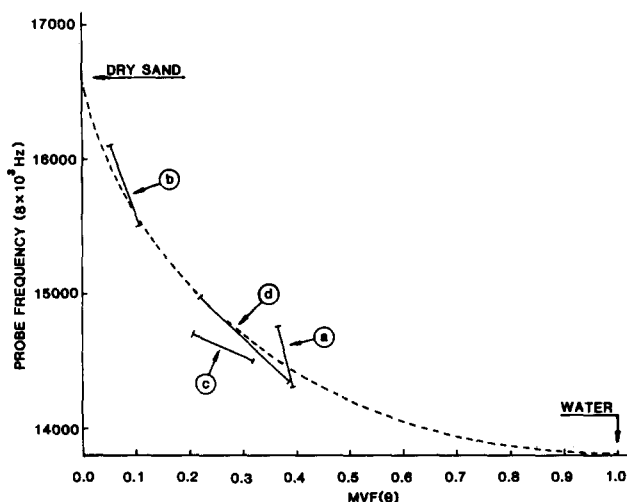


Fig. 2. Overall form of calibration curve from dry sand to water, with regressions from Fig. 1 shown to illustrate the apparent variability of calibration for different soils. Soil descriptions as for Fig. 1.

Linear regressions have been fitted to these with correlation coefficients between 0.74 and 0.86 for soils b, c and d. For soil a, separation of the top soil from the chalk gives coefficients of 0.82 and 0.96 respectively whereas the fit for one line gives 0.59. The use of these regressions for soils c and d produces water content profiles (Fig. 3) which compare well with the gravimetric profiles for the same tubes. Hence the calibration curves may be regarded as linear over the relatively restricted range of soil moisture changes normally experienced for a given soil. However such curves produced for different soils can differ markedly in terms of gradient and intercept.

The relationship between these calibration lines within the full range of water content between dry sand and water is shown in Fig. 2. It is clear that the overall relationship is nonlinear and also that the data sets for different soils may not conform to any one overall calibration line.

First appraisal of the data indicates that there are considerable differences between the gradients of the calibration lines for the different soils. However, within each data set, representing a complete profile, the soil almost invariably is layered to a greater or lesser extent and hence the regressions performed on the full data set for the profile may be bridging different data subsets within the profile. For example, the general form of the profile for soil d, a repacked soil in a lysimeter, suggests that this comprises two layers (Fig. 3b) from 22 to 50 cm and from 66 to 106 cm, with a transitional zone between. In the construction of the lysimeter some attempt was made to reproduce the original profile — silty chalk drift overlying fine alluvial gravel. Thus, two soils are represented here and the fitted line may be inappropriate. Likewise the data for the chalk profile represents two materials: 40 cm of topsoil and cryoturbated chalk beneath. Four data points only are available for each zone; lines may be fitted to the data

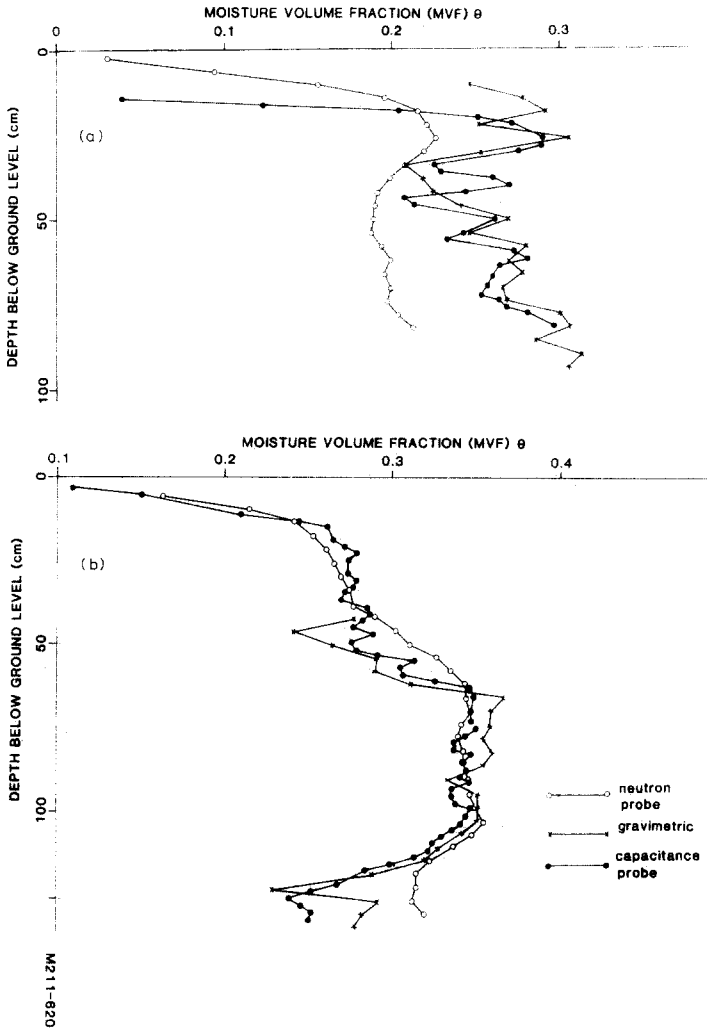


Fig. 3. Comparison between soil moisture profiles determined by capacitance probe, neutron probe and the gravimetric method. (a) soil c, (b) soil d.

for the individual zones that are more compatible with the overall curve (Fig. 2) than the regression for the full set (Fig. 1a). However the data sets are too small to be regarded as a satisfactory calibration.

Theoretical considerations suggest that the dry bulk density of the soil would influence the calibration to a small but significant extent; no allowance has been made for this in the procedures followed so far, except to note that within the data sets for each profile, those soils with lowest density seem to be responsible for the apparent somewhat steep gradient of the calibration. In the case of soils b and c there is much less difference in dry bulk density within the profiles and these regressions match the overall calibration curve quite well.

The separation of density effects from water content and other effects poses severe problems for investigation of this matter experimentally, but undoubtedly more work is required in this area.

The nonlinear form of the curve over the full range poses difficulties for standardisation of instruments. In the case of the neutron probe, which has an effectively linear calibration, data are normalised by expressing the results as the ratio of count in soil to count rate in a standard material (usually water). Thus, any probes with the same source-detector geometry are entirely interchangeable; long-term drift or sudden changes in count rate of a probe are also compensated for by this method.

The factors which govern this curve for the capacitance probe are such that two laboratory standards having stable dielectric properties, spanning the normal soil moisture range, may be required to allow intercalibration of probes. Intercalibrations between three probes have proved to be linear.

#### THE SPHERE OF INFLUENCE

The zone in the soil surrounding the probe centre of sensitivity which contains most of the field lines generated by the probe, can be, by analogy with the neutron probe, termed "the sphere of influence". However, the analogy should not be taken too far, as the physical laws governing the distribution of field lines are entirely different to those determining the probability of slow neutrons returning to the detector of a neutron probe. At present it is not possible to describe the exact shape nor extent of this "sphere" but there is strong evidence that its vertical extent is considerably less than that of the neutron probe, so that superior depth resolution of the instrument is attained. Figures 3a and b provide a comparison of profiles determined in the same access tube by: (a) a Wallingford Neutron Probe count rate (at 4 cm depth intervals); (b) the capacitance probe read at 2 cm intervals (using the appropriate linear regressions shown in Fig. 1); and (c) gravimetric water contents of volumetric samples representing 4 cm depth layers.

The neutron probe water content profile in Fig. 3a is based on a "standard" calibration relationship for sand/gravel soils, resulting in a minor displacement of the plotted profile. For Fig. 3b no standard calibration curve could be assumed as the soil had been repacked, so the data were fitted by a simple matching procedure, justifiable because the objective is merely to provide a basis for comparing the form and hence resolution of the various results.

Figure 3 shows that the neutron probe count rate profile, while broadly similar to the other profiles, has distinctly less depth resolution. Details revealed by the capacitance probe, which are not "seen" by the neutron probe, agree well with detail of the gravimetric profile (due regard being given to the volumetric errors inherent in the latter). The bulk of the capacitance probe response therefore seems to be derived from a soil layer of 4–8 cm thick. However, in proximity to the soil surface there is evidence (see Part I) that the influence of the surface air/soil interface extends down to 20 cm or so (although

where moisture *changes* are being measured, errors within the 10–20 cm depth range are probably negligible). This apparent contradiction is probably explicable by the extreme contrast in dielectric constant between air and wet soil across this interface; this causes the interface effect to be apparent to a greater distance than would be the case with soil layer interfaces occurring within the soil profile. Analogous (but greater) effects occur in the case of the neutron probe, leading to unquantifiable errors which most users have been content to ignore.

#### FIELD CALIBRATION AND ACCESS TUBE INSTALLATION

Because the sphere of influence of the capacitance probe is small, small scale heterogeneity of soil texture, density, composition and water content is much more evident than with the neutron probe. Thus, while profiles only 0.5 m apart may be quite similar in form, in detail there may be many differences (Fig. 4). For this reason the technique used for neutron probe calibration, whereby count rates are plotted against volumetric moisture contents determined gravimetrically from known-volume soil cores removed from around temporary access tubes, cannot be used. The scatter of points is too great to be resolved adequately by means of a linear regression on a reasonable number of samples.

The method devised to overcome this problem enables known-volume calibration samples to be removed from the hole into which the access tube is inserted. Lateral movement of the tube is prevented while it is being installed, thus avoiding the introduction of gaps between the tube and the soil. Such gaps

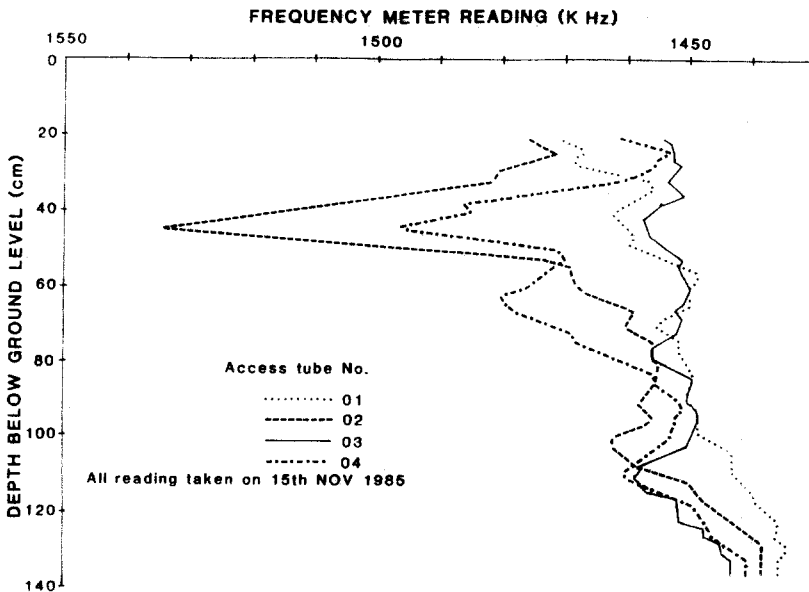


Fig. 4. Profiles of frequency against depth for four access tubes installed along a 5 m line in a soil (soil c) overlying Lower Greensand. A stone layer is known to occur at 40 cm.





Fig. 5. An access tube being installed; a calibration sample is being transferred from auger to plastic bag for gravimetric determination of moisture.

are totally unacceptable, as they would dominate the frequency response. To a much greater extent than with the neutron probe, a perfectly installed access tube is absolutely essential. Installation of an access tube is illustrated in Fig. 5. The access tube is supported internally by a mild steel guide tube (Fig. 6) with a reinforced upper end against which butts the top of the access tube, cut to an accurately matching length. The lower end of the guide tube is threaded, and accepts a specially made steel shoe, which butts up against the lower end of the access tube. The external diameter of the shoe is exactly that of the access tube. The access tube is secured to the shoe by mean of grub-screws.

A close fitting screw auger is operated within the guide tube. The upper end has two holes 4 cm apart which accept a pin which is used to limit precisely the extent to which the auger can extend into the guide tube. The cutting edge of the auger reaches only to the bottom of the shoe with the pin in hole a, but protrudes 4 cm below with the pin in hole b. To hold the tube completely steady

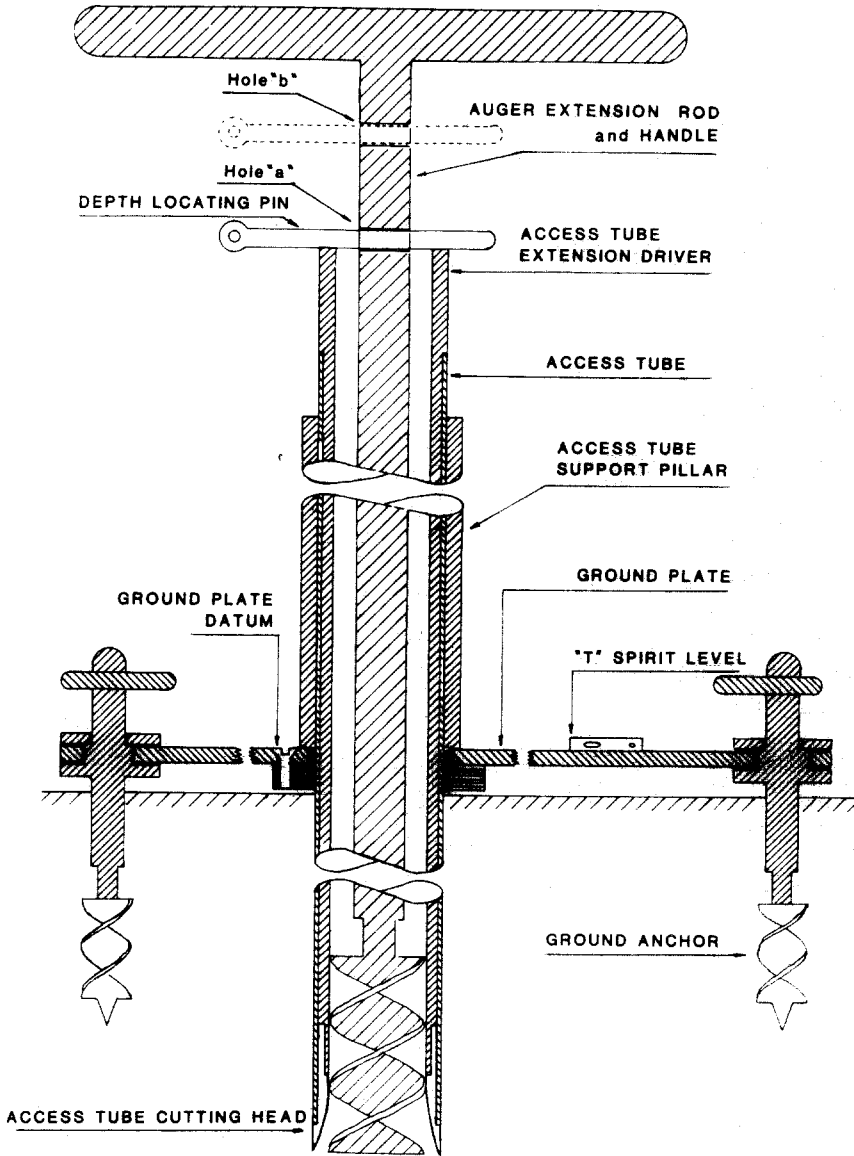


Fig. 6. Diagram of the access tube installation equipment; the ground plate and ground anchors are not to scale (see Fig. 5).

while it is being inserted, it is supported within a steel sleeve which is screw-mounted onto an aluminium ground plate. The latter is firmly secured in a stable horizontal position by means of three adjustable ground anchors, and acts as a datum for all depth measurements during installation. The access tube is marked externally every 4 cm.

The access tube, mounted on its internal guide tube, is inserted into the support sleeve. The material 4 cm ahead is removed by the auger (with the pin

in hole b) and placed in a plastic bag. The tube is then gently tapped down 4 cm by means of the rammer; the remainder of the first sample is augered out (with the pin in hole a) and added to the first sample which, thus completed, represents the layer 0 to 4 cm. This cycle is repeated until the tube is fully installed, with the profile sampled continuously in 4 cm sections. The internal guide tube is then unscrewed and removed from the cutting shoe (which remains in-situ with the access tube). The ground plate is removed and to complete the installation the bottom of the access tube is sealed by rubber bung and a bung is inserted into the top.

Readings are taken at 2 cm depth increments with the capacitance probe immediately the tube has been installed. "Water content" of the samples is determined gravimetrically, as may also be the dry bulk density.

The data obtained permit frequency to be plotted against volumetric water content for each depth and also provide a dry bulk density profile if required. Neutron probe profiles can be determined in the same access tube at the same time. These can be plotted as simple count rate profiles for comparison. Using a conversion factor between 44.5 mm dural and 50 mm PVC tubes, neutron probe soil-water content profiles can be plotted, assuming the neutron probe has already been calibrated for the particular soil.

If the mineral material of the soil profile is uniform, i.e. when it has the same capacitance throughout at any given water content, then all the data can be treated as a single set to provide a single calibration curve for that profile. However, there may be vertical differences in the soil's dielectric constant and it may be necessary to establish more than one calibration relationship for the profile. The best solution may be to assume lateral homogeneity and to plot the data from several access tubes in the same close vicinity, taken at different stages of soil water content, all on one graph, identifying each depth by (e.g.) a different plotting symbol. If more than one calibration curve is concealed in this data, regression on the subsets of data for each depth zone will have a different gradient from a regression using all the data points, undifferentiated. Inspection of the soil recovered and of the dry bulk density profile may well indicate possible zoning of the profile corresponding to different calibration curves. Laboratory calibration using large soil samples removed from the field offers an alternative method but requires prior knowledge that the profile represented by each sample is homogeneous. Furthermore, it is difficult to repack large samples to their natural structure and density and to bring them in sequence to a series of known, stable water contents.

The calibration technique described above may also be used with advantage in the installation of neutron probe access tubes; it offers the prospect of obtaining detailed moisture and density profiles for each access tube, although it takes more time.

## CONCLUSIONS

The capacitance probe described in this paper offers a viable alternative to the neutron probe for measuring soil-water content profiles for many research

and operational purposes. Among the advantages of the method are speed of measurement, lack of radiation hazard, cheapness, portability, high resolution and absence of any random counting error. Also, the system is easily adapted for use with automatic logging equipment. Against these advantages must be set some disadvantages, the nonlinearity and apparent soil dependence of the calibration curve and the requirement that the access tube be installed by an exceptionally careful and rigorous technique. Use in shrinking soils may present difficulties due to development of variable air gaps.

The nonlinearity of the calibration curve is probably not a major disadvantage over the normal range of moisture change in any given soil, and the assumption of a linear calibration for each soil does not lead to serious errors. Profiles measured by the capacitance probe show considerably more detail than profiles determined in the same access tube by the neutron probe; this detail correlates well with profiles determined gravimetrically on volumetric soil samples, each representing 4 cm of profile depth.

It is not clear at this stage whether "soil water content" as defined by the traditional gravimetric method conforms to the definition of that soil water content to which the capacitance probe responds. The latter clearly differs from "water" to which the neutron probe responds. This however does not detract from the immediate value of this system for volumetric soil-moisture determination in agricultural and hydrological applications where profile water content measurements are made repeatedly at the same site over a period of time and, particularly, where the main interest is in water content changes rather than absolute values.

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