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The effect of a gap between the access tube and the soil during neutron probe measurements

J. Li[A], *D. W. Smith*[A,B], *and S. G. Fityus*[A]

[A]Discipline of Civil, Surveying and Environmental Engineering, School of Engineering, University of Newcastle, Callaghan, NSW 2308, Australia.
[B]Corresponding author; email: david.smith@newcastle.edu.au

Abstract

The neutron probe is a tool employed for the measurement of water content in a soil mass. The presence of a gap between the soil and the neutron probe access tube, filled with either air or water, inevitably introduces a systematic error in neutron probe readings. In this study, experimental investigations and numerical analyses were carried out to evaluate the effects of this gap on neutron probe calibration. The numerical model was developed based on the multigroup neutron diffusion equations and the finite element method. The experiments were conducted in a heavy clay soil. The results show that an air gap of 2.5–30 mm between the soil and a 50-mm-diameter aluminium tube could lead to an underestimation of soil water content by 5–45%, but significant underestimation was apparent for air gaps <10 mm. It is also found that the neutron count is significantly overestimated if the gap around the access tube is filled with water rather than air, but this effect is most significant for larger gaps. The results of this research clearly indicate that a gap between the neutron probe access tube and the soil profile should be avoided during field installation, and that if a gap between the access tube and soil develops during service, a systematic error will be introduced into measurements.

Additional keywords: air gap, soil water content, multigroup neutron diffusion equations, finite element method.

Introduction

The neutron scattering method is widely used for measuring the water content along a soil profile, and its change over time. A neutron moisture gauge consists of a source of fast (high-energy) neutrons, a thermal neutron detector, and the associated electronic equipment necessary to power the detector and to display the results (see Fig. 1). Soil water content is estimated by lowering the neutron source into the ground through the access tube, and counting the number of thermalised neutrons that find their way back to the detector.

This method offers the advantages of nondestructive measurement (after initial installation), repeatability, and a large effective sampling volume. However, the accuracy of water content estimation by the neutron scattering method is entirely dependent on the development of a reliable calibration curve to relate neutron count rates to water contents (Bell and McCulloch 1969; Rawls and Asmussen 1973; Greacen 1981; Carneiro and Jong 1985; Chanasyk and Naeth 1996). The calibration relationship is influenced by the strength of the neutron source, the size and type of the neutron detector, the position of the detector relative to the source, the position of the detector relative to the ground surface (or water table), the size and composition of the access tube, the physical and chemical properties of the soil, and the water content of the soil (Schmugge *et al.* 1980; Dickey 1990; Stone 1990; Elder and Rasmussen 1994). In addition, the calibration is also influenced by the access hole geometry like the diameter of the hole, and, of most interest here, any gap between the access tube and the soil profile (Amoozegar *et al.* 1989; Allen and Segura 1990). Although many publications describe calibration of the neutron probe and its attendant difficulties,

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very little attention has been given to the error caused by the inadvertent presence of a gap around the access tube (see Fig. 1), due either to poor installation practice or to the shrink–swell behaviour of a clayey soil after installation. In highly expansive clay soils, a gap is unavoidable due to soil shrinking away from the access tube in a dry season.

Neat installation of the access tube for the neutron moisture gauge is crucial for the development and reliable use of a calibration relationship†. Maximum care is required during installation because a badly installed tube will result in permanently biased neutron readings (AWRC 1974; Prebble *et al.* 1981; Amoozegar *et al.* 1989). Errors in neutron probe reading may be introduced by a loosely fitting access tube. If the gap between the access tube and the soil is filled with air, neutron loss in the air results in neutron counts being underestimated, whereas if the gap is filled with water, more neutrons find their way back to the detector, and the neutron count is overestimated. Quantifying this effect is the primary purpose of this paper.

This influence of a gap around the access tube has been investigated experimentally (but as far as the authors are aware, not numerically). For example, Schrale (1976) indicated that annular air spaces of 12.5 mm and 25.5 mm around an aluminium access tube reduced the neutron count rate by 20–60% for volumetric water contents of the soil ranging between 10% and 36%. More recently, Allen and Segura (1990) reported that an air gap of 20 mm between the access tube wall and auger hole reduced the *slopes* of neutron count ratio to water content relationship by 12% for polyvinylchloride access tubes, and by 9% for aluminium access tubes. The gap between the access tube and soil can also be a preferential flow path for water, resulting in greater wetting near the access tube immediately following rain or irrigation. According to Schrale (1976), an air gap >4 mm surrounding a 51-mm-diameter aluminium tube, when saturated with water, can cause a significant error in the neutron probe reading.

The purpose of this study was to determine the effect of a gap, particularly an air-filled gap, on the soil water content determined by the neutron probe method. Both experimental investigation and numerical analysis are carried out. The numerical analysis enables the generalisation of findings from a limited number of experimental results, for example, by enabling rational corrections to be applied to data collected under less than optimum conditions.

Materials and methods

Soil and site description

The site selected for the study is located on open farmland some 10 km west of the city of Newcastle, NSW, Australia. The soil profile across the site is relatively uniform and can be generally described as 0.25 m silty clay topsoil underlain by high plasticity clay to a depth of approximately 1.2 m, then medium plastic silty clay to approximately 2 m where highly to extremely weathered siltstone is encountered. Soil type changes are gradual with no distinct layer boundaries evident below the base of the topsoil. Clay soils on the site are expansive, realising 5–10% volumetric strain when subjected to a water content change equal to that corresponding to the change from a dry season to a wet season at the field site.

Installation and instruments

Aluminium access tubes of 50 mm external diameter and 1.6 mm wall thickness were used in this study. Because of the low thermal cross-section of aluminium (σ_a = 0.24 barn and σ_s = 1.4 barn) (Stacey 2001), it was considered that aluminium casings would have little effect on the neutron flux, and so were neglected

† Access tubes are usually installed into pre-bored holes by hammering. A neat fit (that is, no gap between the tube and the soil) is achieved by ensuring that the diameter of the bored hole is marginally smaller than the outside diameter of the access tube.

Table 1. The measured neutron count rate (CR) at the Maryland site — comparison of the snug auger hole and the larger holes

Depth (cm)	Volumetric moisture content (%)	Snug auger hole (no. air gap)	Air-filled gap		Water-filled gap	
			Hole 1	Hole 2	Hole 1	Hole 2
0.45	33.5	14 848	8992	8753	21 551	21 393
1.45	32	14 576	9013	8903	21 377	21 125

in the analysis. Three identical access tubes were installed by a conventional hand auger to a depth of 2 m, one snug-fit in a 50-mm-diameter hole (i.e. no air gap between the access tube and the soil profile), and the other two placed in auger holes having a diameter approximately 55 mm larger than the tube size (i.e. 27.5 mm gap around the tube). All holes were slightly larger at the top. The distance between the boreholes was approximately 1 m, so soil conditions at each access tube were similar, though not identical. To maintain the access tube at the center of the larger holes, 105-mm-diameter spacer rings were installed at the top and bottom ends of the access tube. All access tubes were sealed at the bottom.

Undisturbed soil cores, 12 cm long, were collected at several depths during construction of the access holes. Laboratory analysis of the soil samples (according to AS1289) revealed the gravimetric water content and dry bulk density throughout the soil profile. The volumetric water content of the soil was then calculated from these measurements.

Field neutron count measurements were obtained using a Campbell Pacific Nuclear Model 503 Hydroprobe. The probe incorporates a 50 mCi (1.85 GBq) Americium-Beryllium (^{241}Am-Be) source, with a source strength of 111 000 fast neutrons per second, and a helium (^{3}He) proportional counter detector, some 13.2 cm in length and 2.54 cm in diameter.

Field observations

The measured neutron count rates (CR) at the selected depths are summarised in Table 1. It is immediately apparent that an air gap of 2.75 cm around access tubes 1 and 2 resulted in a reduction of the measured CR by approximately 35–40% compared with the snug-fit access tube. It is noted that the neutron counts from apparently similar holes (i.e. 1 and 2) were different; the neutron CR from access hole 1 were slightly higher than those obtained from access hole 2, with a maximum difference of about 3%. This difference may be attributed to the spatial variability of the soil and water content across the site. It should be pointed out that the data given in Table 1 are the average of eight 16-s count numbers.

A gap around the access tube may also fill with water. Significant errors in measured neutron count rates may be introduced if measurements are taken immediately after heavy rain or irrigation. The effect of the presence of water in the gap was also investigated during the field experiments by simply filling the gap with water. From Table 1, it can be seen that the measured neutron count rates immediately after filling the gap with water are increased by approximately 45%.

The influence of a gap on the neutron probe count is dependent on not only the thickness of the gap between the access tube and the soil profile, but also the water content of the soil in which the neutron probe is used. To investigate such effects, a theoretical study is desirable since field experiments can only address specific situations and cannot be generally applied. In addition, field experiments are both time-consuming and labor-intensive. In the present study, a numerical model, based on the multigroup neutron diffusion equations (and solved using the finite element method), has been developed for parametric studies of the effects of gaps of various dimensions around access tubes. In the next section, the theoretical basis of the numerical model is described.

Neutron moisture gauge theory

The neutron scattering method for measuring soil water content exploits neutron 'thermalisation behaviour'. When a neutron probe is lowered through an access tube into the ground, the fast neutrons emitted by the source collide with the atomic nuclei of the surrounding medium (refer Fig. 1). Each collision between a neutron and a nucleus results in a transfer of energy from the neutron to the nucleus. Since neutrons and hydrogen atoms have the almost same mass, fast neutrons are slowed down most effectively by collisions with hydrogen atoms, much like a billiard ball striking a stationary ball of the same size and each moving away with equal speeds (one slowing down and the other speeding up). This behaviour is the fundamental reason why a neutron gauge can be employed to detect the proportion of water molecules present in a soil; the hydrogen in water thermalises neutrons very effectively (relative to most other

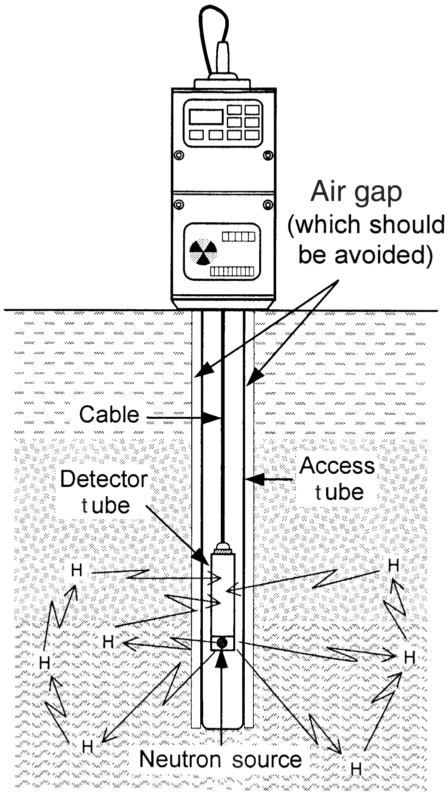

Fig. 1. Schematic drawing of a neutron gauge in use.

commonly occurring elements). Since the detector only senses thermalised neutron, the count rate is strongly correlated to the presence of water.

Neutron interactions with the surrounding material can be classified as either absorption reactions or scattering interactions. Absorption is the process where a neutron enters a nucleus, thereby forming a new isotope in an excited state (which then usually rapidly relaxes by emitting gamma radiation). Absorption reactions are strongly dependent on the neutron energy level. The absorption of fast neutrons can usually be neglected in ordinary soils since absorption rapidly decreases for energies above the thermal range. It should be noted that some elements, such as boron and chlorine, are strong absorbers of neutrons, and the presence of these elements in the soil significantly reduces the neutron gauge reading (Chanasyk and Naeth 1996).

In scattering interactions, the kinetic energy of a neutron is partially or completely transferred to the impacted nuclei in successive collisions through elastic or inelastic scattering. Reactions due to elastic scattering are by far the dominant mode of interaction of fast neutrons in soils (IAEA 1970).

When neutrons have slowed to thermal energies, their spatial movement is quite similar to the diffusion of gases, except that their lifetime is limited by absorption (IAEA 1970). After high energy neutrons are emitted by the source and diffuse outward through the soil, a fraction of the slow neutrons rebound back towards the probe and are absorbed by the nucleus of the gas in the detector, giving rise to a signal that, after processing, is known as the 'neutron count'. The detector only measures slow (i.e. thermal and some 'epithermal') neutrons.

It can be summarised that in a neutron moisture probe the fast, high-energy neutrons emitted from the source undergo simultaneously the processes of transport (by diffusion) and slowing-down (by collision). Therefore, a model describing neutron moisture probe behaviours must take into account the complete energy spectrum of neutrons, from their initial fast state to their thermalised state. A straightforward and practical approach is to subdivide the continuous energy spectrum of all neutrons into a number of discrete energy groups so that each energy group can, to reasonable approximation, be treated as monoenergetic with constant parameters. A set of simultaneous diffusion equations then covers the whole neutron spectrum from fast down to thermalised. This representation of neutron behaviour is known as 'multigroup diffusion theory' (Iliffe 1982).

For a given neutron energy group, the neutron balance (or conservation) equation under steady-state conditions is expressed as (Glasstone and Edlund 1957; Stacey 2001):

$$\underbrace{(\nabla \boldsymbol{J})}_{\text{Leakage}} + \underbrace{\left(\Sigma_{sl_i}\phi_i + \Sigma_{a_i}\phi_i\right)}_{\text{Sink}} = \underbrace{\left(S \text{ or } \Sigma_{sl_{i-1}}\phi_{i-1}\right)}_{\text{Source}} \tag{1}$$

From this neutron balance, the neutron diffusion equation for an n-group diffusion model can be written in the form:

$$\left.\begin{array}{ll} D_1\nabla^2\phi_1 - \Sigma_{sl_1}\phi_1 - \Sigma_{a_1}\phi_1 + S = 0 & E_1 \geq E > E_2 \\ D_2\nabla^2\phi_2 + \Sigma_{sl_1}\phi_1 - \Sigma_{sl_2}\phi_2 - \Sigma_{a_2}\phi_2 = 0 & E_2 \geq E > E_3 \\ D_3\nabla^2\phi_3 + \Sigma_{sl_2}\phi_2 - \Sigma_{sl_3}\phi_3 - \Sigma_{a_3}\phi_3 = 0 & E_3 \geq E > E_4 \\ \cdots \quad \cdots \qquad \cdots\cdots & \\ D_n\nabla^2\phi_n + \Sigma_{sl_{n-1}}\phi_{n-1} - \Sigma_{a_n}\phi_n = 0 & E_n \geq E \end{array}\right\} \tag{2}$$

where S is the high energy neutron source term, D_i is the diffusion coefficient for the ith energy group, $\Sigma_{\mathrm{sl_i}}$ is the slow-down cross-section, $\Sigma_{\mathrm{a_i}}$ is the macroscopic absorption cross-section, and E_i is the energy interval. The unknown quantity ϕ_i is the neutron flux distribution, which is defined as the product of the neutron density and the velocity. The calculation of D_i, $\Sigma_{\mathrm{sl_i}}$, and $\Sigma_{\mathrm{a_i}}$ from the elemental composition of the soil is described in Li *et al.* (2002).

In the crudest approximation, 'multigroup diffusion theory' reduces to a single group. Single group theory assumes that all diffusion and absorption of neutrons occur in a single energy state, i.e. at the thermal energy. Obviously, this model is not a good model for a neutron probe analysis. The 2-group diffusion model breaks the energy spectrum of neutrons into 2 separate groups (i.e. fast and thermal groups), whereas for the 3-group theory, the fast neutrons are further split into an upper and lower fast groups. Analytical solutions to Eqn 2 are available for 1-, 2-, and 3-group diffusion theory, assuming a point source situated in an infinite homogeneous medium (Olgaard 1965).

The analytic solution to the 2-group theory was used by Haahr and Olgaard (1965) to determine a so-called 'sphere of importance'. Olgaard (1965) also used the analytic solution to the 3-group diffusion theory as an improvement on the 2-group theory calculations and achieved reasonable agreement with some experimental measurements in various soil types. Based on the 3-group model developed by Olgaard (1965), Elder and Rasmussen (1994) obtained a calibration equation between neutron counts and water content in an unsaturated tuff. The 3-group approximation was also applied by Morris and Williams (1990) to develop a water content calibration for coal mine tailings. Although these solutions have served to assist in neutron probe calibration, the assumptions made in deriving the analytic solutions clearly ignore the access tube geometry, probe and detector geometry, the spatially variable soil composition, and the boundary conditions likely to be encountered in practice.

Because of the numerous approximations, a numerical model based on 7-group diffusion theory has been developed by the authors to give a better physical description of the problem and to improve upon previous results. A 7-group diffusion theory, whose upper and lower energy limits are given in Table 2, was found to be sufficiently accurate to describe neutron slowing down and diffusion in a neutron gauge (Li *et al.* 2002).

The numerical model

The finite element method is employed to solve the coupled 7-group neutron diffusion equations. The finite element discretisation and formulation are described in detail in Li *et al.* (2002). The neutron source, detector, air gap, and surrounding soils are modelled asymmetrically, as shown in Fig. 2. This geometry is a reasonable representation of the physical arrangement of modern neutron moisture gauges. The volume of the soil shown in Fig. 2 exceeds the 'radius of influence' of the neutron probe, since the effective volume

Table 2. Upper and lower energy limits, E_i, used in the numerical model

Group	Upper limit	Lower limit
1	4.5 MeV	4.0 MeV
2	4.0 MeV	3.0 MeV
3	3.0 MeV	2.0 MeV
4	2.0 MeV	1.0 MeV
5	1.0 MeV	0.1 MeV
6	0.1 MeV	1.44 eV
7	1.44 eV	$5kT_n^A$ eV

$^A T_n$ is the neutron temperature.

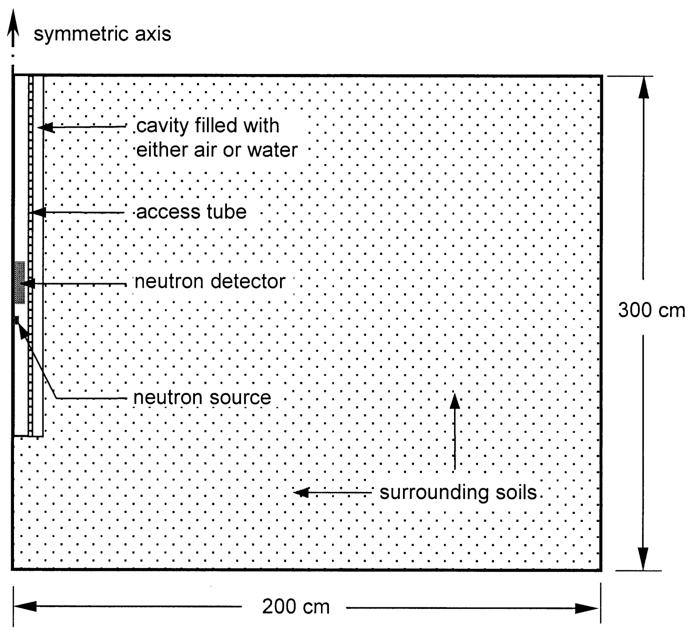

Fig. 2. The cylindrical system used for numerical analysis (not to scale).

'sensed' by a neutron probe is approximately a sphere of radius 20–70 cm, the radius increasing with decreasing water content (because at low water contents, the fast neutrons have to travel greater distances to undergo scattering interactions and so become thermalised).

In order to apply the numerical analysis, it is necessary to first know the elemental composition of the soil. A total of 14 chemical analyses of the Maryland soil at different depths were carried out. The results of the chemical analyses are given in Li *et al.* (2002).

The 2-dimensional axisymmetric finite element analysis was carried out to calculate the thermal flux distribution in the system. The finite element mesh is shown in Fig. 3. A total of 2848 three-node triangular elements were used in the analysis.

Once the distribution of the thermal neutron flux, ϕ_{th}, in the neutron detector (as shown in Fig. 2) is known, the gauge response (i.e. the number of counts or neutrons detected in a given time) can be obtained by integrating $\phi_{th}\ \Sigma_{a,D}$ over the volume of the detector. That is, by evaluating:

$$CR = \int_V \phi_{th} \cdot \Sigma_{a,D} \cdot T \cdot dv \qquad (3)$$

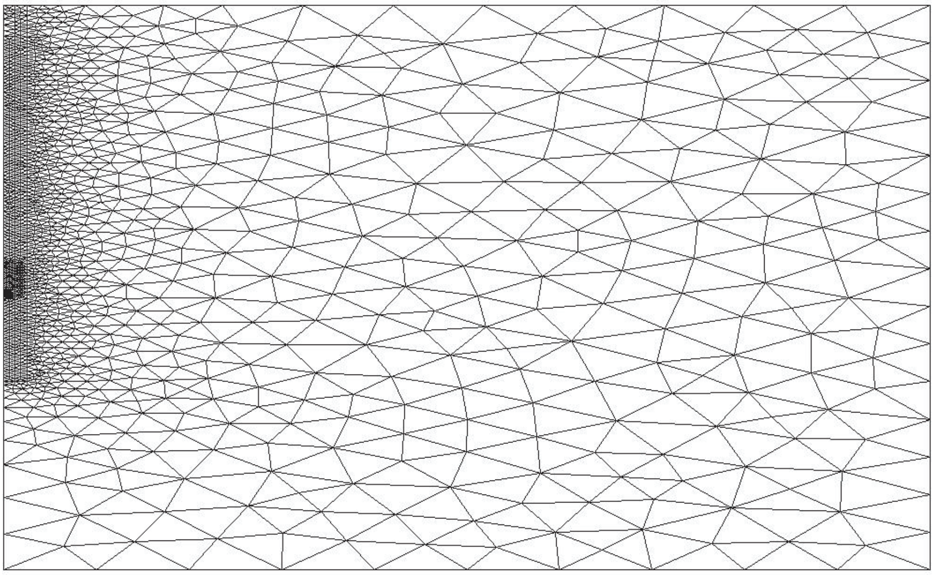

Fig. 3. The finite element mesh.

where CR is the count rate and T is the count period in seconds. The thermal absorption cross-section for the detector gas, $\Sigma_{a,D}$, may be calculated from the following formula:

$$\Sigma_{\mathrm{a,D}} = \frac{0.6023\times10^{24}}{22.41\times10^{3}}\frac{p}{760}\frac{273}{T_D}\frac{E}{100}\frac{\sqrt{\pi}}{2}\sigma_{\mathrm{a}}^{2200}\times10^{-24}\sqrt{\frac{293}{T_n}} \quad (\mathrm{cm}^{-1}) \tag{4}$$

where p is the pressure of the gas in the detector (in mm Hg), T_D is the detector temperature (in degrees Kelvin), E is the percentage of the detector gas in the detector, and T_n is the neutron temperature. For the ^{3}He-filled proportional counter, σ_a^{2200} may be taken as 5330 barns (Mughabghab *et al.* 1981).

It should be noted that the effects of the access tube and absorption in the neutron source itself are not taken into account in this study. Although the numerical approach described here could include these effects, it is believed that their influences on neutron flux at the detector are insignificant (at least for the aluminium access tubes considered here).

The numerical results and discussion

Comparison between the calculated and measured neutron count rates

In order to verify the validity of 7-group neutron diffusion model, a back-analysis of the field measurements was first carried out.

The macroscopic scattering and absorption cross-sections of the air were calculated based on the assumption that air (atmosphere) consists of 79% nitrogen (N_2) and 21% oxygen (O_2). Although a variety of other gases such as argon (Ar), carbon dioxide (CO_2), neon (Ne), helium (He), krypton (Kr), hydrogen (H_2), and xenon (Xe) can be found in the air, they comprise only approximately 1% of the mass and volume of the air and therefore can be ignored in the numerical analysis. It should be pointed out that water vapour may be present in the air, but it is not considered in this study. For the case of the gap filled with water, the volumetric water content of the cavity was taken as 100%.

Based on the laboratory and field measurements, the soil dry density was taken as 1.5 g/cm^3 at the depth of 0.45 m and 1.47 g/cm^3 at the depth 1.45 m. The macroscopic

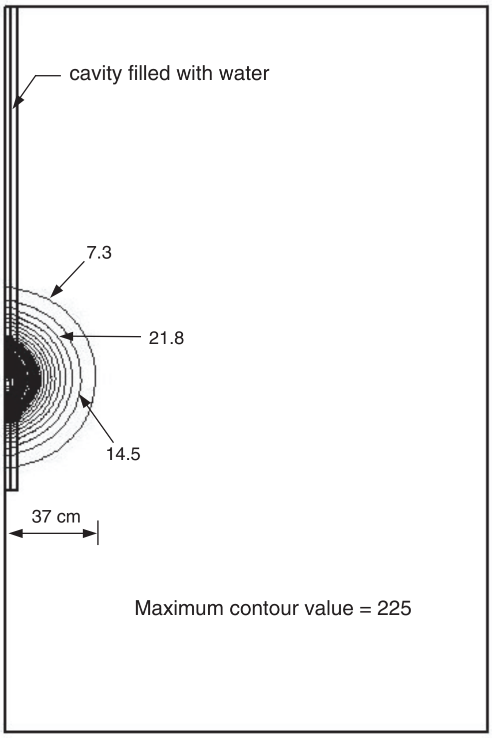

Fig. 4. The contour plot of the calculated thermal neutron flux ϕ_{th} (neutrons/cm^2.s) distribution (2.75 cm cavity filled with water).

Table 3. Comparison of the measured neutron count rate (CR) at the Maryland site and the results predicted by the numerical model

	Depth (m)	Snug auger hole (no air gap)	Air-filled gap Hole 1	Air-filled gap Hole 2	Water-filled gap Hole 1	Water-filled gap Hole 2
Measured CR	0.45	14 848	8992	8753	21 551	21 393
Calculated CR	0.45	14 916	8692		21 657	
Measured CR	1.45	14 576	9013	8903	21 619	21 584
Calculated CR	1.45	14 790	8568		21995	

scattering and absorption cross-sections of the soil were calculated from the chemical composition and dry density of the soil. The calculation involved a summation of microscopic cross-sections over all elements in the soil (see Li *et al.* 2002 for details).

A typical distribution of thermal neutron flux estimated by the numerical model is shown in Fig. 4. It can be seen that the neutron flux decreases rapidly with the distance from the neutron probe. In other words, soil nearest to an access tube makes the greatest contribution to the thermal flux measured by the detector.

The results predicted by the numerical model are summarised in Table 3 to permit comparison between the numerical results and the field data. For the snug-fit access tube without a cavity, the calculated neutron CR is slightly higher than the field observation (by about 0.5–1.5%). However, the numerical model overestimated the percentage reduction in the count rate due to the presence of an air gap, by about 1–5%. This discrepancy may be at least partially attributed to ignoring the water content in the air. For the case of the cavity filled with water, the count rate predicted by the numerical model was about 0.5–1.5%

higher than the field data. This may be explained by the fact that some of the water filled in the cavity rapidly diffused into the surrounding soil during the field experiments, whereas in the numeral analysis, the cavity alone was taken to be full of water.

In general, the numerical results compared favourably with the field data. This gives some confidence in applying the 7-group neutron diffusion model to a parametric study of the influence of gaps on the neutron moisture gauge calibration.

Effects of air gaps around access tubes on neutron count rates

Further finite element analyses were carried out for the soil with a volumetric water content ranging from 5% to 35%. The thickness of the annular shaped cavity, D, was taken as 2.5, 5, 10, 15, 20, 25, and 30 mm, respectively, in order to investigate its effect on the neutron count rate. The dry density of the soil was assumed to be a constant 1.5 g/cm^3. It should be pointed out that for unsaturated expansive soils, both soil volume and density change as the *in situ* soil water content changes. Therefore, a complete description and simulation of the problem with neutron gauge calibration should take into account the influence of the soil dry density. However, the numerical results indicated that such influence on the neutron CR was small for this particular case. The neutron CR, expressed as a fraction of the neutron CR in the absence of the gap, are plotted against the gap width, D, in Figs 5 and 6, respectively.

It is clear that the presence of an air-filled gap decreased the neutron count rates considerably. The qualitative reason for this behaviour can be explained by the air cavity containing comparatively few atoms, and hence, little thermalisation occurred within its volume. It is intuitively clear that when there is an air gap between the access tube and the soil, fast neutrons emitted from the source first have to pass through the air gap (and some may get 'lost' by diffusing up the gap and into the atmosphere), to be thermalised by hydrogen in the adjacent soil, and then return to the detector through the air gap. Therefore, the presence of the air gap also increases the neutron 'path length' between the source and detector. In other words, the fast neutrons have to travel a greater distance to become thermalised, and consequently the number of thermal neutrons returned to the detector is reduced.

From Fig. 5, it can be seen that count rates estimated by the numerical model decreased as the width of air gap increased. An increase in the width of air gap implies that the soil being 'measured' is relatively further away from the source and detector, and this reduces the neutron count rate. This effect is less pronounced at lower water contents owing to the relatively dry soil having properties towards that of air. In other words, the reduction in count rate due to the air gap depends not only on the cavity width but also the volumetric water content of the soil. For example, the decrease in count rate at 5% soil water content due to a 10-mm air gap was approximately 20%, whereas at 20% soil water content the decrease in count rate for the same gap was about 33%. Figure 5 also shows that count rate dropped most rapidly as the air gap increased from 0 and 10 mm, with a much smaller count rate decrease as the air gap increased from 10 and 30 mm. It is apparent from Fig. 5 that for a moist soil, a small air-filled gap may have a very significant influence on the estimated water content of the soil.

Compared with the air-filled gap, a water-filled gap around access tubes has a smaller influence on the count rate at small gap thicknesses, but a greater influence at large gap thicknesses. It can be seen from Fig. 6 that count rate due to the presence of water in the gap can be more than 3 times higher than count rate in a snug-fit access tube. The numerical calculations indicate that bias due to a water-filled cavity of 10 mm could lead to an

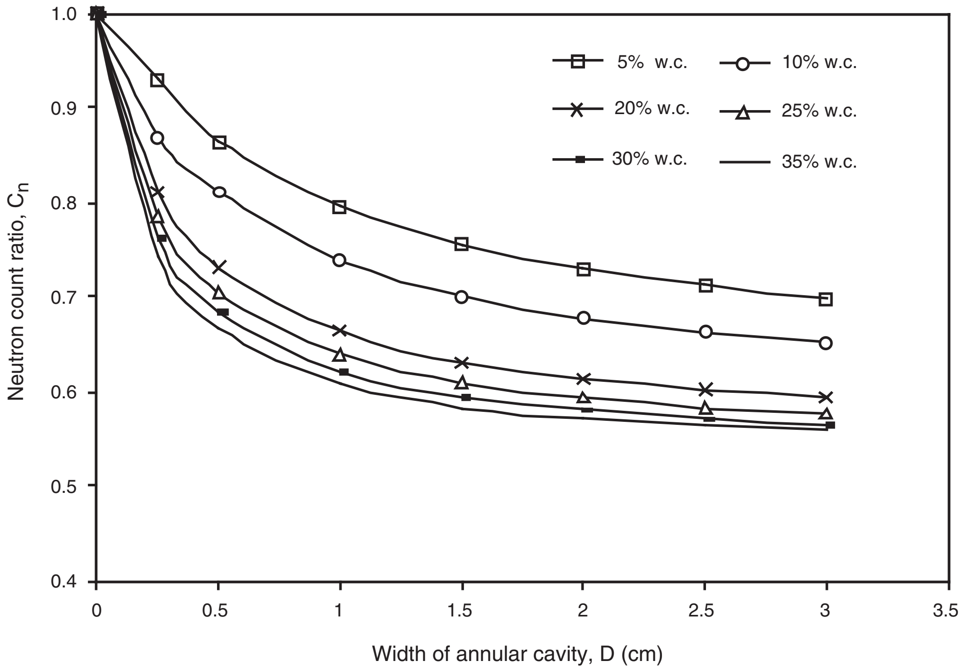

Fig. 5. Effect of the air-filled cavity of width D (C_n is ratio of the count rate with an air-filled cavity presented to the count rate in the absence of the cavity).

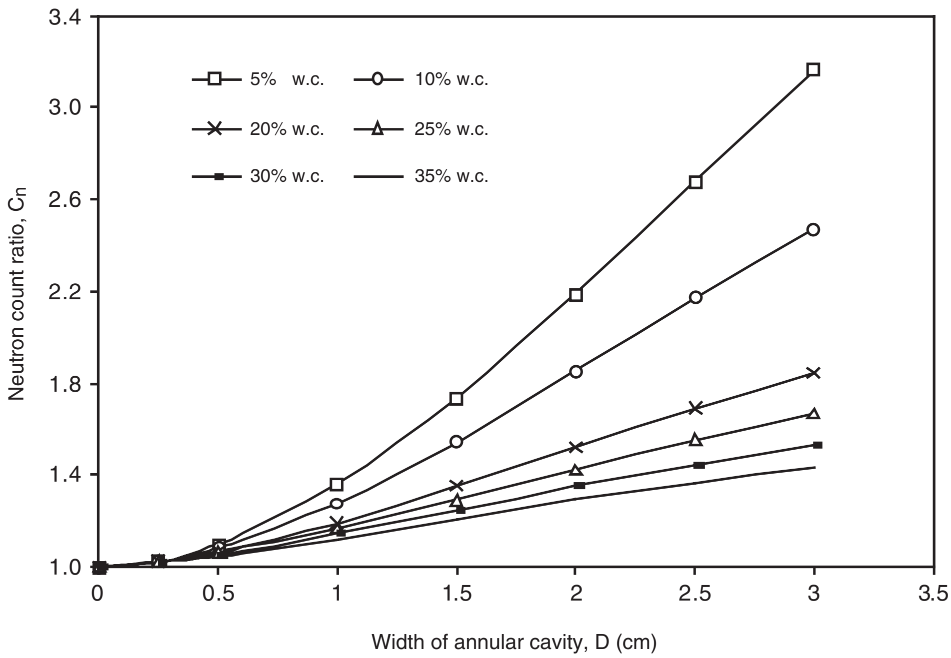

Fig. 6. Effect of the water-filled cavity of width D (C_n is ratio of the count rate with an water-filled cavity presented to the count rate in the absence of the cavity).

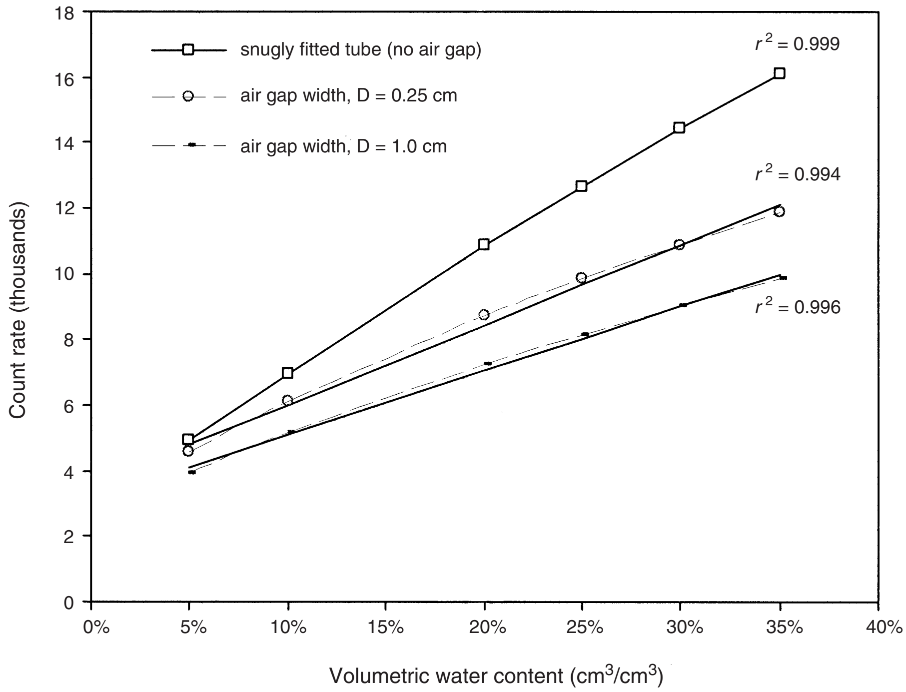

Fig. 7. Count rate as a function of volumetric water content for Maryland soil; comparison of a snug-fit access tube and an access tube with air gap.

overestimate of count rate by approximately 15–35%, depending on the soil water content, compared with an underestimate of 20–40%, depending on soil water content for the same gap filled with air.

Effects of an air gap on calibration curves

An air gap around access tubes not only lowers the neutron probe readings but also results in some loss of sensitivity. Sensitivity of a neutron probe is defined by the slope of the calibration curve, that is, the change in count rate of the probe per unit change in water content of the soil. Clearly, it is desirable if sensitivity is as high as possible (Greacen 1981). As can be seen from Fig. 7, the slope of the count rate *v.* soil water content curves generally decreases with increasing the width of air gaps (i.e. the curve becomes flatter), which indicates a narrower range of count rates for a given range of soil water contents. Compared with the curve for a snug fit access tube, the slopes were reduced by approximately 10% for a 2.5-mm air gap and 15% for a 10-mm air gap. Similar observations about the loss of sensitivity—but based on the field observations—have been reported by other researchers (Amoozegar *et al.* 1989; Allen and Segura 1990). Inspection of Fig. 7 also reveals that the calibration curves for access tubes with air gap were slightly non-linear, contrasting with a more nearly linear relationship for a snugly fit tube.

The theoretical calibration curves for a water-filled gap are plotted in Fig. 8. The curves for the neutron counts are significantly higher than the curve for a snug-fit tube. The error is, however, almost constant in magnitude and so leaves the calibration curves almost 'parallel'. This implies that the presence of water in the gap can cause a significant error in estimating absolute soil water content but has little impact on the measurement of the

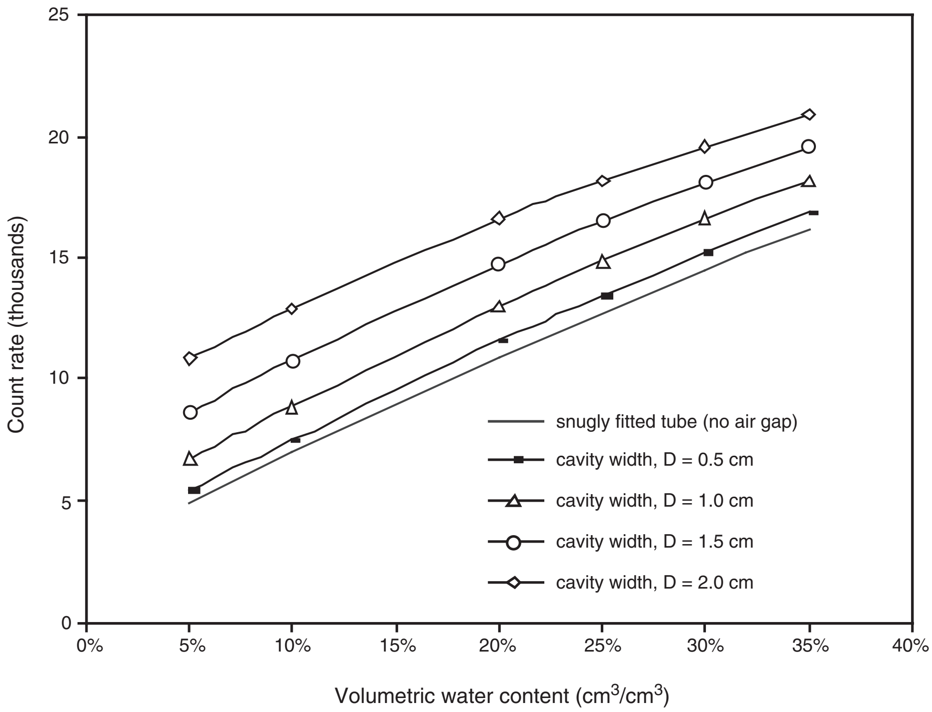

Fig. 8. Count rate as a function of volumetric water content for Maryland soil; comparison of a snug-fit access tube and an access tube with water-filled gap.

change in soil water content, as any error introduced by the presence of water in the gap will tend to cancel out in a subtraction of one water content estimate from another.

In practice, access tubes having a larger diameter than the neutron probe are often used (Tyler 1988). The effect of an increased tube diameter on a neutron probe readings is similar to the effect of the presence of an air gap surrounding a tube. Therefore, the information presented in the Figs 5–8 and Table 3 can also be used to estimate the influence of an increase of the access tube diameter on neutron moisture calibration.

Summary and conclusions

In practice, it is often difficult to drill an accurately sized hole due to limitations of site or soil conditions (for example, a residential area may not be readily accessible by heavy equipment, or due the presence of tree roots or rock fragments in the access holes). In these cases, it may be more practical to accept a gap around the access tube, and drill a larger-than-required hole and place the neutron probe at the center of this hole for water content measurements (Tyler 1988; Amoozegar *et al.* 1989). Alternatively, the wet–dry cycling of an expansive clay soil can lead to the development of a gap between the access tube and the soil. The presence of an air- or water-filled gap around access tubes will then inevitably introduce an error in neutron probe reading. For these reasons, the influence of a gap on the accuracy of water content estimation by the neutron probe method requires evaluation.

In this study, both experimental investigation and numerical analysis were carried out to evaluate the effects of an air- and water-filled gap on neutron probe calibration. A numerical model, based on multigroup diffusion theory, was developed to predict the neutron flux distribution in a neutron probe and surrounding soil. Neutron count rates predicted by the numerical model based on the soil dry density, elemental composition, and the size of the gap were found to agree reasonably well with the measured data in a heavy clay soil at the field site.

The results of the field investigation and numerical analysis clearly show that the neutron probe reading and calibration are significantly influenced by the existence of an air gap between the access tubes and the surrounding soils, and this influence was evident even for small gaps. The bias due to an air-filled gap around the access tube could lead to an underestimate of soil water content by between 5% and 45%. The numerical analysis revealed that the influence of an air-filled gap was more pronounced at higher water contents, since the contrast between the properties of air and soil is greater. The presence of an air gap also resulted in a loss of sensitivity (that is, decreasing slope of the count rate *v.* soil water content curves), and so increased the relative error of water content change estimates. It was also found that significant errors in neutron count rate could be introduced if water entered the gap between a loose fitting tube and the soil, although the changes were most pronounced when the gap thickness was large.

The results of this research clearly indicate that gaps between the neutron access tube and the soil profile should be avoided during field installation. When air- or water-filled gaps are unavoidable, it is desirable that the dimension of gap is minimised, and a specific calibration developed for a known gap geometry.

Finally, this paper makes clear that the task of neutron probe calibration can be made significantly easier with a numerical analysis complementing the interpretation of limited experimental data.

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