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"Using a Computed Tomography Miniscanner in Soil Science"

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USING A COMPUTED TOMOGRAPHY MINISCANNER IN SOIL SCIENCE

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In a previous paper (Crestana et al. 1985) we demonstrated the possibility of using computed tomographic (CT) scanning for investigations in soil science. One of the main limitations was the complexity and high cost of medical CT scanners. In this paper we report on the characteristics and use of a very inexpensive, homemade CT miniscanner dedicated to soil science analysis. This new apparatus was applied to carrying out tomographies of soil with various water contents and also to obtaining the best conditions and adequate physical parameters for optimized attenuation measurements in soil. Our results demonstrate that it is now possible to have a CT miniscanner, without the limitations of the medical CT scanner, that should be invaluable for advanced studies in soil science.

The ideal technique for monitoring bulk density and water content in soil should be nondestructive, sensitive, rapid, and able to resolve small differences in bulk density and water content over distances of a few millimeters.

A quite similar problem was solved in diagnostic radiology by using the technique of computer-assisted tomography (CAT) (Newton and Potts 1981).

In this method the *map of linear attenuation coefficients* for x rays in a scanned section of the sample is obtained. For biological objects, at the energy values usually employed in CAT (approximately 70 to 80 keV mean energy) attenuation coefficients are due, at more than 90%, to the Compton effect, which is proportional to the electronic density δ_e of materials (McCullough 1975), where

$$\delta_e = N_{AV} \frac{Z}{A} \delta \qquad (1)$$

N_{AV} is Avogadro's number, Z and A are the atomic number and the atomic weight, respectively, of elements constituting the sample, and δ is the physical density.

Except for materials containing hydrogen, the electronic density δ_e is with good approximation proportional to the physical density.

The situation is not very different for analyzing soil samples. For soils the contribution of the Compton effect is approximately 80% at 80 keV, the remaining contribution being mainly due to the photoelectric effect. Therefore, a tomographic map of soil at 60 to 100 keV is to a first approximation proportional to the distribution of the physical density, while a tomographic map at lower energy (20 to 30 keV) would be mainly proportional to a high power of the atomic number Z (photoelectric effect).

Commercially available CAT scanners are therefore suited to measure spatial changes in soil bulk density and water content (Crestana et al. 1985). However, CAT scanners are extremely expensive and not very flexible in the energy output to be employed routinely for studies of soil and plant systems.

In this paper we discuss the applications to soil science of a very inexpensive and dedicated CAT miniscanner, which we used to carry out tomographies of soil with various water contents, and also attenuation measurements, to deduce the best conditions for the tomography and other important physical parameters.

MATERIALS AND METHODS

The apparatus for measuring attenuation coefficients of soil samples is schematically shown in Fig. 1 (Cesareo and Giannini 1980). It consists of a radioisotopic source of ^{241}Am (45 and 300 mCi), an x-ray tube with secondary targets, and an NaI(Tl)-x-ray detector. When the Bremsstrahlung radiation of the tube interacts with the secondary target, quasi-monoenergetic x rays are emitted, characterized by K_α and K_β radiation of the element constituting the target. By varying the secondary target, one can therefore have radiation varying over a large interval of energy (Cesareo and Viezzoli 1983).

The source-detector solid angle was very small (diameter of both collimators: ϕ = 1 to 4 mm; distance source-collimator: about 20 cm) to avoid the contribution of undesired Compton scattered radiation in the detector. As an alternative to the NaI(Tl)-detector, an HP-Ge-detector was employed, characterized by an energy resolution of 250 eV at 6.4 keV. The attenuation coefficient of water, measured with this apparatus at 60 keV was

$$\mu_w = 0.203 \text{ cm}^2\text{g}^{-1} \qquad (2)$$

in good accord with the best reported values (see, for instance, Gardner et al. 1972).

The miniscanner, constructed at the University of Rome, Centre for Bioengineering (Cesareo et al. 1983), is characterized by (Fig. 2)

- monoenergetic sources obtained both with radioisotopes and an x-ray tube with secondary target as described previously
- an NaI(Tl)-x-ray-detector
- a rotation-translation system
- a multichannel analyzer employed as multiscaler or a quad counter-timer
- a personal computer—Apple II-Europlus with a reconstruction algorithm working in PASCAL[3]

The cost of the miniscanner with the radioactive source is approximately \$2 × 10^4, which is a factor of 10^2 lower than the commercial apparatus. With the x-ray tube the cost increases to about \$5 × 10^4.

Another CT scanner with similar characteristics, dedicated to soil science analysis, was also built at the UAPDIA-EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária, São Carlos, Brazil) and is now being used for soil research in Brazil, proving the general feasibility of the use of this new method (Crestana 1985).

To prepare Tables 1 and 2 and Figs. 3 and 4, we used soil samples collected from the Ap horizon of a Barretos, Brazil, fine sandy loam soil. The soil (air-dried) was passed through a 1.0-mm sieve and packed into thin-wall Plexiglas boxes.

The thickness of these samples containing soil ranged from 2 to 3 cm. To pack the soil samples we used the methodology usually adopted in soil physics (Hillel 1971). To obtain samples with different water contents, ranging from 0 to 30%, we used several samples of soil equilibrated with water. This was obtained adding a known volume of water to a known volume of soil previously air-dried.

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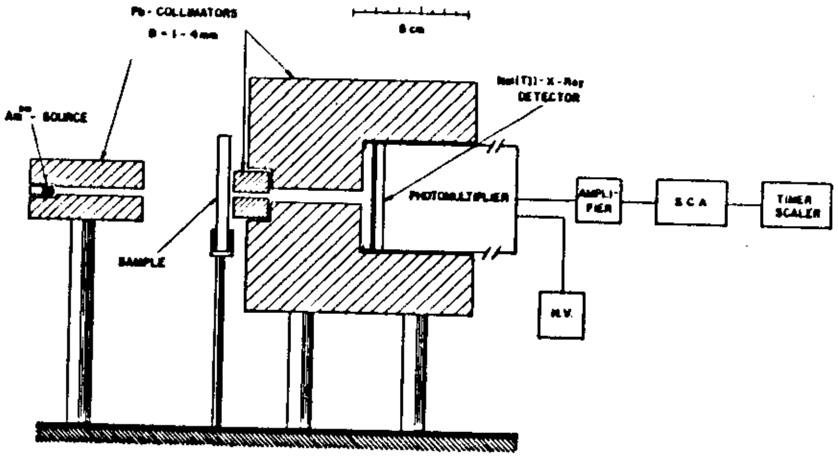

FIG. 1. Apparatus for measuring attenuation coefficients of soil.

[3] The complete program can perform as follows: to simulate the matrix of expected numbers, it requires the number of angle steps, the total translation, the number of linear steps, the angle step and the linear step, the number and dimensions of simulated bodies, and their attenuation coefficient (TAC-Simulator and Matrix Editor). It can also give the matrix of measured numbers, the matrix of linear attenuation coefficients, the matrix of Hounsfield numbers, and the image in various dimensions, in black and white or color.

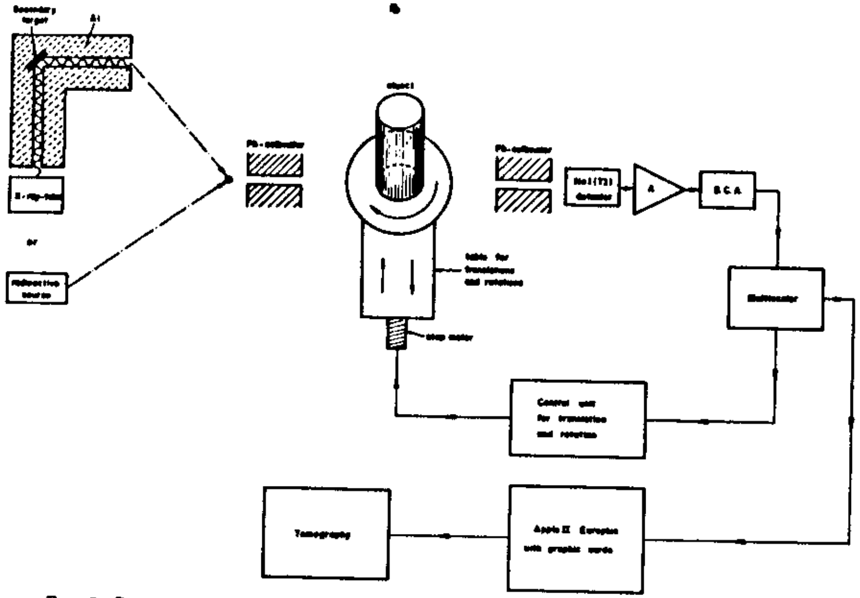

FIG. 2. Complete diagram of the CT miniscanner used to obtain tomographies of soil samples.

The values plotted in Fig. 4 (tomography linear curve) were obtained from the mean absorption values (HU) over the entire sample cross sections.

MEASUREMENTS OF ATTENUATION COEFFICIENTS OF SOIL

The physical principles of a tomographic image consist in a series of attenuation measurements, where the "spatial contrast" of the image is simply correlated to the difference in the attenuation coefficients of the various materials constituting the sample.

The main problem in x-ray tomography of water in the soil is to obtain the maximum contrast between soil and water. Accurate measurements of attenuation coefficients of soil samples from Barretos, Brazil, versus energy were therefore carried out and compared with the well-known attenuation coefficients of water. Measurements were carried out by employing a radioactive source of ^{241}Am and an x-ray tube with various secondary targets in order to obtain quasi-monoenergetic X-lines (K_α and K_β—lines of the element constituting the secondary target).

The results are shown in Fig. 3 and summarized in Table 1. Only the value at 60 keV can be compared with similar measurements reported in the literature and carried out at the same energy. Values ranging from about 0.3 to about 0.5 cm^2 g^{-1} are reported for 21 brazilian soils (Ferraz 1974). For these measurements an HP-Ge detector was employed, characterized by an energy resolution of about 250 eV at 6.4 keV. A very sharp collimation was employed, both for the source and for the detector, to limit undesirable scattered photons in the detector (Davisson and Evans 1952).

From Fig. 3, it is clearly visible that the difference in attenuation coefficient between soil and water increases with decreasing energy. Otherwise, the optimum thickness of the crossed soil sample decreases, requiring more and more intensity for samples of constant thickness.

Errors are on the order of 2 to 5% and are also due to the difficulty of having a reproducible and homogeneous soil sample.

Measurements were then carried out on wet soil, at different percentages of water content and at energy values of Ba-x rays (32 keV), Ce-x-rays (34.5 keV), and 60 keV (^{241}Am). The results are summarized in Table 2.

Deviations from a linear dependence are high and probably due to the inhomogeneous distribution of water in the soil sample.

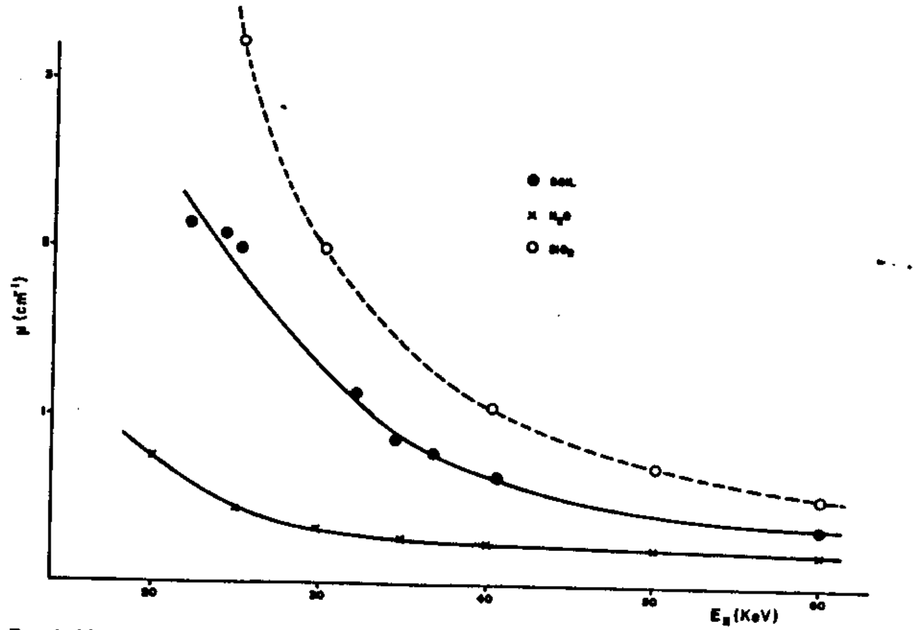

FIG. 3. Mass soil attenuation coefficients of soil, water, and silica as a function of incident energy. The mean error ranges from 2 to 4%.

TABLE 1

Mass attenuation coefficient values of Brazilian soil from Barretos versus incident energy E

E, keV	μ, cm^2 g^{-1}
14.9	3.1
17.4	2.5
22.0	2.15
24.1	2.1
25.1	2.0
32.0	1.25
34.5	0.86
36.7	0.79
39.8	0.65
60.0	0.37

MEASUREMENTS WITH THE TOMOGRAPH MINISCANNER

One of the main advantages of the miniscanner is the possibility of varying the monoenergetic incident energy by varying the secondary target coupled to the x-ray tube. It is therefore important to select the optimal energy of the radiation to obtain the best conditions. Following Fig. 2, and considering that to a first approximation water mainly substitutes for the air contained in the soil sample, we can write the mass attenuation coefficient of the soil plus water sample as

$$\mu_t \ (\mathrm{cm^2/g}) = \mu_s \delta_s + \mu_w C_w \qquad (3)$$

where μ_t, μ_s, and μ_w are, respectively, the total mass attenuation coefficients of the sample (soil + water) and of soil and water, δ_s is the dry bulk density of the soil sample, C_w is the concentration of water, and the volumetric density of pure water is 1 g/cm^3.

From Eq. (3), substituting the values of μ_s, μ_w, δ_s, and C_w, one can deduce that the best spatial contrast, i.e., the greatest difference (in percentage) in the attenuation coefficient for a given quantity of water in soil is reached at energy values greater than about 30 keV. The 60-keV γ rays of ^{241}Am are therefore very well suited for tomographs of soil. One of the advantages of using lower energy values lies in the possibility of having at our disposal higher intensities, which imply smaller scanning times.

Tomographs of soil samples from Barretos, Brazil, at various water contents have been carried out at various energies, but particularly at 60 keV, and numerical data have been analyzed, both in terms of attenuation coefficients and Hounsfield numbers.

In fact, with CT scanning, it is preferable to employ the Hounsfield number H, instead of the attenuation coefficient μ. The Hounsfield number is defined with reference to water, and the following definition is usually employed

$$H = \left(\frac{\mu_s - \mu_w}{\mu_w}\right) \times 10^3 \qquad (4)$$

TABLE 2

Mass attenuation coefficient values μ of Brazilian soil from Barretos versus water content at incident energies of 32, 34.5, and 60 keV

Water content, %	μ, cm² g⁻¹		
	32 keV	34.5 keV	60 keV
0	1.195	0.865	0.395
11	1.4	1.07	0.445
17.5	1.42	1.1	0.485
25	1.53	1.22	0.54
28	1.48	1.16	0.54

where μ_s and μ_w are the attenuation coefficients of soil and water, respectively.

Hounsfield numbers represent an "amplification factor" of the difference between the attenuation coefficients of the sample and of water. For a given sample the Hounsfield number depends on the energy of incident radiation.

We have measured attenuation coefficients, employing the highly collimated geometry described in Materials and Methods carried out tomographs of soil at various water contents. The relative Hounsfield numbers are reported in Fig. 4. The agreement is quite good. The Hounsfield numbers deduced from attenuation coefficients are a certain percentage higher. That depends on the fact that the collimation for attenuation coefficients is stronger and values of attenuation coefficients are higher.

From the same measurements we can consider the minimum quantity of water in soil that can be analyzed. Assuming that one is actually able to discriminate an approximate difference of 1% in the attenuation coefficient, a sensitivity of 1% water in soil can be deduced. This quantity

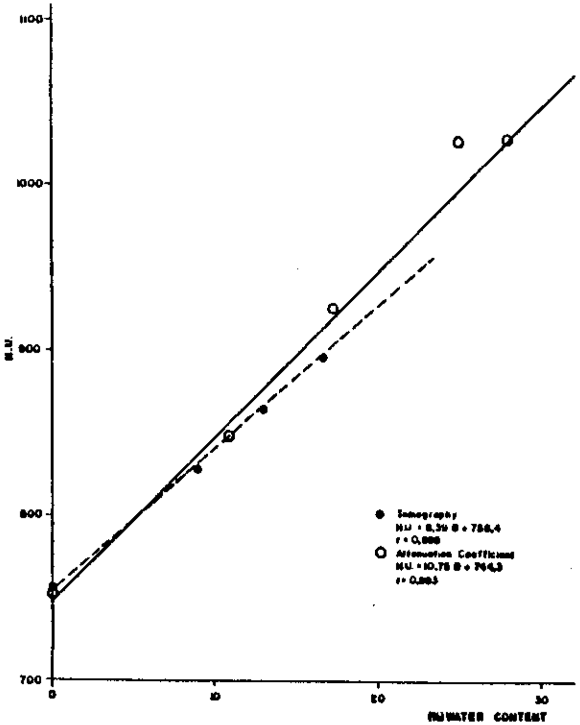

FIG. 4. Hounsfield units as a function of water content, showing the good accord between the linear calibration curves obtained by tomography and by direct attenuation coefficient measurements.

can be decreased by increasing the source intensity or the measuring time.

CONCLUSIONS

We have showed that it is possible to design, build, and use a CT miniscanner dedicated to soil science research, such as to perform bulk-density and water-content tomographic analysis. We have also showed that the CT scanner has advantages over the commercial medical scanner, particularly allowing the use of several beam energies and different radiation sources, such as isotopic sources or x-ray fluorescence targets. We also concluded that the use of 30 to 40 keV is the best energy for water-content resolution.

Last, but not least, the cost of this homemade equipment is 100 times lower than commercial medical tomographs.

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