Reprint from

"ISOTOPE AND RADIATION TECHNIQUES IN SOIL PHYSICS AND IRRIGATION STUDIES 1983"

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1983

IAEA-SM-267/17

SOME CONSIDERATIONS FOR SOIL MOISTURE GAUGING WITH NEUTRONS

S. KASI, J. IMMONEN, K. SAIKKU
Physics Laboratory,
Helsinki University of Technology,
Espoo, Finland

Abstract

SOME CONSIDERATIONS FOR SOIL MOISTURE GAUGING WITH NEUTRONS.

The sensitivity of the moisture gauge, especially the neutron gauge, is discussed. The neutron gauge is very sensitive to hydrogen content. The interference of other elements including the most significant absorbers of thermal neutrons is computed. The so-called composition effect is made quantitative. Normally it is not very significant. A calculation of the weight function of the neutron gauge is reported, and a simple formula given for the 95% "sphere" of influence. To simulate the subsurface gauge a procedure is presented and applied by using available experimental data. The procedure is not a very good approximation of the transport theory:diffusion theory with a neutron absorbing sphere. The position and size of this sphere were two fitting parameters; altogether five gauge parameters were used for a fitting.

1. SENSITIVITY OF THE MOISTURE GAUGE

In agricultural use of soil its moisture content should not remain long below wilting-moisture content and above field capacity. Irrigation or drainage is needed to keep water within this range. On the other hand, the soil may have pores for relatively large amounts of gravitational water. All these moisture quantities — wilting moisture, available water, moisture deficit, field capacity, saturating water content etc. [1], can be presented as density quantities which have the unit kg/m^3. Let us denote this quantity by w.

The user of a moisture gauge can have a requirement Δw for its accuracy. Roughly a constant absolute accuracy of moisture determination is often appropriate. Then the sensitivity quantity

$$S = \frac{1}{R}\frac{dR}{dw} \tag{1}$$

where R is the response of the moisture gauge, offers a good basis for comparing instruments which have a response function of the type $R = R(w)$. In some such comparisons it is better to use[2] the relative sensitivity $S_r = (dR/R)/(dw/w)$.

For neutron gauges many types of sensitivity evaluation have been proposed. S of Eq. (1) has been used, e.g. in Ref. [3]; the relative sensitivity, see Ref. [4], is best when a constant $\Delta w/w$ is demanded (as in many mass gaugings); the sensitivity quantity dR/dw [5] has the advantage of being proportional to source strength, but these sensitivity evaluators have no basis in the statistical error of radioactivity such as the quantity

$$E = \frac{1}{R^{1/2}} \frac{dR}{dw} \tag{2}$$

presented in Ref. [6] has (see Ref. [7:a]). The higher E is, the smaller is the statistical error in the moisture w measured. The modifications of E in the cases of measured background or standard count-rate comparison have been given in Ref. [6].

A requisite for a nuclear gauge is that radiation risk must be at a minimum. This certainly has been achieved when natural radiation is used. Relatively slow moisture processes near the soil surface can be followed by cosmic radiation [8].

The neutron measurement used for moisture determination is in first place the protium (^1H) density determination. Therefore, the hydrogen content of the matrix must be very accurately known. Consider gaugings with a "point probe", i.e. with the probe where the source and detector are close. When you measure very organic soil matter, e.g. peat, and when its dry density $\rho = \rho_t \cdot w$ does not vary (ρ_t is the total density), then $R \propto \rho_t$, and thus $S \simeq 1/\rho_t$. In this matter the point neutron and gamma probes gauge similarly [9]. For neutron gauging in mineral soil, where the matrix includes little hydrogen, the effect of density is relatively weak and the counting rates, at least without background, are small for a point in dry substance. Thus, $S \simeq 1/w$.

2. BASIC CALIBRATIONS

For a neutron moisture gauge the dependence of calibration on matrix density is minimal when the substance is free from hydrogen. When the hydrogen content of the matrix is known, the equivalent moisture content can be used [10], and the calibration which was done for a substance which has no hydrogen in its composition.

The hydrogen content of the soil matrix should be determined accurately. For this, thermogravimetric methods can be useful. Many other soil elements that considerably interfere with the neutron measurement cannot be analysed easily. Fortunately, the effect of composition is not usually very significant, (see Section 4). For calibration, a basic composition can be selected which is most representative for the tasks of the gauge. For soil studies the best basic matrix composition is

TABLE I. INTERFERING POWER S_i (kg/m^3)/(kg/m^3) OF THE ELEMENT i CALCULATED FOR A NEUTRON MOISTURE GAUGE WHEN THE DETECTOR, BLACK FOR THERMAL OR EPITHERMAL NEUTRONS, IS A CONCENTRIC SPHERE WITH A POINT AmBe SOURCE.
The free density of the matrice substance is 1500 kg/m^3 and it has the averaged composition of the earth's crust, except the hydrogen content $p_H = 0$. The moisture content w = 100 kg H_2O/m^3

Element	Content p_i	Interfering power S_i in	
i	value ± SD	thermal	epithermal
O	464 ± 30 g/kg	0.11	0.36
H	0 ± 0	8.0	6.0
Si	282 ± 100 g/kg	0.04	0.22
Al	82 ± 30 g/kg	0.025	0.19
Fe	56 ± 30 g/kg	−0.08	0.20
Ca	41 ± 20 g/kg	0.005	0.14
Na	24 ± 10 g/kg	0.06	0.4
Mg	23 ± 10 g/kg	0.07	0.27
K	21 ± 10 g/kg	−0.13	0.13
Ti	5.7 ± 3 g/kg	−0.3	0.24
P	1050 ± 500 mg/kg	0.04	0.20
Mn	950 ± 450 mg/kg	−0.6	0.27
S	260 ± 120 mg/kg	−0.004	0.17
C	200 ± 90 mg/kg	0.17	0.5
Cl	130 ± 60 mg/kg	−2.6	0.15
N	20 ± 9 mg/kg	−0.23	0.5
Li	20 ± 9 mg/kg	−32	−0.3
B	10 ± 5 mg/kg	219	−6.6
Gd	7.3 ± 3.6 mg/kg	−708	−1.0
Sm	7.3 ± 3.6 mg/kg	−187	−2.3
Eu	1.2 ± 0.6 mg/kg	−115	−4.0
Cd	200 ± 100 μg/kg	−84	0.07
In	100 ± 50 μg/kg	−5	−0.08
		measurement	

that of the earth's crust, but even for some mineral soils it must be modified, e.g. for $CaCO_3$ [11].

For light organic soils, which usually include a high water content, a good basic calibration is that which has been determined for H_2O.

3. INTERFERENCE OF ELEMENT

An increase of density ρ_i of an element i in a substance causes a change of gauge counting rate. A certain change of water density will cause the same counting rate change. We can define the ratio of this water density change (increasing or decreasing) to the increase of the element density, i.e.

$$S_i = -(\partial w/\partial \rho_i)_R \tag{3}$$

as the interfering power of this element, or as the sensitivity of the gauge to the density of this element.

To make calculational investigations concerning the basic calibration for mineral soils, the composition of the earth's crust was taken from Krauskopf [12]. For hydrogen the content zero was selected. The composition and the result of a calculation are presented in Table I. The first elements up to manganese are the most common in the earth's crust. The last seven elements have a very high absorption cross-section for thermal neutrons. They absorb 30% of thermal neutrons in the soil when it is dry. One can calculate, when w = 10% by volume, that an increase of 3.6 ppm in gadolinium content causes $\Delta w = -3.8$, and that a 5 ppm increase in boron content gives $\Delta w = -1.6$ kg H_2O/m^3 as the error of moisture reading.

The hydrogen sensitivity is generally higher in gauges that detect thermal than in those that detect epithermal neutrons – see Table I [7:b, 13]. In calculations with models of different "point" gauges we found that in the thermal measurements S_i for hydrogen varies between 6–9 for rather mineralized soil, and decreases with moisture. In the case of epithermal detection S_i may in such cases be below the value of 4. The reason for the low epithermal sensitivity is that the increase of slowing-down power decreases flux with respect to the slowing-down density at the same energy; the growth in the response is due to the decrease of diffusion. Otherwise, when the detector is a very strong absorber of even epithermal neutrons, the spectrum of detectable neutrons is to be hardened considerably. For this case, our 3-group diffusion calculations (though comprising flux depression treatment) may be misleading.

Now we also define, by the same means as S_i,

$$S_\rho = -(\partial w/\partial \rho)_R \tag{4}$$

TABLE II. THE INTERFERING POWER OF DENSITY S_ρ, ITS VARIANCE D_c AND THEIR RATIO E_c
The type of gauge, matter and moisture as in Table I. The used estimates of $\sigma(p_i)$ are also presented there

Neutron detector	$S_\rho \pm D_c$	E_c
Thermal	0.0500 ± 0.0069	13.8%
Epithermal	0.283 ± 0.026	9.4%

to be the interfering power of dry density ρ. The values of this are given in Table II for the same cases as in Table I. The increase $\Delta\rho = 100$ kg/m^3 is eliminated with $\Delta w \simeq -5$, or $\simeq -28$ kg H_2O/m^3 in thermal or epithermal detection, respectively.

Change of density does not generally cause a unique S_ρ. We define it to be the change of dry density without any change of composition, i.e. $d\rho_i = p_i d\rho$. Thus,

$$S_\rho = \sum_i p_i S_i. \tag{5}$$

4. EFFECT OF COMPOSITION

It is supposed that the variance of the content of each element i is known. $\sigma(p_i)$ is the standard deviation. If we suppose that the p_i are independent – though their sum must be 1 and they co-exist in many minerals – then Eq. (5) gives the variance

$$\sigma^2(S_\rho) = \sum_i S_i^2 \sigma^2(p_i) \tag{6}$$

Thus, the composition causes in S_ρ the standard deviation

$$D_c = \sigma(S_\rho) \tag{7}$$

The interfering effect of composition is properly defined, we consider, with the measure

$$E_c = D_c/S_\rho \tag{8}$$

D_c and E_c, in addition to S_ρ, have been calculated in Table II for the case we have been using as an example.

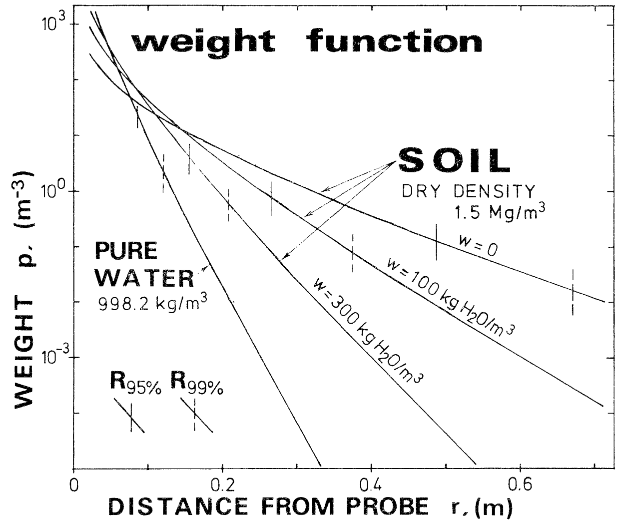

FIG.1. The weight function p(r) calculated with the model of a "point" probe in homogeneous media: water and a soil with three values of moisture. The soil has the composition of the earth's crust – see Table I – with an H content of 1400 mg/kg. The radii of the 95% and 99% influence spheres around the probe are shown.

5. ILLUSTRATION OF SAMPLE VIRTUALLY GAUGED

The region measured by a neutron gauge is often represented as a sphere [14]. A soil hole, surface, etc., however, considerably deforms this picture [13], even for a "point" probe. There have been few attempts to determine a weight function [15] appropriate for the real geometry of measurement, while the subsurface gauge calculations with a finite sphere, in which the probe is in the centre, have been common.

For our basic soil composition with $w = 100\ \mathrm{kg\ H_2O/m^3}$ the slowing-down effect of water below 100 keV represents about 90% of the total slowing-down power. We can rather definitely define the weight function p by considering the number of hydrogen scatterings during the slowing-down of the detected neutrons: we establish that the ratio of the number of these scatterings in a small soil element dV to their total number is given by pdV [14]. In the model of a point source in homogeneous medium we have

$$\int_0^{R_t} p 4\pi r^2\, dr = t \qquad (9)$$

where $t = 1$ when $R_t = \infty$. The solution R_t of Eq. (9) is the radius of the 100 t% influence sphere in moisture gauging.

The weight function p decreases very rapidly with the distance from the point probe – see Fig. 1. In the calculations, a 3-group diffusion model has been used [14].

In Fig. 1 the radii of the spheres that have an influence of 95% and 99% in the counting rate are presented. For the radius of the 95% region of influence, in the case of a point probe in a Danish soil (composition near that of the earth's crust) which has a hydrogen content 0.326%, we have the formula

$$R_{95\%} = \frac{4.3}{L_1^{-1} + L_2^{-1}} \tag{10}$$

Eq. (10) is based on the observation presented in Ref. [14] concerning the relation between 3-group and 2-group diffusion results. L_1 and L_2 are the slowing-down length and thermal diffusion length, respectively. Their formulae can be found in the references.

6. SIMULATIONS OF GAUGE

The exact theory of a neutron gauge is the transport theory [16]. Its normal form and the combined one [16] can be used. The latter gives the probability of detecting a neutron. Both are needed for exact determination of the weight function – Section 5 and Ref. [14].

We have found such a model to calculate the fitting to any measured data which seem to be useful. The rather poor data that must be used in calibration today are presented in Fig. 2. The data were neasured with the Danish subsurface probe BASC and a Miniscaler in an access iron tube.

In our model we use a point source in an infinite medium and calculate with a 3-group diffusion model. The detector is a sphere at a certain distance from the source and it absorbs all incoming thermal neutrons and part of the epithermal ones. The effect of the detector is taken into account by depressing the fluxes calculated in a homogeneous medium.

As soil parameters in our data we have had to use: (1) moisture, (2) heating loss, and (3) bulk density, but not the absorption of thermal neutrons, although we have made a certain effort with our facilities to measure the absorption cross-section, as has been determined elsewhere, e.g. Ref. [11]. As instrumental fitting parameters we had: (1) distance between source and detector; (2) radius of detector sphere; (3) multiplier for the calculated counting rate; (4) fraction of the detected epithermal neutrons; and (5) an additional constant term (it made fitting better).

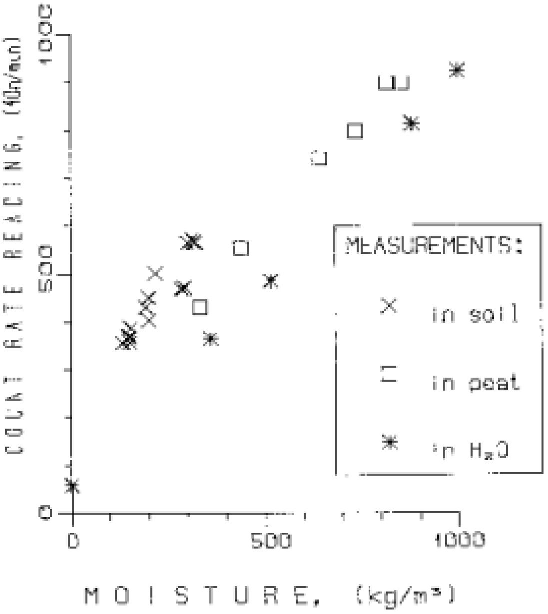

FIG.2. The present experimental data of subsurface gaugings using an iron access tube. The soil data were measured in the lysimeter of Helsinki university [17], at least 0.5 m below the surface of each soil column. The dry densities of these sandy soils are about 1500 kg/m^3 and they have hydrogen contents from 0.3 to 0.5%. The samples for weighing were taken 0.5 m from the access tube. Peat measurements in field (dry density $\simeq$ 73 kg/m^3 and ash content $\simeq$ 3%) may have suffered from moisture inhomogeneity. The samples were taken just around the access tube. In H_2O measurements in ice and snow it required a considerable effort to make the gauge function in the cold. The zero moisture value was obtained with the probe in air.

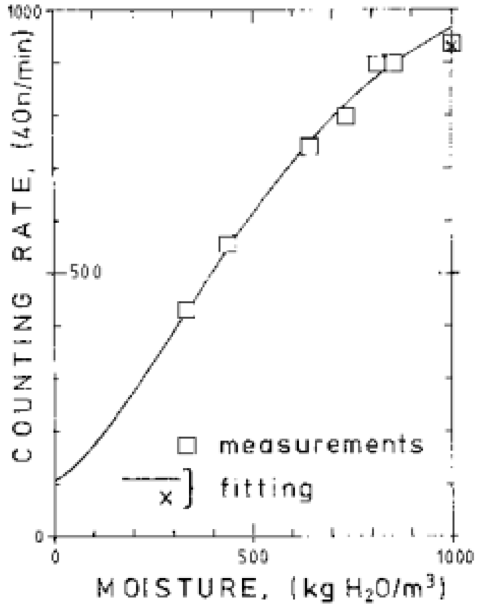

FIG.3. The optimized calibration to the peat and water data of FIG.2. The computer model and parameters are described in the text.

A fitting with our model is shown in Fig. 3. For the geometric fitting parameters this gave the value 6.2 cm for the distance between source and detector sphere, and 1.38 cm for the radius of the sphere; these values are in accordance with the probe measurements.

The trivial geometry and incompatible theory need improvements in our simulation. The best experimental data for the calibration can be achieved by making measurements in a laboratory with homogeneous materials which have certain elemental compositions. We prefer to get different "moisture" contents by mixing materials which possibly contain water of crystallization.

The simulation depends considerably on gauge type, and on special features in the soil geometry (surface against air, etc.).

ACKNOWLEDGEMENT

In preparing the fitting program we received considerable help from the Institute of Mathematics of Helsinki University, who allowed us to use a program they had developed for searching for the maximum of a non-linear parametric representation, see e.g. Ref. [18].

REFERENCES

[1] LINSLAY, R.K., Jr., KOHLER, M.A., PAULUS, J.L.H., Hydrology for Engineers, McGraw-Hill Kogakusha, Ltd., Tokyo (1975) 192.

[2] SEGAL, Y., NOTEA, A., SEGAL, E., "A systematic evaluation of nondestructive testing methods", Research Techniques in Nondestructive Testing (SHARPE, R.S., Ed.) Vol. 3, Academic Press (1977) 293.

[3] ARTSYBASHEV, V.A.,Yaderno-Geofizicheskaya Razvedka, Atomizdat, Moscow (1980) 146.

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Neutron Moisture Gauges, Technical Reports Series No. 112, IAEA, Vienna (1970).

[5] GARDNER, R.P., ELY, R.L., Jr., Radioisotope Measurement Applications in Engineering, Reinhold Publishing Corp., New York (1967) 254.

[6] KASI, S.S.H., Consideration for evaluation and design of radiation gauges, Isotopenpraxis, to be published.

[7] FILIPPOV, E.M.,Yadernaja Geofizika, Vols 1 and 2, Izdatelstvo "Nauka", Sibirskoe otdelenie, Novosibirsk (1973). [a] Vol. I, p.173; [b] Vol. II, p. 21.

[8] KASTNER, J., "Effects of soil and water on cosmic ray", Extra-Terrestrial Matter, Northern Illinois Univ. Press (1969) 265.

[9] ØLGAARD, P.L., "Neutron and gamma gauges, their design and application", Radiation Engineering in Academic Curriculum (Proc. Study Group, Haifa, 1973), IAEA, Vienna (1975) 147.

[10] CAMERON, J.F., "Nucleonic soil density and moisture gauges", Nucleonic Techniques and Mineral Resources (Proc. Symp. Buenos Aires, 1968), IAEA, Vienna (1969) 81.

[11] COUCHAT, Ph., et al., "The measurement of thermal neutron constants of the soil; Application to the calibration of neutron moisture gauges and to the pedological study of soil", Proc. 4th Conf. Nuclear Cross Sections and Technology, CEA-CONF-3167, USA, 3–7 March 1975.

[12] KRAUSKOPF, K., Introduction to Geochemistry, McGraw Hill Book Co. (1967) 639.

[13] COUCHAT, Ph., Mesure Neutronique de l'Humidité des Sols, Rep. FRNC-TH-566, Toulouse (1974).

[14] KASI, S.S.H., An attempt to calculate correctly the region of influence in gauging moisture with neutrons, Int. J. Appl. Radiat. Isot. 33 8 (1982) 667.

[15] FEARON, R.E., Neutron well logging, Nucleonics 4 6 (1949) 32.

[16] BELL, G.I., GLASSTONE, S., Nuclear Reactor Theory, New York (1970).

[17] VAKKILAINEN, P., Maa-alueelta Tapahtuvan Haihdunnan Arvioinnista, Acta Univ. Oul. C 20.1981, Oulu (1982) 24.

[18] VIRKKUNEN, J., A Cyclic Coordinate Ascent Algorithm in Linearly Constrained Nonlinear Optimization, Rep. HTKK-MAT-A57, Espoo (1974).