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"Static and Dynamic Three-Dimensional Studies of Water in Soil Using Computed Tomographic Scanning"

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STATIC AND DYNAMIC THREE-DIMENSIONAL STUDIES OF WATER IN SOIL USING COMPUTED TOMOGRAPHIC SCANNING[1]

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Previous work of Petrovic et al. (1982) demonstrated the possibility of using x-ray transmission, computed tomography (CT) scanning for soil bulk density analysis in soil. We show that CT can also be used for measuring the water content of soil. We also show that CT can be applied to measure and follow dynamically the motion of water in soil in three dimensions. Furthermore inhomogeneities of water content and motion in soil can be observed with this technique. Using a third-generation CT scanner, several different techniques can be applied, such as differential, real-time, and spatial distribution scanning modes. A linear dependence was demonstrated for the Hounsfield units (HU) used in CT and water content. The use of CT for water content and motion in soil in three dimensions opens new possibilities in this area of investigation.

The study of water content and motion in soil has fundamental importance to soil science. In the past, several methods have been applied to measuring water content in soil, such as gamma-ray absorption, the neutron-probe technique, direct water content evaluation by weighting and drying, and others (see, for instance, Taylor 1972; and Vose 1980). Only gamma-ray absorption and neutron-probe methods can be used for dynamical studies of water in soil. All these methods do not take account of soil inhomogeneities and do not evaluate three-dimensional profiles of water content and motion. Recently Petrovic et al. (1982) demonstrated the use of CT scanning for soil bulk density analysis in three dimensions. They reported, however, that they were unable to obtain consistent results in measurements of soil moisture by CT. Nevertheless, CT scanning provides excellent opportunities for spatial and time studies of water content in soil. Recently independent studies by Hainsworth and Aylmore (1983) and Crestana et al. (1984) demonstrated the appropriateness of CT scanning for water content in soil. By using a third-generation CT scanner (GE CT/T 8800) and judiciously choosing such parameters as extended scale, differential level scanning, and window value, we have been able to obtain reproducible and quantitative information on 3-D space and time scanning of water in soil.

A complete review of all the aspects of CT scanning can be found in Newton and Potts (1981). A very interesting and instructive introduction to CT can be found in the Nobel Award address given by A. M. Cormack (1980). Essentially CT scanning is penetrating electromagnetic radiation, such as x or gamma rays, which are absorbed or scattered by matter, and the expression

$$I = I_0 \exp - \mu x$$

can be used to evaluate the emerging intensity I of the radiation beam of incoming intensity I_0 after traversing a sample of homogeneous material of absorption coefficient μ and thickness x. When the material is not homogeneous, as in a sample of real soil or a part of the human body, the more general expression

$$I = I_0 \exp - \int_s f \, ds$$

can be used where f is now a distribution function for the varying absorption coefficient along any direction s across the sample. The central problem of CT is obtaining the distribution function f (as a function of position for any direction in the sample) when a sufficiently large number of absorption measurements along different scanning directions s have been performed. The image of the object is then obtained as a map of absorption coefficients μ for any

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desired section (slice) of the sample. This process is performed mathematically with the help of computers and is called *image reconstruction*. In his original work Cormack demonstrated all the necessary mathematical theorems for image reconstruction. He was also able to build a very simple CT scanner, which incidentally may be "revived" for soil science applications, as we propose in this work. Hounsfield (1980) developed independently the reconstruction theory and also the first commercial CT scanner for medical use. Essentially in the video of a CT scanner a plot of the attenuation coefficient μ is shown on a gray-level viewing system in so-called Hounsfield units (HU), usually taken to be the following (Newton and Potts 1981)

$$H = 1000 \frac{(\mu - \mu_w)}{\mu_w}$$

where μ_w is the attenuation coefficient of water. For the plotting, a relative scale is sometimes used, where μ_w is taken as a reference level arbitrarily considered as zero.

In practice, CT scanners are now sophisticated machines capable of on-line image reconstruction or image storage for later analysis in dedicated consoles. Third-generation CT scanners are also capable of being used in dynamic modes with scanning times as short as 5.7 s and scan interval times of 1 s.

Though CT scanners are expensive, they are now commonly found in most large hospitals and may eventually be used for such other applications as the one we propose in this paper. We also propose that small, dedicated mini-CT scanners be built and used in future for special purposes, such as in soil science, at a vastly reduced cost—perhaps a few thousand dollars—comparable to present equipment using gamma-ray or neutron-probe techniques.

MATERIALS AND METHODS

Scans of soil samples were obtained with a General Electric CT/T 8800 scanner of the Istituto di Radiologia, Universite di Trieste, Italy. This is a third-generation rotate-rotate CT scanner, which means that the x-ray tube and the detectors rotate simultaneously during the scan. The detector array consists of a 30° arch that contains 523 high-pressure xenon detectors. The x-ray tube and the detectors are located inside the gantry. The operating characteristics of the tube are 120 kV, and the milliamperag may range from 20 to 500 mA.; the milliampe age depends on the scanning time and can rang from 30 to 1152 mA. We have used the maximu available for the instrument, depending upo the parameters used (dynamic scan or not an slice thickness). The gantry aperture for patier positioning is 60 cm in diameter. The scan tim may change from 5.7 to 11.5 s. The interv between two scans is about 30 s, but may b reduced to 1 s when the dynamic technique i used. The dynamic scan consists of a series c scans that may be performed at the same slic location or at different locations. The intersca delay may be 1 s or longer, as desired. Th dynamic technique enables one to obtain plot of the density changes during time. The slic thickness may be 1.5, 5, or 10 mm. The standar image reconstruction circles are 25 cm, usuall used for brain studies; 35 cm; and 42 cm, usuall used for body studies. The matrix size is 320 : 320 pixels. The single pixel size depends on th image reconstructions circles (25, 35, or 42 cm and is, respectively, 0.8, 1, or 1.2 mm. The pixe size may be further reduced to 0.25 mm by usin high-resolution image reconstruction. The re construction algorithm (both standard and high resolution) assigns to each pixel in the imag matrix the x-ray linear attenuation coefficien of the material within that volume of the objec represented by the pixel. These coefficients ar converted into CT numbers before the image i viewed. This conversion is done by scaling at tenuation coefficients to the coefficient of wate The normal CT number scale runs betwee −1000 HU (air) to +1000 HU (bone). A C number of 0 is assigned to water. To visualiz density greater than 1000, an extended scale ha been added to the scanner, which allows the C number scale to run between −1000 and +300 HU.

We used different soil textures collected fron the Ap horizon of a Trieste, Italy, sandy soil an a Barretos, Brazil, fine sandy loam soil. We als used two types of acrylic cylindrical columns for horizontal flow a syringe 5 cm in diamete and 20 cm long; and for vertical flow a cylinde 10 cm in diameter and 30 cm high, internall divided by a thin plastic wall, so that dry an wet soil could be compared simultaneously during scans.

The columns were positioned in the gantry ir the most judicious way to avoid artifacts fo such chosen parameters as kVp, mA s, scan time, and slice thickness, as previously discussed. Water flow was introduced either by a hydraulic head or by direct spraying or by contact with wet cotton. To obtain the calibration curve (Fig. 1) for dry bulk density as a function of measured attenuation in HU, we used eight samples of known average bulk densities ranging from 1.10 to 1.4 g/cm^3 and obtained the mean absorption value (HU) over the sample cross section. The soil (air-dried) was passed through a 1.0-mm sieve and packed into the acrylic cylinders. We employed the usual methodology for packing the soil samples (see, for instance, Hillel 1971). To obtain the calibration curve (Fig. 2) for water content as a function of HU, we used nine samples uniformly sieved (1-mm) and packed with soil in the acrylic column. Each sample was equilibrated at a given water content ranging from 0 to 30%. The water content of the soil in each sample was obtained by adding a known volume of water to a known volume of soil previously air-dried. We chose the mean absorption value (HU) over the entire sample cross section.

RESULTS

We introduced several experimental techniques to study water content and motion, and we describe them in sequence. The experiments, as shown in Figs. 3, 4, and 5, clearly indicate the

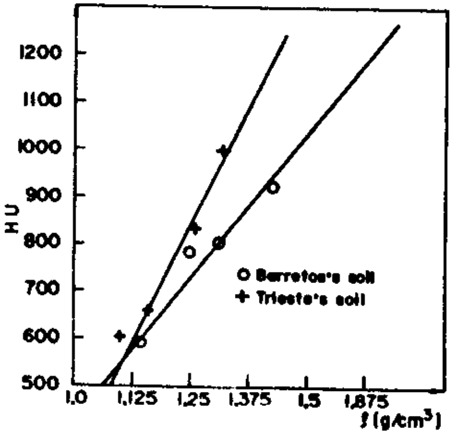

FIG. 1. Linear calibration curve of Hounsfield units (HU) as a function of dry bulk density ρ (mass of dried soil per volume of dried soil). The average value of standard deviation is 32.5 HU.

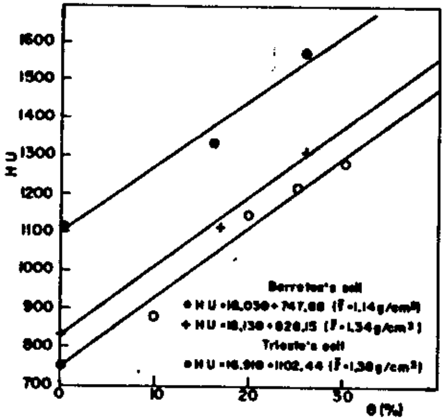

FIG. 2. Linear calibration curve of Hounsfield units (HU) as a function of water content (θ) (volume of water per volume of soil). The average bulk density was obtained from Fig. 1, and the average standard deviation is 63.2 HU.

appropriateness of CT for measuring water content. By selecting an appropriate area in the image, the attenuation in HU can be measured directly in the video console. Indicators of variable geometry and area, like circles (Fig. 3) or rectangles (Figs. 4 and 5), allow the attenuation to be measured in the region of interest (ROI). The system also furnishes coordinates, area, and the standard deviation of the attenuation in the ROI box. In Fig. 1, we show the results of the calibration curve of the system expressed in HU, as a function of dry bulk density (ρ). A linear dependence was found for two different soils (Barretos and Trieste), confirming the result of Petrovic et al. (1982) and showing the variation of attenuation coefficients for each soil.

In Fig. 2, we show the results of the calibration curve of the system, also expressed in HU, as a function of water content in soil (θ) (volume of water per volume of soil). As with dry bulk density, we found a linear dependence for the different soils and densities. It was possible to see the dependence of density in the Barretos soil when we used two different mean density values (1.14 g/cm^3 and 1.34 g/cm^3). The curves are parallel, showing with good agreement that the density is responsible only for the change in the intercept of the calibration curve, in agreement with Fig. 1. With these results, it is possible to obtain the bulk density and the water content directly from a complex image contain-

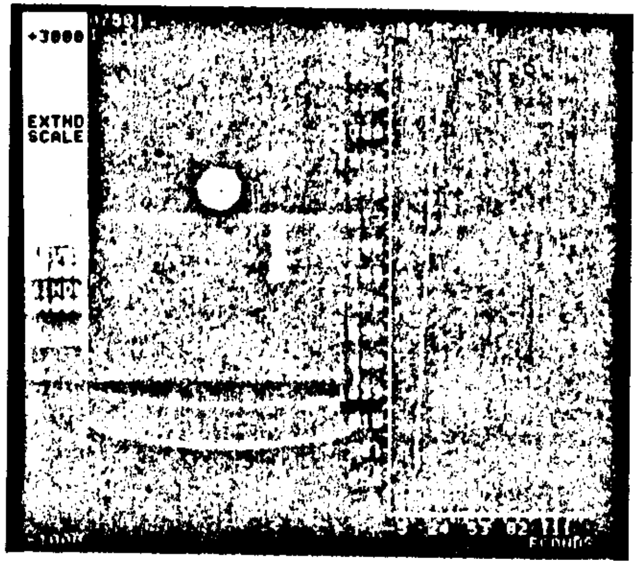

FIG. 3. Dynamic experiment made after introducing water into a horizontal column showing a fixed slice. Ten sequential scans (right-side curve) in HU (absolute scale) as a function of time are shown. The number 1 represents points at the chosen slice.

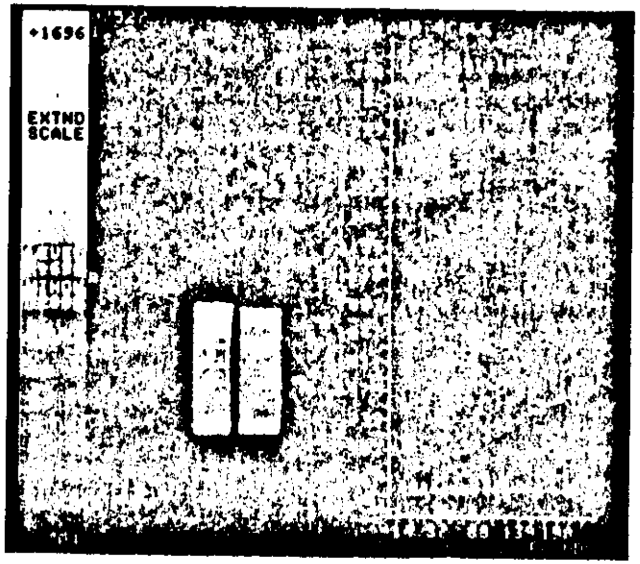

FIG. 4. Spatial and real-time (dynamic) measurement made with a vertical column (left side) at different time intervals. The attenuation was measured in different regions with the ROI (region of interest) boxes indicated by numbers 1, 2, 3, and 4 from top to bottom of the column. On the right side we plotted the variation of water content as a function of time for the different regions.

ing inhomogeneous soil or water distribution for that sample.

We performed dynamic experiments after introducing water into the columns. Results are shown in Figs. 3 and 4. In Fig. 3 we see the cross section (one slice) of the horizontal syringe with set soil. We took several scans at the same position at different times and chose a circle as the ROI box. With appropriate software for the CT scanner, we plotted the curve ABS scale (HU) versus time (s). The ROI circle, indicated by the number 1, expresses the variation of the attenuation coefficient (HU) with time in the area enclosed by the circle.

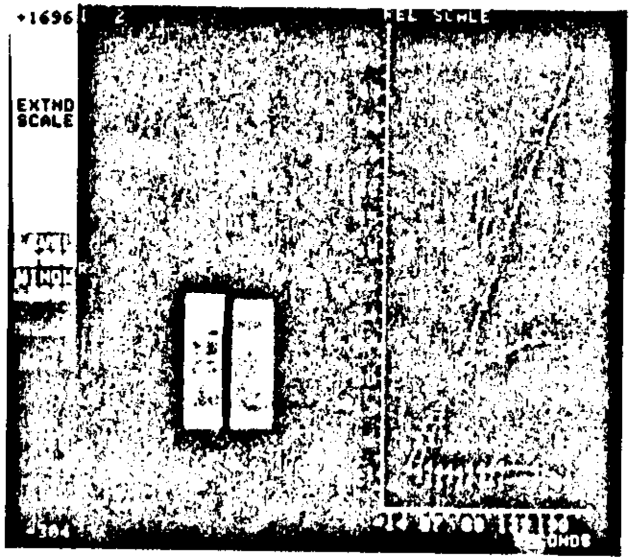

FIG. 5. With the same system described in Fig. 4, we plotted the differences of water content for different regions 1, 2, 3, and 4 as a function of time. In region 3, for instance, we see a continual increase in water content with a more drastic relative change.

For this experiment, the slice was located 50 mm from the entrance section of the column, which corresponds to an average speed as large as 1.6 mm/s, for from Fig. 3 (right-side curve) it is possible to observe the sudden arrival of the water front in the chosen slice (about 30 s after the introduction of water). We used scan intervals of about 5 s and slice thicknesses of 1.5 mm. The number 1 indicates sequential scans in Fig. 3 (right side).

A combined spatial and real-time (dynamic) measurement was also made for the vertical column. In this case, to obtain slower water speeds, we put wet cotton in contact with the top of the column. This, can be seen, though with difficulty, in Fig. 4. With this limited amount of fluid available it was possible to scan at different time intervals and measure the attenuation in different regions with the ROI boxes indicated by the numbers 1, 2, 3, and 4 from top to bottom of the column. In Fig. 4, right side, we show a plot of the variation of water content as a function of time for the different regions. In Fig. 5, for the same system and configuration, we show a very instructive curve obtained from the data of the experiment of Fig. 4 by plotting the differences of water content for different regions, 1, 2, 3, and 4, as a function of time. It is seen that in ROI box 1 the water content quickly became constant (in about 15 s); in ROI box 2, heterogeneities can be seen from the CT scan, but the average water content increases with time and attains a smaller average value. In region 3 there is a continual increase in water content with a more drastic relative change. Finally, like region 1, which attained a constant value, in region 4, where the water had not yet arrived, there was no change in attenuation.

DISCUSSION AND CONCLUSIONS

From the above results, one can see that CT scanning has much potential for soil science. These preliminary results also show that many aspects still need to be developed. One of the first is connected with the instrumentation itself. We are performing soil science investigations with an instrument that was specifically designed for medical investigations of human beings. In principle a much simpler instrument can be developed. For medical CT, the limitations of dose to the patient impose severe restrictions on the mode of operation of the system. For instance the radiation exposure and thus tube conditions of operation, like kV and mA s are correspondingly limited. Patient motion and positioning comprise another limitation that again imposes particular aspects on the design and functioning of CT scanners. Obviously, for soil science, such restrictions are not

necessary. Also image reconstruction need not be made on-line as we did. Another important aspect is connected with the radiation quality itself. Most CT scanners for medical applications have supporting software for image reconstruction based on a small range of radiation quality (spectrum). If the amount of kilovolts to the tube is changed the spectrum is changed, and the software no longer corrects for many artifacts known to be present in CT. For instance, it might prove to be advantageous to use different kilovoltages. We have used 120 kV, and, in fact, many times we have worked at the limit of power of the system. We have now performed additional investigations using different x-ray energies showing that there is an optimum range for tomographic investigations of soil (Crestana et al. 1985). From this preliminary study, we drew various basic conclusions and summarize them below

1. CT scanning can be used to observe and measure quantitatively water content in soil;
2. CT scanning can be used for dynamic (real-time) studies of water motion in soil, including measuring water speeds as high as 1.6 mm/s;
3. CT scanning can be used to obtain information on heterogeneities of water content and 3-D information by using the slicing technique, as discussed here, or by obtaining complete 3-D reconstruction from those data (not presented in this paper);
4. Simultaneous spatial and time distributions of water content can be obtained by the use of appropriate CT techniques, as demonstrated in this work;
5. The slope of linear dependence of Hounsfield units (HU) on water content (θ) changes for different soils, but is independent of bulk density for the same soil. This conclusion shows that HU are a function of both ρ and θ, that is, a CT image of soil is in fact at least a bidimensional function HU (ρ, θ). This very important point has to be taken into account if a quantitative interpretation of soil CT images is required.

Mini-CT scanners costing on the order of $10 000 have been built for dedicated applications like archeology and wood analysis (Cesareo et al. 1983), and we are starting to construct a simple x-ray system in São Carlos, SP, Brazil, for soil science applications (for instance, studies of compaction and swelling of soils, vertical and horizontal infiltration in dry and wet soil, simulation of drop irrigation, growth of a seed, studies of evapotranspiration, etc.) in which many of the limitations mentioned above will not be present. Another possible method for water observation would be NMR CT scanning, and we are also investigating this problem in our laboratory at the Institute of Physics and Chemistry at São Carlos.

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