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Soil Bulk Density and Water Content Measurements by Gamma-Ray Attenuation Techniques

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University of Hawaii
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SOIL BULK DENSITY AND WATER CONTENT MEASUREMENTS BY GAMMA-RAY ATTENUATION TECHNIQUES

ERRATA

Inside front cover: **Lance T. Santo** was graduate research assistant, Department of Agronomy and Soil Science, College of Tropical Agriculture, University of Hawaii. He is Assistant Agronomist, Department of Agronomy, Hawaiian Sugar Planters' Association.

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equation (8): should be $\overline{\mu}_s = \ln(N_c/N_d)/\overline{\rho}_s x_s$

equation (9): should be $\overline{\rho}_s = \ln(N_c/N_d)/\overline{\mu}_s x_s$

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INTRODUCTION

Direct water content measurements in static soil-water characteristic determinations and in transient water flow experiments have primarily been restricted to gravimetric methods. Indirect measurement of water content can be gained by the use of tensiometers, electrical resistance blocks, thermocouple psychrometers, thermistors, and other methods. Gravimetric procedures generally result in the disturbance of the soil-water system during sectioning, while indirect methods must allow for lag time if precise water content measurements are made. With the advent of gamma-ray attenuation techniques, rapid nondestructive determination of soil bulk density and soil-water content is now possible.

Vomocil (1954), Bernhard and Chasek (1955), and van Bavel et al. (1957) were among the first researchers to use the gamma-ray attenuation technique to measure soil bulk density. Later, Ferguson and Gardner (1962), Gurr (1962), and Davidson et al. (1963) applied this technique to determine water contents in thin layers of soil.

The first gamma-ray attenuation unit in the State of Hawaii for soils work was designed and fabricated by the soil physics group of the Department of Agronomy and Soil Science, University of Hawaii, in 1971. A theoretical discussion and initial results related to the testing of that gamma-ray unit are presented in this report. The methods and techniques employed herein are applicable to similar laboratory or field instrumentation that is now commercially available. Potentially, such instrumentation can be used for *in situ* water content and density measurements at different soil depths, and these resulting determinations will be much more precise than those obtained by the neutron probe because of the better resolution of the collimated gamma-ray beam.

THEORY

Fundamental principles of gamma-ray densitometry for monoenergetic primary radiation are based on the attenuation equation which may be expressed as

$$I = I_o \exp(-\mu\rho x) \quad \ldots(1)$$

where I is the attenuated intensity of the gamma-ray beam, I_o is the intensity at the source, and μ, ρ, and x are the mass attenuation coefficient (cm^2/g), density (g/cm^3), and thickness (cm) of the attenuating material, respectively.

Equation (1) can be rewritten as

$$N = N_o \exp(-\mu\rho x)$$

or

$$\ln(N_o/N) = \mu\rho x \quad \ldots(2)$$

where N and N_o refer to instrument photon counting rates instead of actual intensity. This is valid only if the detector recordings correlate directly with the radiation intensity. Verifying the validity of equation (2) is synonymous to experimentally demonstrating that a proportional relationship exists between $\ln(N_o/N)$ and ρ or x.

For single component systems such as pure water or dry soil, equation (2) can be applied directly by substituting in the necessary constants. For a multicomponent system, such as the one existing in moist soils, the following general relationship is applicable:

$$N = N_o \exp(-\mu_1\rho_1 x_1 - \mu_2\rho_2 x_2 - \ldots - \mu_n\rho_n x_n) \quad \ldots(3)$$

where $\mu_1, \ldots, n$, $\rho_1, \ldots, n$ and $x_1, \ldots, n$ are the mass attenuation coefficients, densities, and the sample thicknesses of each of the individual components, respectively.

For moist soil packed in a Plexiglas cylinder, the attenuation equations of interest may be expressed as

$$N_c = N_o \exp(-\mu_c\rho_c x_c) \quad \ldots(4)$$

and

$$N_m = N_o \exp(-\mu_c \rho_c x_c - \mu_s \rho_s x_s - \mu_w \rho_w x_w \theta) \quad \ldots (5)$$

where N_c is the intensity through the empty Plexiglas container, N_m is the intensity through both moist soil and container, θ the volumetric water content, and subscripts c, s, and w refer to the Plexiglas container, soil, and water, respectively. Combining equations (4) and (5) yields

$$N_m = N_c \exp(-\mu_s \rho_s x_s - \mu_w \rho_w x_w \theta) \quad \ldots (6)$$

For an oven-dried soil, where $\theta = 0$, equation (6) will reduce to

$$N_d = N_c \exp(-\mu_s \rho_s x_s) \quad \ldots (7)$$

where N_d equals the intensity of the beam transmitted through dry soil. Given either the mean soil bulk density $\overline{\rho}_s$ or the mean mass attenuation coefficient of soil $\overline{\mu}_s$ the other can be calculated by rearranging equation (7) such that

$$\overline{\mu}_s = \ln(N_c/N_d)\,(\rho_s x_s)^{1/2} \quad \ldots (8)$$

and

$$\overline{\rho}_s = \ln(N_c/N_d)\,(\overline{\mu}_s x_s)^{1/2} \quad \ldots (9)$$

The mean bulk density is determined by measuring the mass of soil packed in the Plexiglas cylinder of known volume. The mean mass attenuation coefficient can be measured experimentally by varying the mean bulk density in equation (8).

For water alone, equation (6) will reduce to

$$N_w = N_c \exp(-\mu_w \rho_w x_w) \quad \ldots (10)$$

which on rearrangement yields

$$\mu_w = \ln(N_c/N_w) / \rho_w x_w \quad \ldots (11)$$

where ρ_w is the density of water and x_w the inside dimension of the container. With constants μ_w, ρ_w, and x_w known, the soil-water content can be calculated at given positions in the soil column. By combining equations (6) and (7) to yield

$$\theta = \ln(N_d/N_m)/\mu_w \rho_w x_w \quad \ldots (12)$$

The attenuation equation assumes that the densities of the attenuating materials remain constant at each position in the soil column where the analysis is to be made. Nonisothermal conditions and either expansion or contraction of the soil-water system would result in erroneous data.

Equation (1) is theoretically valid only for monoenergetic primary radiation that is transmitted to the detector without alterations. Gamma-ray photons interact with the sample by being either absorbed or scattered. Absorption is characterized by the disappearance of a photon while scattered photons are deflected from their original direction either with or without a loss of energy. Energy changes due to either the photoelectric effect, Compton scattering, or electron pair production may invalidate the assumption of a monoenergetic radioactive source (Kohl et al., 1961; King, 1967). In the lower energy range (less than 0.5 MeV), the process of importance is the photoelectric effect, which involves the absorption of a photon with subsequent ejection of an atomic electron. Compton scattering predominates in the middle energy range of 0.5 to 1.0 MeV. In this process, an elastic collision occurs between a photon and a single electron, which results in the transfer of energy from the former to the latter with the subsequent deflection of the photon path and the ejection of the electron from the atom. Electron pair formation involves the absorption and pairing of an incoming photon with an electron, giving it sufficient kinetic energy to escape from the atom. A minimum of 1.02 MeV (Kohl et al., 1961) is needed for the phenomenon to occur. The mechanism of electron pair production can be considered to be negligible in soil-water analysis since water is a poor absorber of high-energy gamma rays (Ferguson and Gardner, 1962). As a consequence, radioactive sources used in water content measurements are limited to those emitting primary radiation in the middle or lower energy range. Cesium-137, with a pri-

mary energy peak at 0.663 MeV, satisfies this condition. In this middle energy range, Compton scattering is the most important of the three processes (Gurr, 1962).

Van Bavel et al. (1957) emphasized that the attenuation equation cannot be used to calculate water content in soils unless all scattered and secondary radiation had been discriminated against through pulse-height analysis. On the other hand, Saxena et al. (1970) suggested that pulse-height analysis was not required if long narrow slits were used to collimate the gamma-ray beam. For precise water content measurements, however, pulse-height analysis is desirable. A method described by Fritton (1969) can also be used to correct gamma-ray attenuation measurements for the combined effects of resolving time (the minimum time that the detector can separate two consecutive photons), gamma-ray scattering, and absorption.

MATERIALS AND METHODS

Soil

The Molokai series of the clayey, kaolinitic, isohyperthermic family of Typic Torrox was used in this study.

Instrumentation

The source of gamma radiation was cesium-137,[1] which had a strength of 220 millicuries. Selection of cesium-137 was based primarily on its ready availability, long half-life (33 years), and monoenergetic peak at 0.663MeV. The cesium-137 source, sealed in a stainless-steel capsule, was placed in the center of a cylindrical lead container, 16 cm in diameter and 16 cm in height. A rectangular slit, 2 cm in width and 1 mm in height, was cut to the center of the lead container. This allowed emission of a collimated beam of gamma radiation to be transmitted to a NaI (TI) scintillation detector.[2] The crystal face of the detector was covered by a 4-cm-thick lead collimator with a rectangular slit measuring 3 cm in width and 1 mm in

[1] Nuclear-Chicago Corporation, 1611 Beverly Boulevard, Los Angeles, California.
[2] Ibid., Model 956.

height. This collimator minimized scattered radiation from reaching the detector.

Both detector and source housing could be manually adjusted until the collimated gamma-ray beam was aligned. Perfect collimation was reflected by the maximum counting rate recorded by a ratemeter[3] and scalar[4] via a pulse-height analyzer.[5] With the pulse-height analyzer set at the wide differential counting mode and a 1-volt window, the emitted gamma radiation lacked the necessary intensity to yield adequate count rates for small counting times. Hence, the pulse-height analyzer was switched to integral mode and set to discriminate against photons of energy of less than 0.550 MeV. Collimation of gamma rays permitted analysis of soil thickness nearly equivalent to that of the detector slit width.

[3] Ibid., Model 9733.
[4] Ibid., Model 812830.
[5] Ibid., Model 8725.

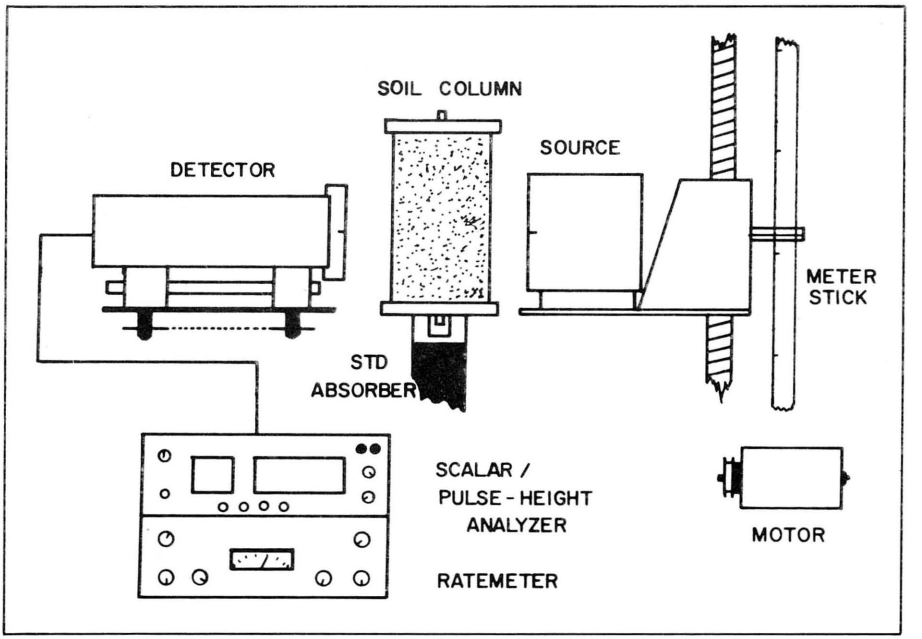

Figure 1. Diagram of gamma-ray assembly and instrumentation.

Detector and source housing were secured on a horizontal platform and were driven in either vertical direction by a ¼-HP motor connected to a vertically positioned threaded rod (Figure 1). A double-throw electrical switch controlled the positioning of both source and detector along the length of a stationary soil column. "Standard" counting measurements were made through a permanently positioned aluminum absorber, 8.89 cm in diameter. These measurements were frequently repeated in order to check for any changes in the counting rate due to instrumentation or alignment of the collimated beam and to radioactive decay. The absorber also served as the holder for the vertically positioned soil column.

Correction Factor for Variation in Standard Counts

The standard count is that scalar reading (count/time) obtained after the collimated gamma-ray beam passes through the standard absorber (permanent aluminum base). Over short time intervals, the detection and counting instruments are relatively stable; however, significant differences between standard count measurements may be observed because of daily instrumental variations and radioactive decay of the source. A correction factor is required to scale the gamma-ray data of one day to that of another for comparison purposes. The correction factor may be expressed as

$$CF = N_{1\text{std}}/N_{2\text{std}} \qquad \ldots(13)$$

where $N_{1\text{std}}$ and $N_{2\text{std}}$ are standard counts obtained at different times. The scaled data reading, N_{corr}, is

$$N_{\text{corr}} = N_{\text{obs}}/CF \qquad \ldots(14)$$

Counting Precision

The standard deviation σ of a counting rate from a random emitting radioactive source is approximately

$$\sigma = (N/t)^{1/2} \qquad \ldots(15)$$

where N is the radiation count and t the counting time. For our soil,

N/t was approximately 160,000 counts/minute, and one standard deviation was equivalent to 400 counts/minute.

Instrumentation errors depend upon the characteristics of the particular equipment. The error is generally small; however, it is common practice to multiply the standard deviation by a factor of 1.5 to 2 to account for instrumentation error.

Calibration-curve errors must be considered subjectively since they depend upon the care taken in the calibration process and the degree to which experimental conditions are comparable to calibration conditions. The common practice is to regard such errors as negligible, compared to those arising from experimental variability.

Resolving Time Correction

The combined effects of scattering, absorption, and resolving time tend to lower the overall accuracy of the system. Fritton (1969) described a method in which the observed results could be corrected for the aforementioned effects. The observed counting rate N (counts/minute) was corrected by using

$$R = N/[1 - (T)(N)] \quad \ldots (16)$$

where R is the true counting rate (counts/minute) and T the resolving time (minutes/count). T is an experimentally determined constant, which minimizes the deviation from linear regression for data of $\ln(N)$ versus x (thickness).

Fritton (1969) experimentally found the resolving times for soil and water to be almost identical; therefore, he was able to use a single T for his soil-water system. For our soil-water system, the resolving time was determined and compared using air-dried soil and distilled water.

Verification of Attenuation Equation

Water, Molokai soil, and a mixture of both were used to test the validity of the attenuation equation for our experimental conditions. This procedure essentially involved the test of proportionality between the semilogarithm of gamma-ray intensity ratio and the variables ρ and x in the quantity $\rho\mu x$.

To test the attenuation equation for our experimental system and to determine the mass attenuation coefficient of water, a cylindrical Plexiglas container with equally spaced partitioned compartments was used. The thickness of water was successively increased by filling the compartments after each measurement. N_c was taken as the initial intensity reading through the empty container. Verification of equation (11) for water would also permit the mass attenuation coefficient of water to be computed from the slope of the $\ln(N_c/N_w)$ and x plot.

For Molokai soil, it was easier to pack a cylindrical Plexiglas container with air-dried soil to a range of bulk densities instead of varying the thickness of the sample. In accord with equation (7), values of $\ln(N_c/N_d)$ were plotted against corresponding values of $(\mu_s \rho_s x_s)$ in order to verify the proportional relationship between them. The final test was to establish the accuracy of the instrumentation in measuring soil-water content. This was accomplished by using the gamma-ray data to calculate the water content from equation (12) and then sectioning and gravimetrically determining the water content at each analyzed position of the soil column.

RESULTS AND DISCUSSION

Use of equation (2) to measure soil density and water content is only valid if an exponential or a linear semilogarithmic relationship can be shown to exist between the ratio of photon count (N_o/N) and $\mu\rho x$.

Counting Precision and Resolving Time

The counts/minute variation was approximately twice the standard deviation, or 800 counts/minute for a gamma-ray scan at a given position.

Resolving times for both soil and water were determined to be 4.9 μsec.

Attenuation Coefficient for Water

When water alone was the attenuating material, a linear semilogarithmic relationship between $\ln(N_c/N_w)$ and x_w with an intercept of

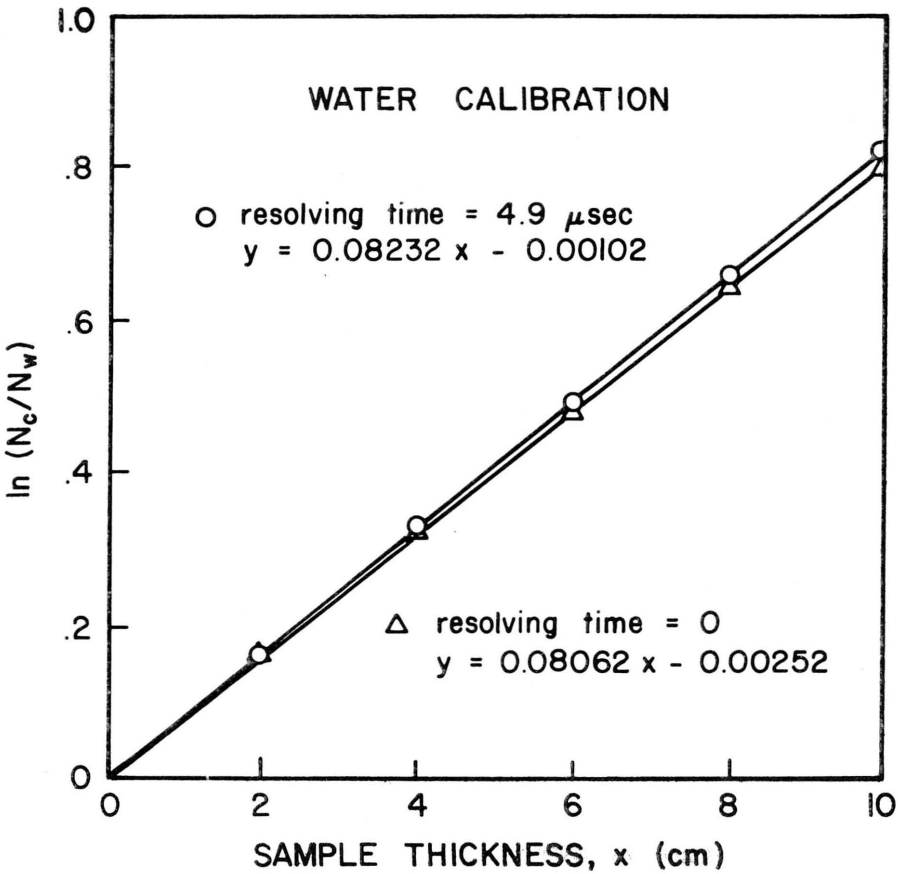

Figure 2. Experimental verification of the gamma-ray attenuation equation, with water thickness as the independent variable.

-0.00252 was obtained (Figure 2). With a water density of 0.9978 g/cm^3 at 22°C, the mass attenuation coefficient of water from the slope of the computed regression line with no resolving time correction was 0.08062 cm^2/g. Davidson et al. (1963) and Kirkham et al. (1967) reported uncorrected values of 0.0815 and 0.0802 cm^2/g, respectively. Using Fritton's (1969) correction method, a resolving time correction of 4.9 μsec was obtained. With resolving time corrections of 9 and 5 μsec, Gurr (1962) and Fritton (1969) obtained

mass attenuation coefficients of water of 0.0856 and 0.0867 cm^2/g, respectively. Grodstein (1957) reported a theoretical value for water of 0.0857 cm^2/g.

Attenuation Coefficient for Molokai Soil

Air-dried Molokai soil of less than 2-mm size was the second material used in testing equation (2). A cylindrical Plexiglas container, 5 cm in height and 8.19 cm in diameter, was packed with soil to different bulk densities. Gamma-ray measurements were taken at positions 0.5 cm apart on the column. The mean $\ln(N_c/N_d)$ for each packing was plotted against the respective mean bulk density (Figure 3), and the correlation was found to be significantly linear for the uncorrected and corrected plots. Based on equation (8), the mass attenuation coefficient for Molokai soil could then be calculated by dividing the slope of the regression line by the soil thickness (8.19 cm). Average uncorrected and corrected values of 0.07619 and 0.07785 cm^2/g were obtained. Mass attenuation coefficients of 0.07785 cm^2/g (Reginato and van Bavel, 1964), 0.0710 cm^2/g (Shalhevet and Yaron, 1967), and 0.0689 cm^2/g (Kirkham et al., 1967) have been reported. The latter two values were uncorrected for resolving time. The disparity of values reported was probably due to the different mineral composition of the soils used.

Comparison of Water Content Measurements

Based on the experimental mass attenuation coefficients for water and soil, the volumetric water content can be calculated by using equation (12). A 20-cm-long Plexiglas column with an 8.19-cm diameter was packed with soil to a uniform density and partially saturated with water by capillarity for 48 hours. The volumetric water content at positions along the length of the column was calculated from gamma-ray attenuation data. The column was then sectioned and oven-dried. The results for both determinations are tabulated in Table 1. A mean difference of 0.0078 cm^3/cm^3 was found between water contents determined from gravimetric and gamma-ray measurements when the resolving time correction of 4.9 μsec was used on the latter. A larger difference was noted if no resolving time correction was used. Discrepancies between water contents at different positions were attributed to methodology. The gamma-ray beam

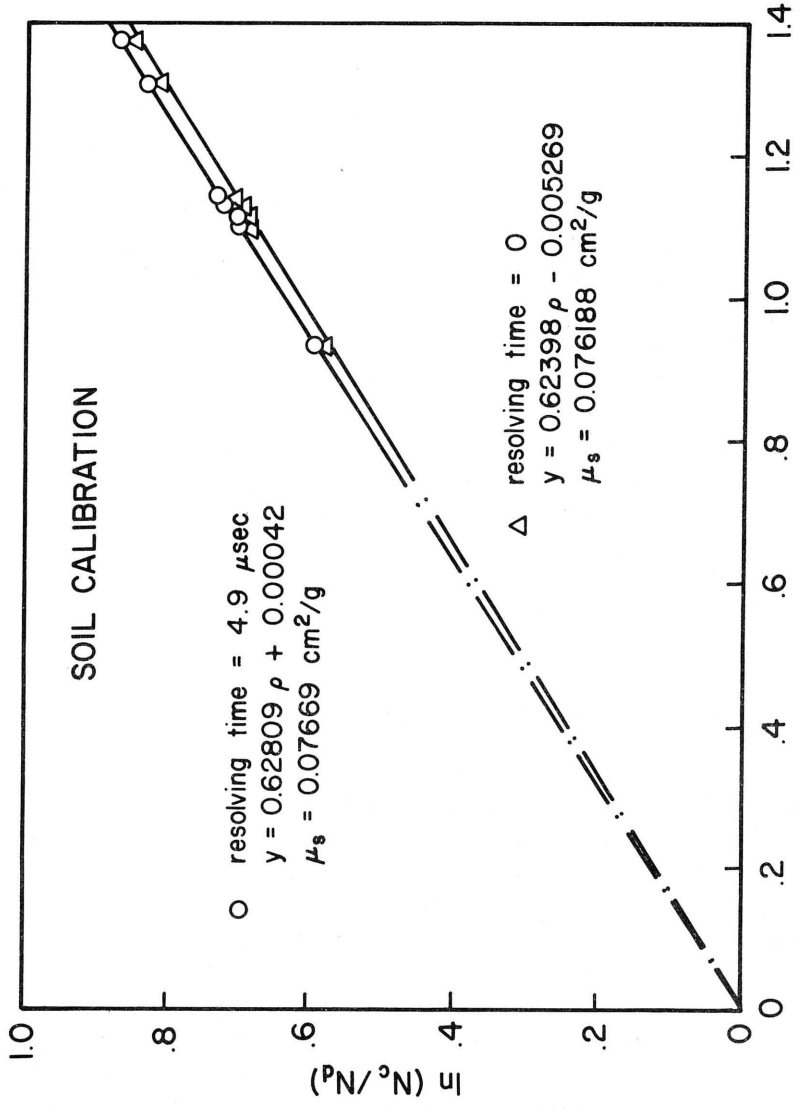

Figure 3. Experimental verification of the gamma-ray attenuation equation for Molokai soil, with mean bulk density as the independent variable.

Table 1. Bulk density and volumetric water content measurements for Molokai soil

Position (cm)	Bulk density (g/cm^3)	Water content (cm^3/cm^3)		
			By gamma-ray attenuation	
		By weight	T = 0	T = 4.9†
5	1.2276	0.5134	0.5184	0.5184
6	1.2431	0.5149	0.5154	0.5188
7	1.2399	0.5113	0.5161	0.5195
8	1.2509	0.5161	0.5146	0.5180
9	1.2543	0.5220	0.5137	0.5170
10	1.2573	0.5170	0.5133	0.5166
11	1.2614	0.5154	0.5083	0.5115
12	1.2538	0.5095	0.5085	0.5091
13	1.2536	0.5112	0.5106	0.5139
14	1.2518	0.5194	0.5066	0.5099
15	1.2485	0.5178	0.5031	0.5065
16	1.2360	0.5098	0.5101	0.5135
17	1.2301	0.5039	0.5070	0.5105
Mean	1.2468	0.5140	0.5112	0.5144
Standard deviation	0.0106	0.0048	0.0044	0.0046
Difference			0.00545	0.00078

†Resolving time correction of 4.9 μsec.

scanned a 1-mm section, whereas gravimetric determinations were made on 1-cm-thick sections.

CONCLUSIONS

The gamma-ray attenuation technique is another valuable tool in soil-water studies. Rapid and nondestructive bulk density and water content measurements can be made with a high degree of accuracy once instrument calibration and verification of the attenuation equation for the experimental system are complete. Use of experimentally determined mass attenuation coefficients rather than the theoretical values of the attenuating mass is desirable for precise measurement of water content and density.

Limitations of the system are as follows: (1) it is valid only for nonexpanding porous media; (2) equipment is costly; and (3) considerable shielding is required for a 220-millicurie cesium-137 source. Americium-241 may be a more suitable source for field work since it requires less shielding.

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