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STATIC AND DYNAMIC 3 DIMENSIONAL STUDIES OF WATER IN SOIL
USING COMPUTED TOMOGRAPHIC SCANNING

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STATIC AND DYNAMIC 3 DIMENSIONAL STUDIES OF WATER IN SOIL USING COMPUTED TOMOGRAPHIC SCANNING +

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ABSTRACT

Previous work of Petrovic, Siebert and Rieke(1) demonstrated the possibility of using X-ray transmission computed tomography (CT) scanning for soil bulk density analysis in soil. We show in the present work that CT can also be used for the measurement of water content in soil. In our case we also show that CT can be applied to measure and follow dynamically the motion of water in soil in 3-dimensions. Further, more 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 3-dimensions opens new possibilities in this area of investigations.

INTRODUCTION

The study of water content and motion in soil is of fundamental importance in soil science. In the past, several methods have been applied for the measurements of water content in soil such as gamma-ray absorption neutron probe technique, direct water content evaluation by weighting and drying and others (see for instance refs.2 and 3). Only gamma-ray absorption and neutron probe methods may be used for dynamical studies of water in soil. All of 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 3-dimensions (1). CT scanning provides excellent possibilities for spatial and time studies of water content in soil.

Petrovic *et al* mention that they have been unable to obtain consistent results for measurements of

soil moisture by CT. By using a third generation CT scanner (GE CT / T8800) and using an advantageously appropriate choice of parameters such as extended scale, differential level scanning and judicious choice of 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 reference (4). A very interesting and instructive introduction to CT may be found in the Nobel Award Address given by A. M Cormack (5). Essentialy the problem of CT scanning is the following: Penetrating electromagnetic radiation such as X or gamma-rays are absorbed and/or scattered by matter and the expression:

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

may be used to evaluate the emerging intensity $\underline{I}$ 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, such as the case of a sample of real soil or a part of the human body, the more general expression

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

may be used where f is now a distribution function for the varying absortion coefficient along any direction s across the sample. The central problem of CT is the obtention of 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 has been performed. The image of the object is then obtained as a map of absorption coefficients μ for any desired section (slice) of the sample. This process is performed mathematically with the help of computers and is called image reconstruction technique. 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. G. N. Hounsfield developed independently the reconstruction theory and also the first commercial CT scanner for medical use (6). Essentialy in the video of a CT scanner a plot of the attenuation coefficient μ is shown on a gray level viewing system in the so called Hounsfield Units (HU) usually taken to be the following (4)

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

where μ_ω is the attenuation coefficient of water. For the plotting a relative scale is sometimes used where μ_ω 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. CT-third generation scanners are also capable of being used in dynamical modes with scanning times as short as 5.7 sec. with scan interval times of even 1 sec..

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

MATERIALS AND METHODS

Scans of soil samples have been obtained with a General Electric CT/T 8000 scanner of the Istituto di Radiologia, Universita'di Trieste, Italy. This is a third generation rotate-rotate CT scanner meaning that the X-ray tube and the detectors rotate simultaneously during the scan. The detector array consists of a 30° arch in which are contained 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 while the mA may range from 20 to 500 mA.; the mAs depends on the scanning time and can range from 30 mAs to 1152 mAs. We have used the maximum mAs available for the instrument depending the parameters used (dynamic scan or not and slice thickness). The gantry aperture for patient positioning is 60 cm. in diameter. The scan time may change from 5.7 to 11.5 sec.. The scan interval between two scans is about 30 sec. but may be reduced to 1 sec. when the dynamic technique is used. The dynamic scan consists of a series of scans that may be performed at a same slice location or with different locations. The interscan delay may be 1 sec. or longer, as desidered. The dynamic technique enables us to obtain plots of the density changes during time. The slice thickness may be 1.5 mm., 5 mm., 10 mm.. The standard image reconstruction circles are 25 cm. usually used for brain studies, 35 cm. and 42 cm. usually used for body studies. The matrix size is 320 x 320 pixels. The single pixel size depends on the image reconstructions circles (25 cm., 35 cm., 42 cm.) and is respectively 0.8, 1, 1.2 mm. The pixel size may be further reduced till 0.25 mm by using the high resolution image reconstruction. The reconstruction algorithm (both standard and high resolution) assigns to each pixel in the image matrix the X-ray linear attenuation coefficient of the material within that volume of the object represented by the pixel. These coefficients are converted into CT numbers before the image is viewed. This conversion is done by scaling attenuation coefficients to the coefficient of water. The normal CT number scale runs between - 1000 (air) H.U. to + 1000 (bone) H.U.. A CT number of 0 is assigned to water. In order to visualize density more than 1000 the extended scale has been added to the scanner which allows the CT number scale to run between - 1000 and + 3000 H.U.

We have used a sandy soil and two types of cylindrical acrylic columns: for horizontal flow a 5 cm diameter, 20 cm long syringes and for vertical flow a 10 cm diameter by 30 cm height cylinder, internally divided by a plastic thin wall, so that a comparison could be made between dry and wet soil simultaneously during scans.

The columns were positioned in the gantry in the most judicious way to avoid artifacts for the chosen paremeters like kVp, mAsec, scan time and slice thickness, as previously discussed. Water flow was introduced either by a hydraulic head or by direct wetting by spraying or from contact with a wet cotton. For the obtention of a calibration curve (fig. 2) for water content as a function of measured attenuation in H.U., a known volume of water was added to a known volume of soil previously dried.

RESULTS

Several experimental techniques were introduced for the study of water content and motion and we describe them in the sequence. The first experiment, as shown in fig. 1, clearly indicates the appropriateness of the use of CT for water content measurement. By selecting an apropriate area in the image, the attenuation in HU can be measured directly in the console. Indicators of variable geometry and area like circles (fig. 3) or rectangles(fig. 4) 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 (see fig. 1). In fig. 2, we show the results of the calibration curve of the system expressed in HU as a function of water content in soil volume of water per volume of soil. A linear dependence was found from which direct water content can then be obtained from a complex image containing inhomogeneous soil or water distribution for that sample.

Dynamical experiments were performed in the following way: a fixed slice was chosen in the column and sequential scans were made as a function of time after the introduction of water in the column. Results are shown in fig. 3. Even for a high conductivity soil like the one we have used, it is possible to observe the sudden arrival of the water front in the chosen slice (fig. 3, right side curve) some 30 seconds after the introduction of water. The slice was located 50 mm from the entrance area of the column which corresponds to an average speed as large as 1.6 mm/sec. For this experiment the slice thickness was 1.5 mm. The number 1 indicates scans in the fig. 3, Scan interval was about 5 sec.

A combined spatial and real time (dynamical) measurement was also made for the vertical column. In this case to obtain smaller water speeds, a wet cotton was put in contact with the top of the column. This is barely seen 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 numbers 1, 2, 3, 4 from top to bottom of the column. On the right-hand side of Fig. 5 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 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-boxes number 1 the water content remains constant quickly (in about 15 sec.) for ROI-boxes 2, hetero-geinities can be seen from the CT-scan but the average water content increases with time and attains a smaller average value. For 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 did not yet arrive, there was no change in attenuation.

DISCUSSION AND CONCLUSIONS

From the previous results it is seen that CT scanning has many potentialities for soil science. From these preliminary results it is also seen that many aspects still need to be developed. One of the first is connected with instrumentation itself. We are performing soil science investigations with an instrument that was specifically designed to be used for medical purposes for human beings. In principle a much more simple instrument can be developed. For medical CT the limitations of dose to the patient impose severe restrictions on the mode of operations of the system. For instance the radiation exposure and thus tube conditions of operation, like kV and mAsec are correspondigly limited. Patient motion and positioning is another limitation which again imposes particular aspects on the design and functioning of CT-scanners. Obviously for the case of soil science, such restrictions are not necessary. Also image reconstruction does not need to be made on line like in our case. Another important aspect is connected with the radiation quality itself. Most CT-scanners for medical applications have a supporting software for image reconstruction based on a small range of radiation quality (spectrum). If the kV to the tube is changed the spectrum is changed and the software does not correct any longer for many artifacts known to be present in CT. For instance it might prove to be advantageous to use higher kV. In our case we have used 120 kV and in fact in many cases we have worked at the limit of power of the system. Higher kV might allow larger columns to be used and eventually provide better contrast in images. Another preliminary limitation of our experiment is that we did not perform classical soil science experiments with standard columns and accessories but improvised due to limited experimental conditions in the hospital. However in this preliminary study various basic conclusions could be obtained, and are summarized below:

a) CT scanning can be used to observe and measure quantitatively water content in soil;

b) CT scanning can be used for dynamical (real time) studies of water motion in soil, including the measurement of water speeds as large as 1.6 mm/sec.;

c) CT scanning can be used for the obtention of information on hetero geneities of water content and 2-d information by the use of the slicing technique as used in this work or by the obtention of complete 3-d reconstruction from that data (not presented in this paper);

d) Simultaneous spatial and time distributions of water content can be obtained by the use of appropriate CT techniques as demonstrated in this work.

Mini CT scanners costing less than US 7000 have been built for dedicated applications like archeology and wood analysis (7) and we are starting to construct a simple system in Barretos, SP, Brazil, for soil science applications in which many of the limitations mentioned above will not be present. Of course the ideal method for water observation would be NMR CT scanning and we are presently investigating this problem in our Lab. at the Inst. of Phys. Chem at S. Carlos with the help of H. Panepucci and coll.

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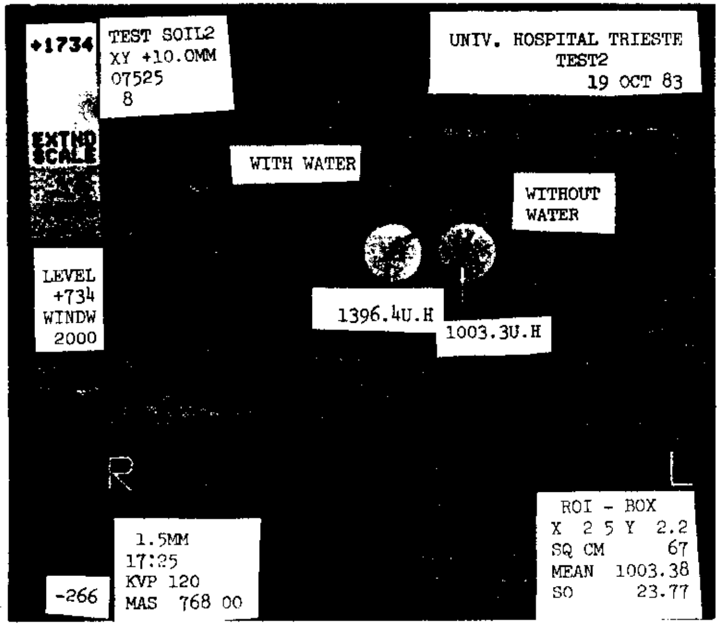

Figure 1 - Appropriateness of the use of CT for water content measurement. We show the differences of two samples with water and without water and the associate values of the water content measured in H.U. (Hounsfield Units).

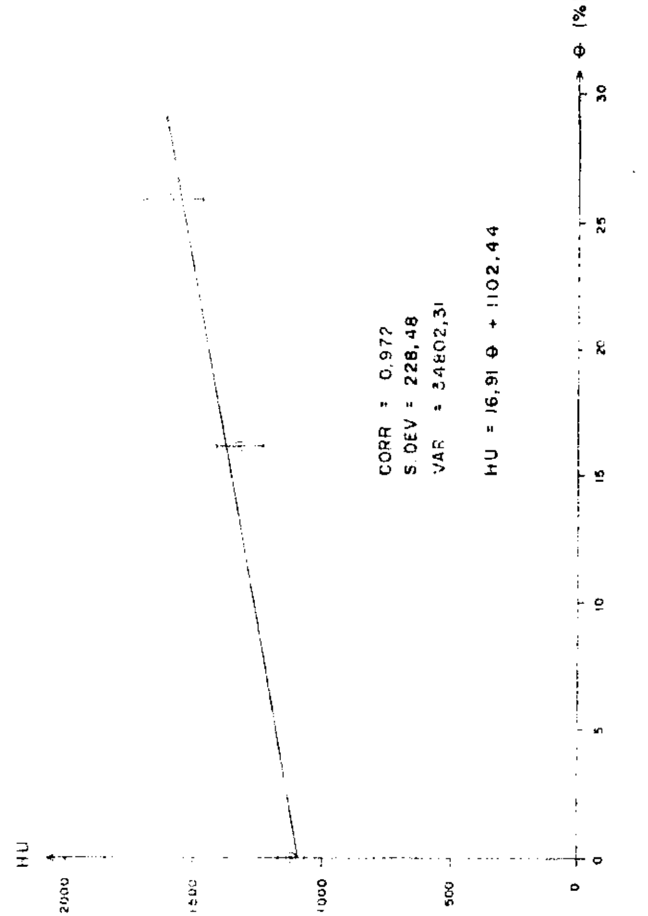

Figure 2 - Linear Calibration curve of Hounsfield Units (H.U.) as a function of water content (θ) (volume of water per volume of soil).

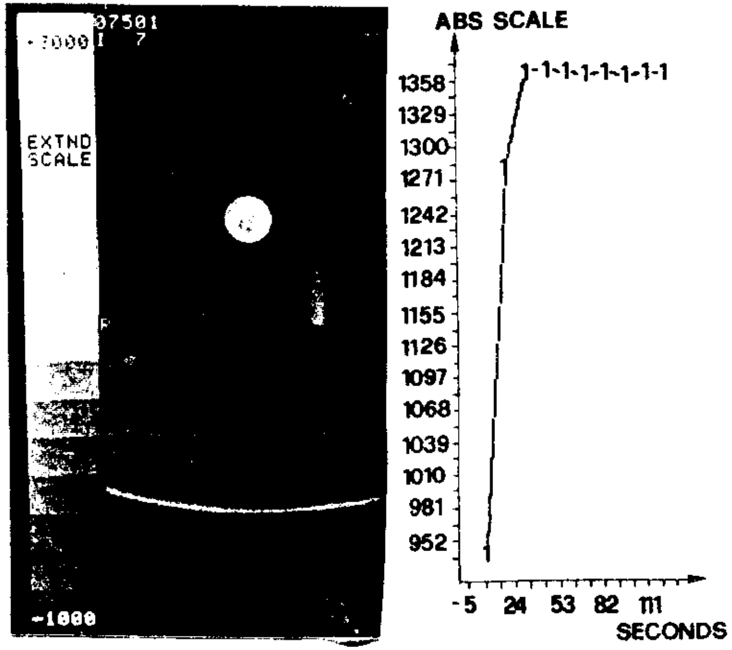

Figure 3 - Dynamical experiment made with a horizontal column showing a fixed slice where sequential scans (absolute scale in H.U.) as a function of time after the introduction of water in the column. The number 1 represents the position of the slice and the size of the area.

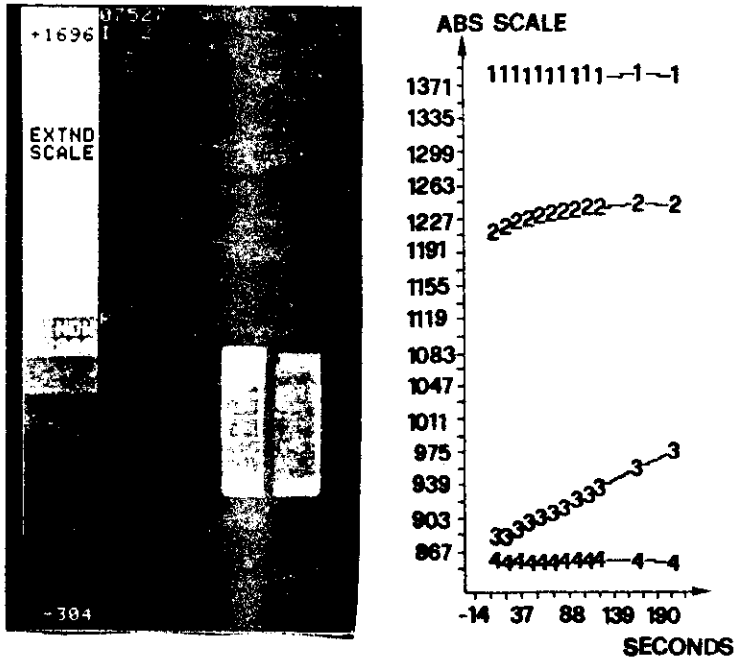

Figure 4 - Spatial and real time (dynamical) measurement made with a vertical column (left side) at different time intervals. The attenuation was measured in different regions with the ROI (Region of interest) boxes indicated by numbers 1, 2, 3 and 4 from top to bottom of column. On the right side we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

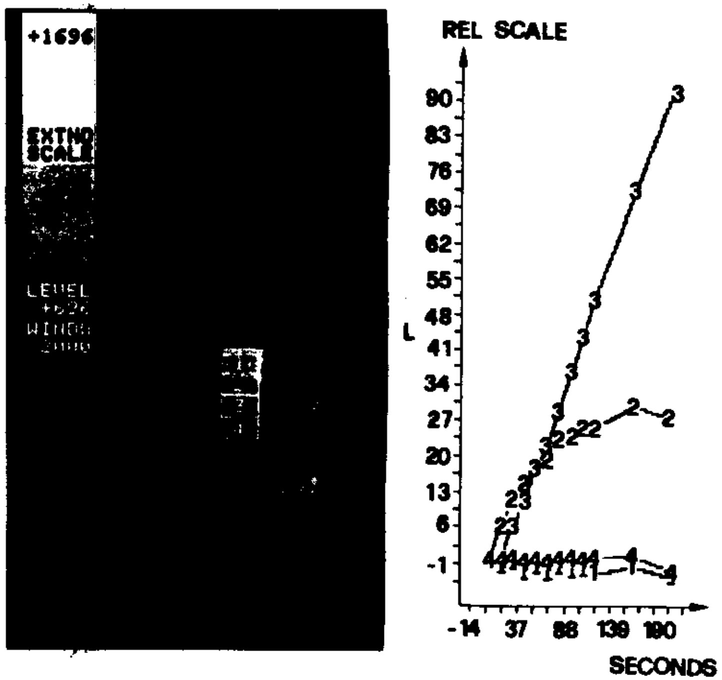

Figure 5 - With the same system described in fig 4, we plotted above the differences of water content for different regions 1, 2, 3 and 4 as a function of time. In the region 3 for instance, we see a continual increase in water content with a more drastic relative change.