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"Computerized Tomography as a Method for Physical Studies of Soil Water"

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COMPUTERIZED TOMOGRAPHY AS A METHOD FOR PHYSICAL STUDIES OF SOIL WATER

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INTRODUCTION

The study of bulk density, water content and motion of water in soil has fundamental importance to soil science. Usually several methods have been applied to measure bulk density and or water content such as gravimetry, gamma-ray absorption-scattering, neutron-probe technique and others. Only gamma-ray and neutron methods can be used for dynamical studies of water in soil. All these methods do not take into account soil inhomegeneities and do not evaluate tri-dimensional profiles of bulk density, water content and motion. The ideal technique for monitoring bulk density, water content and other physical parameters in soil should be nondestructive, sensitive, rapid and able to resolve small differences in the measured parameters over distances of a few millimeters.

A quite similar problem was solved in diagnostic radiology by using the technique of computer-assisted tomography (CAT) (or only computerized tomography CT). Essentially CT scanning is penetrating electromagnetic radiation, such as X or gamma ray. The expression (Beer's law)

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

can be used to evaluate the emerging intensity I of the radiation beam of incoming intensity I_o after traversing a sample of homogeneous material of absorption coefficient μ and thickness x.

A typical apparatus that we used (Crestana, 1985 and Crestana et al. 1986) for measuring attenuation coefficient of soil samples is schematically shown in Fig. 1.

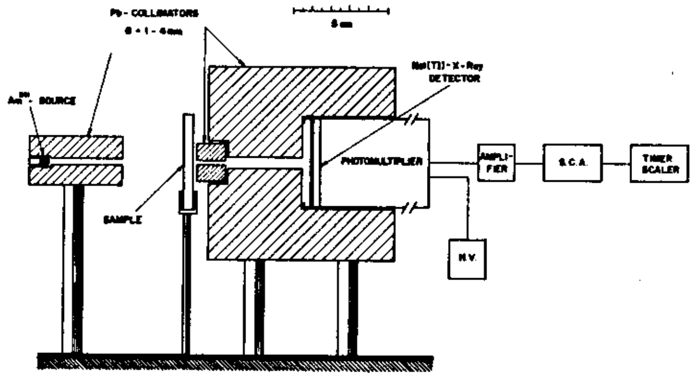


Fig. 1. Apparatus for measuring attenuation coefficients of soil

It consists of a radioisotopic source of Am^{241} (60Kev) or 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, quasí-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 over a large interval of energy. The source-detector solid angle was very small (diameter of both collimators: Ø = 1 to 4mm; distance source-collimator: about 20cm) 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 250ev at 6.4Kev.

Fig. 2 show mass soil attenuation coefficients of fine sandy loam soil, collected from the Ap horizon of a Brazilian soil, water and silica as a function of incident energy.

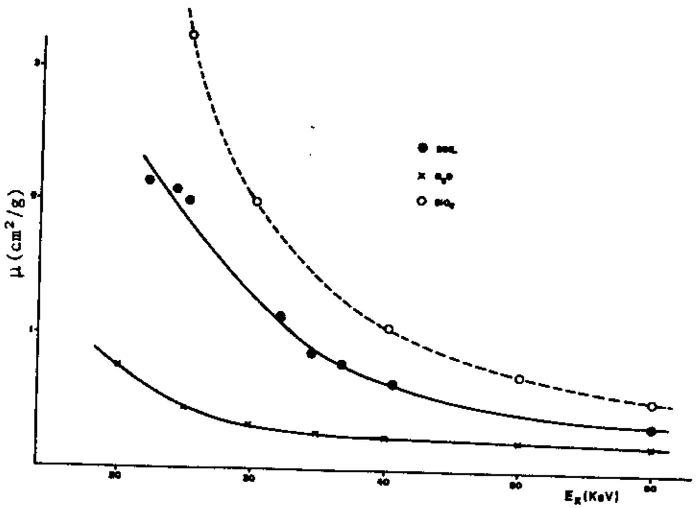


Fig.2. Mass soil attenuation coefficients of soil, water, and silica as a function of incident energy. The mean error ranges from 2 to 4%

From Fig. 2, it is clearly visible that the difference in attenuation coefficient between soil and water increases with decreasing energy. On the other hand, the optimum thickness of the crossed soil sample decreases, requiring more and more intensity for samples of constant thickness.

We conclude that 30 to 40Kev is the best energy to use for water-content resolution. Usually, in soil physics studies, the energy of 60kev and 662Kev are employed because of the commercial availability of radioactive sources as Am^{241} and Cs^{137}. Thus, the use of X-Ray radiation and X-ray fluorescence of secondary targets (monoenergetic radiation) is an advantage.

When the material is not homogeneous, as in a sample of real soil or a part of the human body, the more general expression

$$I = I_o \exp^{-\int_s f ds}$$

must 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 for any desired section (slice) of the sample. This process is performed mathematically with the help of computers and is called **image reconstruction.**

A typical commercial third-generation CT scanner for medical use is shown in the Fig. 3.

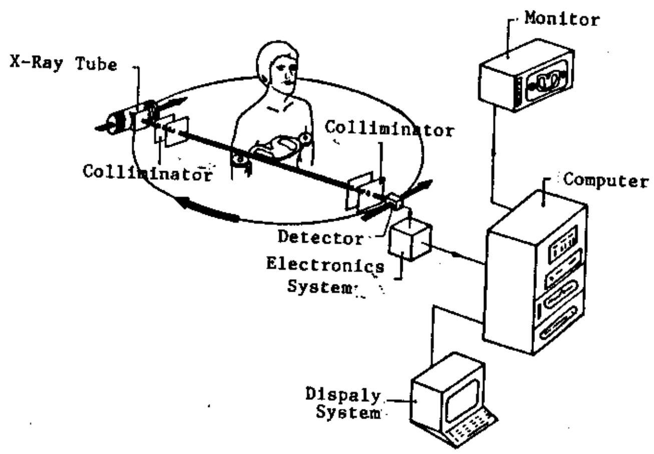


Fig. 3. Typical diagram of a CAT system dedicated to medical purposes

Essentially in the video of a CT scanner a plot of the attenuation coefficient is shown on a gray-level viewing system in so-called Hounsfield Units (H.U.), defined as

$$H.U. = 1000 \left(\frac{\mu - \mu_w}{\mu_w}\right) \quad ,$$

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. For instance, third-generation CT scanners are also capable of being used in dynamic modes with scanning times as short as 5.7s and scan interval times of 1s.

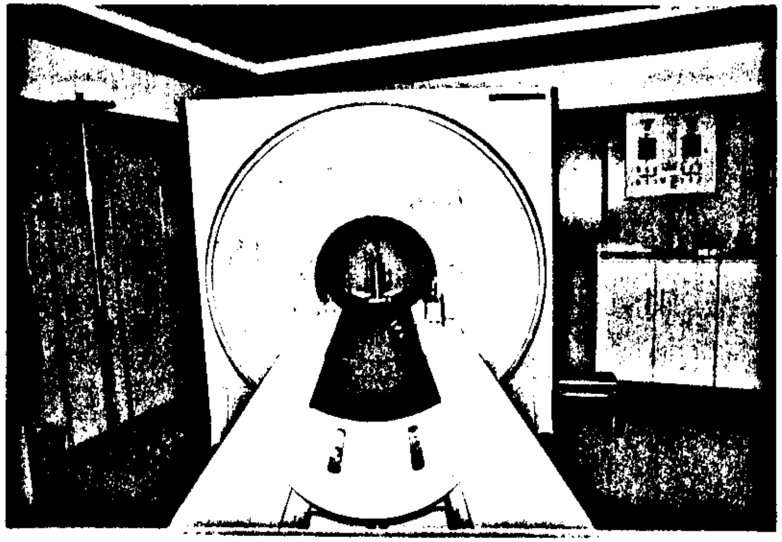
Though CT scanners are expensive, they are now commonly found in most large hospitals and may eventually be used for such other applications as the one we propose in this text (Crestana et al, 1984, 1985). We also proposed and built a small mini-CT scanner to be used for special purposes, such as in soil science, at a vastly reduced cost (50 to 100 times lower than commercial medical tomography) (Crestana et al, 1986 and Cruvinel, P.E., 1987 and Cesareo et al, 1988).

THE C.T. AS A NEW METHOD IN SOIL SCIENCE

We introduced (Crestana et al, 1984, 1985) several experimental techniques to study bulk density, water content and motion. We briefly describe them in sequence.

We used different soil textures collected from the Ap horizon of a Trieste, Italy sandy soil and a Barretos, Brazil, fine sandy loam soil. We also used two types of acrylic cylindrical columns: for horizontal flow a syringe 5cm in diameter and 20cm long; and for vertical flow a cylinder 10cm in diameter and 30cm high, internally divided by a thin plastic wall, so that dry and wet soil could be compared simultaneously during scans. For the CT scans of soil samples we employed a third-generation General Eletric CT/T8800 scanner of the Istituto di Radiologia, Universitá di Trieste, Italy (Picture 1).

The experiments, as shown in Figs 4, 5 and 6,clearly indicate the appropriateness of CT for measuring water content or bulk density. By selecting an appropriate area in the image, the attenuation in H.U. can be measured directly in the video console. Indicators of variable geometry and area like circles (Fig.4) or retangles (Figs 5 and 6), 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.



Picture 1. Third-generation Medical Computerized tomograph GE CT/T8800, employed to perform several experiments with soil. At the first plane it is possible to observe the movable table used to position the patient. At the second plane, it is possible to observe the gantry for examination of the patient. Notice the column of soil inside the gantry, used to accomplish an experiment with plant (a seed of corn).

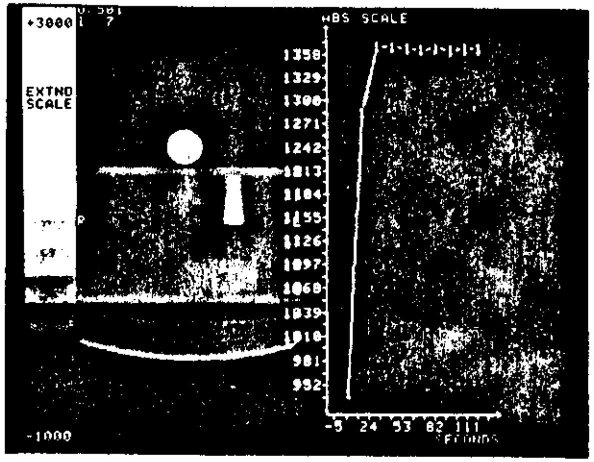


Fig. 4. Dynamic experiment made after introducing water into a horizontal column showing a fixed slice. Ten sequential scans (right-side curve) in HU (absolute scale) as a function of time are shown. The number 1 represents points at the chosen slice.

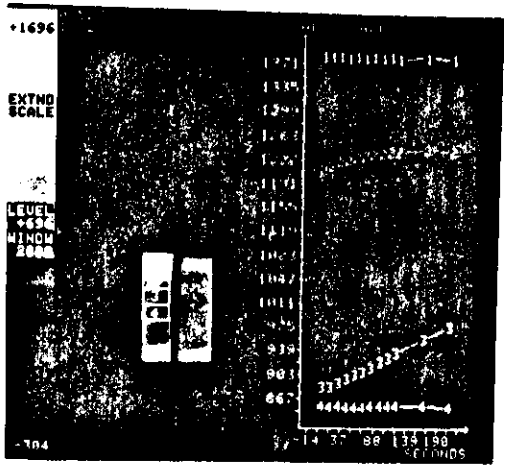


Fig. 5. Spatial and real-time (dynamic) measurement made with a vertical column (left side) at different time intervals. The attenuation was measured in different regions with the ROI (region of interest) boxes indicated by numbers 1, 2, 3 and 4 from top to bottom of the column. On the right side we plotted the variation of water content as a function of time for the different regions.

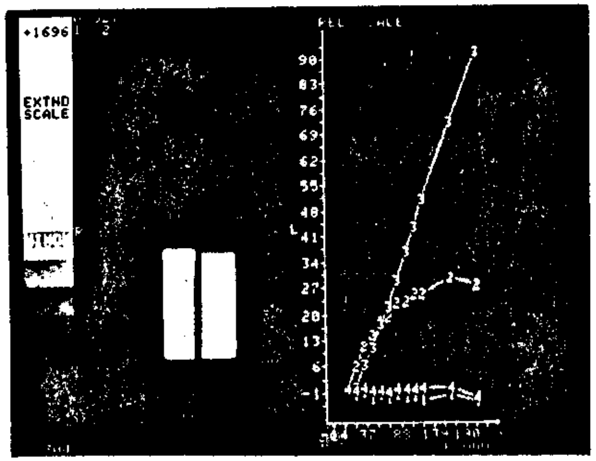


Fig. 6. With the same system described in Fig.5, we plotted the differences of water content for different regions 1, 2, 3 and 4 as a function of time. In region 3, for instance, we see a continual increase in water content with a more drastic relative change.

In Fig. 7, we show the results of the calibration curve of the system expressed in H.U., as a function of dry bulk density (ρ). A linear dependence was found, showing the variation of attenuation coefficients for each soil.

In Fig. 8, we show the results of the calibration curve of the system, also expressed in H.U., as a function of water content in soil (θ). As with dry bulk density, we found a linear dependence for the different soils and densities. With these results, it is possible to obtain the bulk density and the water content directly from a complex image containing inhomogeneous soil or water distribution for the sample.

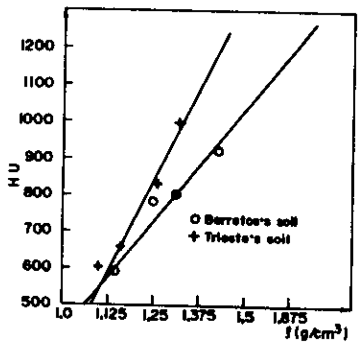


Fig.7. Linear calibration curve of Hounsfield Units (HU) as a function of dry bulk density (mass of dried soil per volume of dried soil). The average value of standard deviation is 32,5 HU.

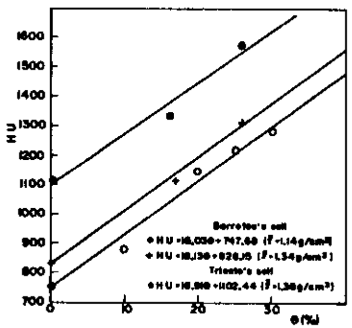


Fig.8. Linear calibration curve of Hounsfield Units (HU) as a function of water content (θ) (volume of water per volume of soil). The average bulk density was obtained from fig. 7, and the average standard deviation is 63,2 HU.

We performed dynamic experiments after introducing water into the columns. Results are shown in Figs 4 and 5. In Fig.4, we see the cross section (one slice) of the horizontal syringe with wet 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 (H.U.) versus time (s). The ROI cicle, indicated by the number 1, expresses the variation of the attenuation coefficient (H.U.) with time in the area enclosed by the circle. For this experiment, the slice was located 50mm from the entrance section of the column; which corresponds to an average speed as large as 1.6mm/s, for from Fig.4 (right-side curve) it is possible to observe the sudden arrival of the water front in the chosen slice (about 30s after the introduction of water) we used scan intervals of about 5s and slice thickness of 1.5mm. The number 1 indicates sequential scans in Fig. 4 (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 cotton in contact with the top of the column. 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. 5, right side, we show a plot of the variation of water content as a function of time for the different regions. In Fig. 6, for the same system and configuration, we show a very instructive curve obtained from the data of the experiment of Fig. 5 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 15s); 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.

THE COMPUTED TOMOGRAPHY MINISCANNER

From all previous results 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. Now, we report briefly on the characteristics and use of a very inexpensive, CT miniscanner dedicated to soil science analysis. More details can be seen in Crestana et al, 1986. This new apparatus was applied to carrying out tomographies of soil with various water contents and bulk densities.

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 mAs are correspondingly limited. Patient motion and positioning are others limitations that again impose 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. Due to these aspects it was possible to build a much simpler instrument.

The miniscanner, dedicated to soil science analysis, built at the UAPDIA-EMBRAPA (Empresa Brasileira de pesquisa Agropecuária, São Carlos, Brazil) has similar characteristics

of the miniscanner constructed at the University of Rome, Centre for Bioengineering, dedicated to biomedical analysis(*)

The characteristics of the miniscanner are (fig. 9):

- monoenergetic sources obtained both with radioisotopes and an X-ray tube with secondary target
- 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 with a reconstruction algorithm working in PASCAL.

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

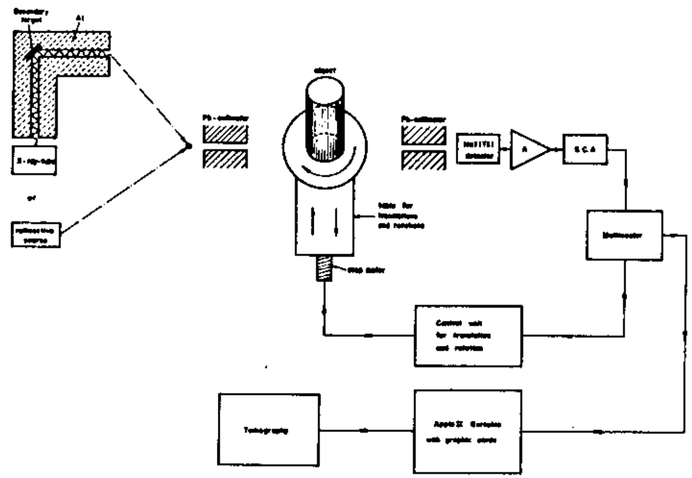


Fig. 9. Complete diagram of the CT miniscanner used to obtain tomographies of soil samples

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. We deduced 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 30Kev (see figure 2). 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.

Using the miniscanner, after several experiments with different soil samples under different bulk densities (ρ) and water contents (θ), we obtained the same linear behavior previously described using the medical CT scanner, relating Hounsfield Units, ρ and θ.

Typical tomographies made using the miniscanner can be seen in figures 10, 11, 12, 13, 14 and 15.

OTHER RESULTS FROM COMPUTERIZED TOMOGRAPHY WITH POSSIBILITIES OF APPLICATIONS IN THE STUDY OF THE SOIL-PLANT-AIR CONTINUUM

We present here some qualitative results obtained with the medical CT scanner and the miniscanner dedicated to soil science applications.

Our intention is to show some potentialities of this new method of investigation (CT), leading to new results (otherwise impossible to be obtained) in the areas such as Soil Science, Soil Physics, Plant Physiology and others.

These new possibilities are consequences of the peculiarities of this new method. This is the case of bi and tri-dimensional image reconstruction of the object (such as soil, water, seed, root, etc), absolute and relative non-invasive measurements of bulk density and water content of soil as function of time, detection of inhomogeneities, and so on. Besides this, resources such as the dynamical technique and amplification of the image resolution (extended scale) can be used.

1. COMPACTION AND DISTRIBUTION OF SOIL IN A COLUMN USING THE C.T. MINISCANNER

The quantification of the physical parameters bulk density, water content and resistance of the soil to the penetration (and their correlation "a posteriori") is a problem of fundamental importance in modelling and studying the compaction phenomenon. This is the case of detection of a "blade" of compacted soil. Such millimeter thick "blades" may occur on sucessive plowing.

Several columns of dry soil profiles with different bulk densities and compactions were simulated in our laboratory. After the scanning of these columns, tomographic sections were obtained and quantified possibilitting the accurate measurement of a "blade" about 3 milimeter-thick and density variations of about $0,01 g/cm^3$ (Crestana et al, 1988).

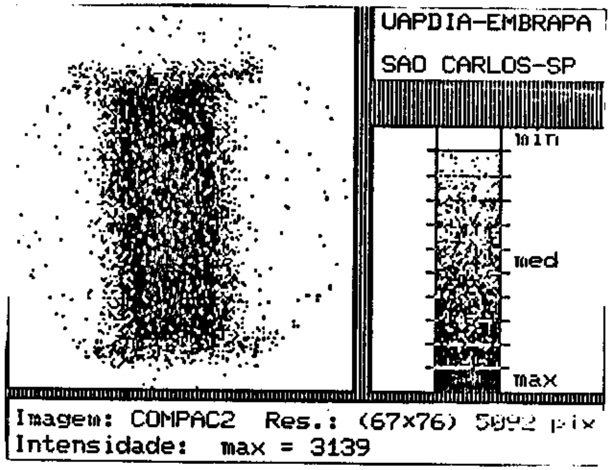


Fig. 10. Tomografic scanning of a retangular column of acrylic (26mm x 51mm) with soil inside not compacted

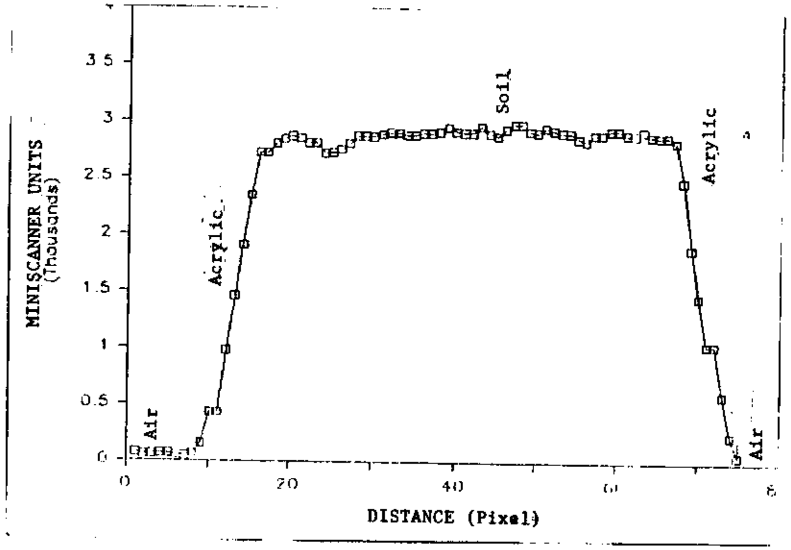


Fig. 11. Vertical profile of the column of Fig. 10, showing quantitativelly the densities of air, acrylic and soil

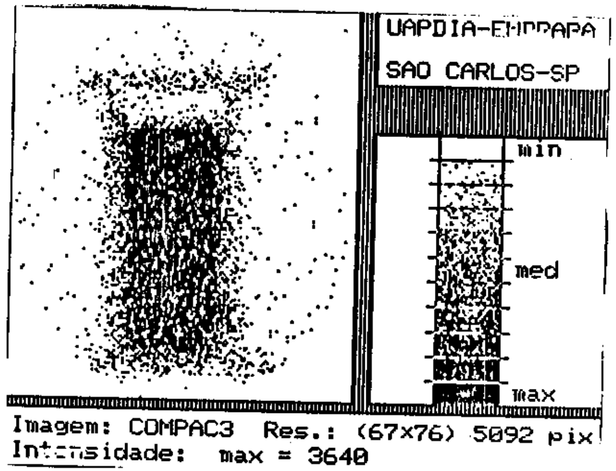


Fig. 12. The same column scanning of Fig. 10, after compaction of the soil on the top. The displacement of the top soil was about 4mm

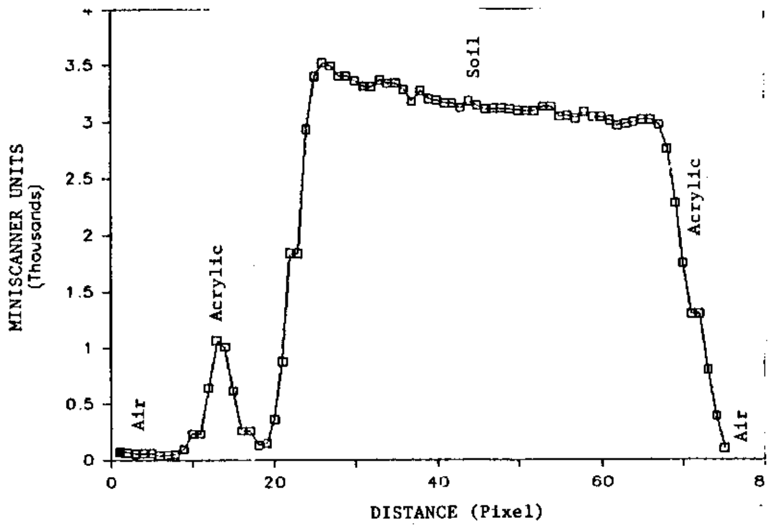


Fig. 13. Vertical Profile ofthe compacted column showed at Fig. 12. The gradient of soil distribution can be observed

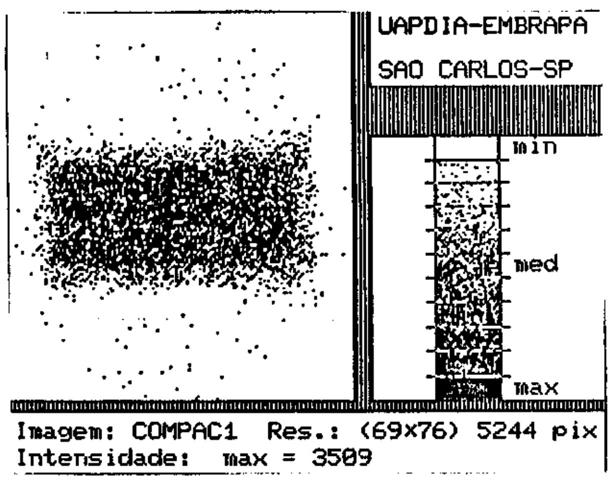


Fig. 14. Column scanning of soil,performed in lab simulating a "blade" of 3mm of dry compacted soil (density about 1.4g/cm³,near the center of the column) with a bulk density about 1.1g/cm³.

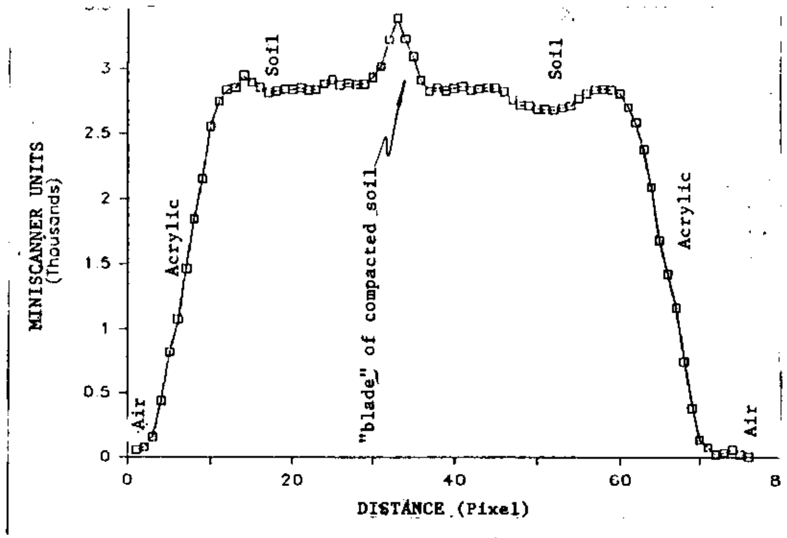


Fig. 15. Vertical Profile of the column of Fig. 14 clearly showing the "blade" of compacted soil near the center of the column.

Using a calibration curve (H.U. as a function of density) for this soil it was possible to calculate the accurate density distribution in the profile and the position of the "blade".

Consequently these results open new frontiers of investigations in the research of the compaction phenomenon. Another immediate application of this result is in aiding to analyse and to construct homogeneous soil columns in the laboratory.

2. DYNAMICAL AND TRI-DIMENSIONAL SIMULATION OF DRIP IRRIGATION IN A COLUMN OF SOIL

The study of drip irrigation has a large pratical interest.On the other hand, it is impossible to solve analitically Darcy's equation in three dimensions considering the specific boundary conditions of this problem (a complicator element is the discret source of water). Experimentally, using the usual techniques of Soil Physics, such as γ-Ray absorption, it is not possible to accompany tri-dimensionally the wetting frontier, even the two-dimensional horizontal plane. Due to these limitations we used medical CT scanner to make several tomographies to introduce a new tool in this important area.

The tomographies of Fig.16 and Fig. 17 illustrate this.

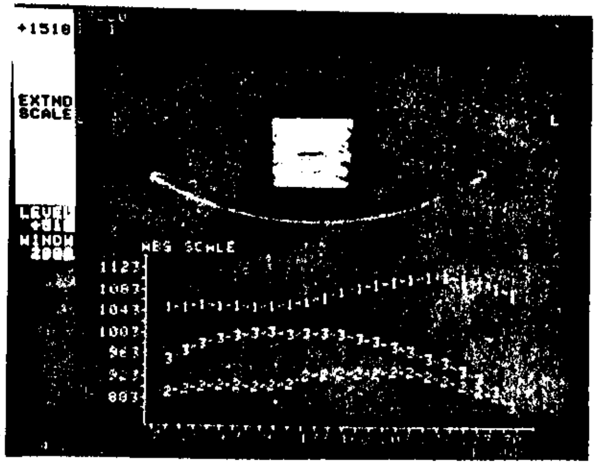


Fig. 16. Cylindrical column of 7,5cm height, 8,3cm of internal diameter submitted to a constant dripping flux of water equal to 4,8cm³/min. It is possible to observe from the indicated points 1, 2 and 3 the distribution of water in the horizontal plane in function of time, measured in H.U. and seconds. Note that the water preferentially flows to the region 3 than to the region 2.

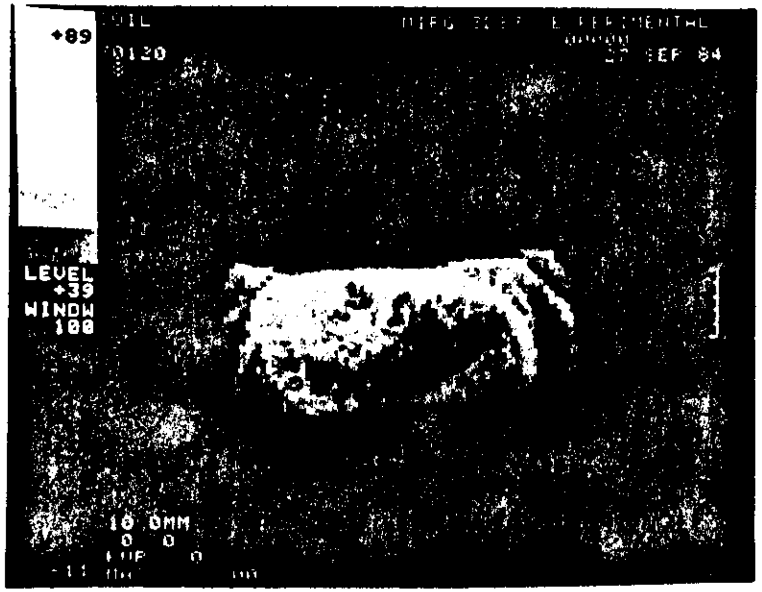


Fig. 17. View of tri-dimensional image reconstruction of water drainning in soil, simulating drip irrigation (horizontal and vertical infiltration) of the wetting front. It is possible to observe details of the boundaries (frontiers) of the water in the soil.

From these two tomographies it is possible to observe preferential directions in the movement of water in the soil. Certainly, this is due to the presence of heterogeneities in the soil (distribution of densities not homogeneous in the column), compaction, different hydraulic conductivities, holes, difficulty in the remotion of water out of the pores, etc.

Other tomographies such as tomography of Fig. 17 under other views (angles, planes or positions) in a certain instant of time also are possible to be reconstructed.

3. SEED GERMINATION, GROWTH AND UPTAKE OF WATER BY ROOTS

We present here two tomographies of a column of soil with a seed of corn inside.

As the two previous examples, the application of C.T. to physico-chemical studies concerning the germination of a seed, growth of plant roots, evapotranspiration (like a matricial poptencial) also can furnish subsidies and the observation of new results in different fields of Soil Physics, Plant Nutrition, Morphogeny and Plant Physiology.

The fact that the C.T. method, is non invasive has advantages, allowing studies involving, for instance, the genetic seletion of the best seeds and plants, studies of statistics of germination motion of solutes in the soil (nutriests and polluents), evapotranspiration and so on.

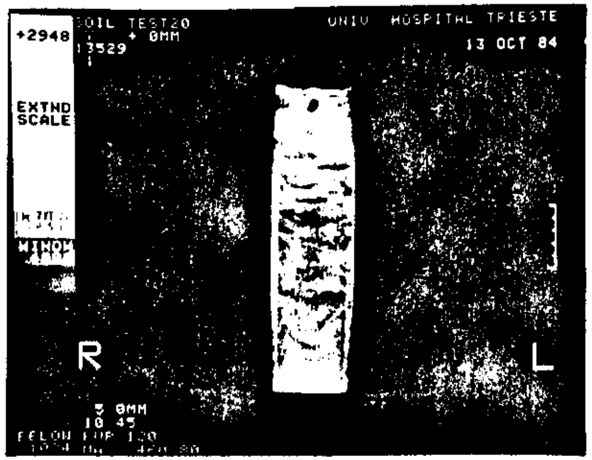


Fig. 18. Tomographic view of a cylindrical column of soil of 25cm height and 57cm internal diameter containning a grain of corn before germination. Notice the presence of inhomogeneities in the distribution of density of the column and the presence of water on the top and bottom of it.

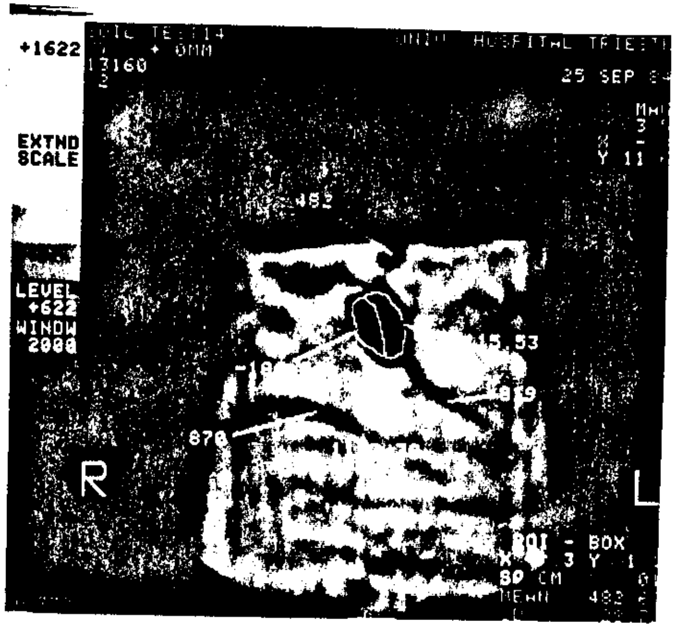


Fig. 19. Tomographic bi-dimensional view of the previous seed (Fig.18) germinated, where it is possible to observe clearly the measurements of soil water content (1112,38H.U.), the densities of the roots (819 H.U. and 870 H.U.), the densities of the seed (115.53H.U. and -186H.U.) as well as that of the plant (482 H.U.). As in the previous tomography, the presence of inhomogeneities can be observed. Periodical measurements of the densities of the soil, of the seed and of the roots in the same position or in different angles allow the following of the detailed germination of the seed, the development of roots, as well the uptake process of water and nutrients, the distribution and redistribution of water in the column etc.

The tomographies shown are all in two dimensions. On the other hand a tri-dimensional and real time view is also possible.

This is carried out using a suitable computer program of tri-dimensional image reconstruction employing the dynamical technique (like those in figs 4,5,6) or by means of several bi-dimensional tomographies taken at different times and angles.

Finally, it is interesting to observe that periodical measurements of the region of seed revealed that from the beginning to the end of the germination process the mean density of the seed changed from a value of 267,9 H.U. to -15,97H.U. The variation of the standard deviation changed from 102,86 to 212,92 respectively. After the germination, the seed presents at least two distint regions: one of mean density equal 115,53 H.U. and other of mean density equal -186,04 H.U.. We know that negatives values imply the presence of air. In conclusion it is evident that the process of germination of a seed occurs from a larger consumption of nutrients of a certain region of the seed, leading finally to a hole of air. The high value of the standard deviation (higher than the value of itself measurement) is a demonstration of the high non uniformity of the measured region, which is the case of the presence of a hole of air. Though more detailed studies are needed it is evident the great potentiality of the method.

CONCLUSIONS

From this exposition, we can draw various basic conclusions and we summarize them below.

1. CT scanning can be used to observe and measure quantitatively bulk density and 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 1.6mm/s;

3. CT scanning can be used to obtain information on heterogeneities of bulk density, water content and 3-D information;

4. Simultaneous spatial and time distributions of water content and bulk density can be obtained by the use of appropriate CT techniques;

5. The slope of the linear dependence of Hounsfield Units (H.U.) on water content (θ) changes for different soils, but is independent of bulk density for the same soil. Thus, the H.U. are a function of both ρ and θ, that is, a CT image of soil is in fact at least a bidimensional function H.U. (ρ,θ). This very important point has to be taken into account if a quantitative interpretation of soil CT images is required;

6. It was 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;

7. The CT miniscanner 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;

8. The use of 30 to 40Kev is the best energy for water-content resolution;

9. The cost os the CT Miniscanner is 100 times lower than commercial medical tomographs;

10. The use of CT scan opens new possibilities of research in Soil Physics such those shown in the sections 1, 2, and 3.

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