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"Soil Imaging Techniques: Some Results"

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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.

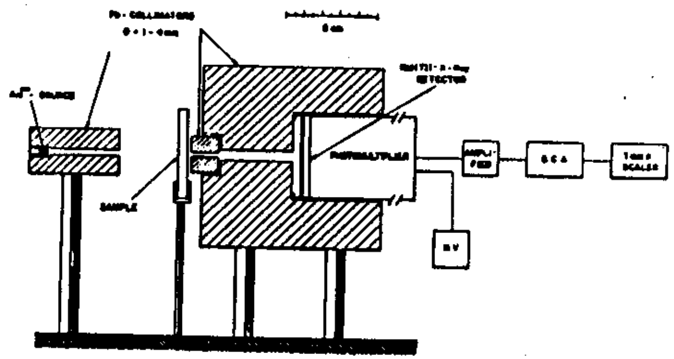


Fig. 1. Apparatus for measuring attenuation coefficients of soil

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, 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 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.

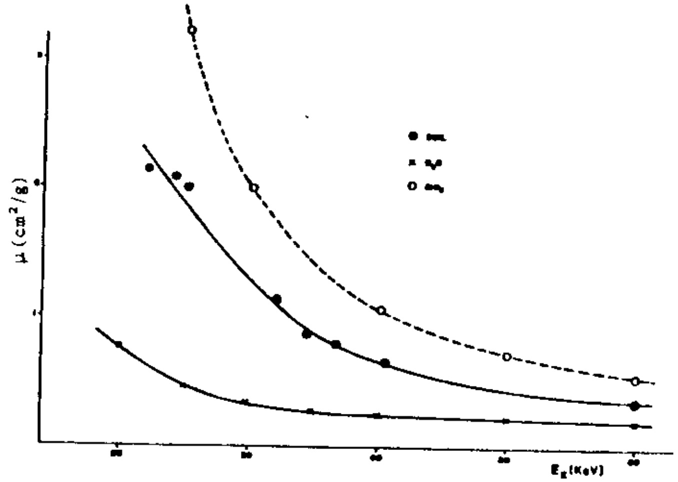


Fig.2. Mass soil attenuation coefficients of soil, water, and silica as a function of incident energy. The mean error ranges from 2 to 4%

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 <u>s</u> across the sample.

The central problem of CT is obtaining the distribution function <u>f</u> (as a function of position for any direction in the sample) when a sufficiently large number of absorption measurements along different scanning directions <u>s</u> 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.

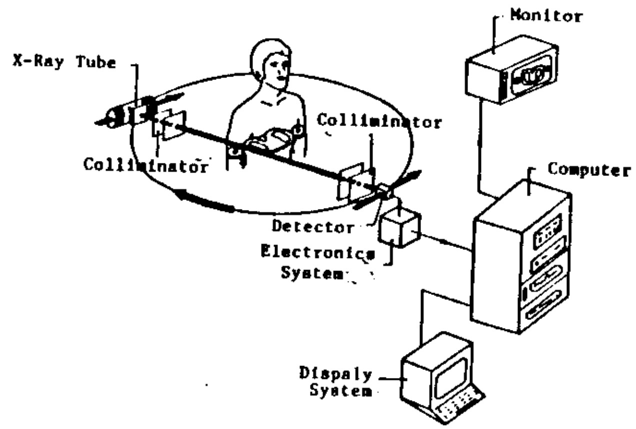


Fig. 3. Typical diagram of a CAT system dedicated to medical purposes

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

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

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.

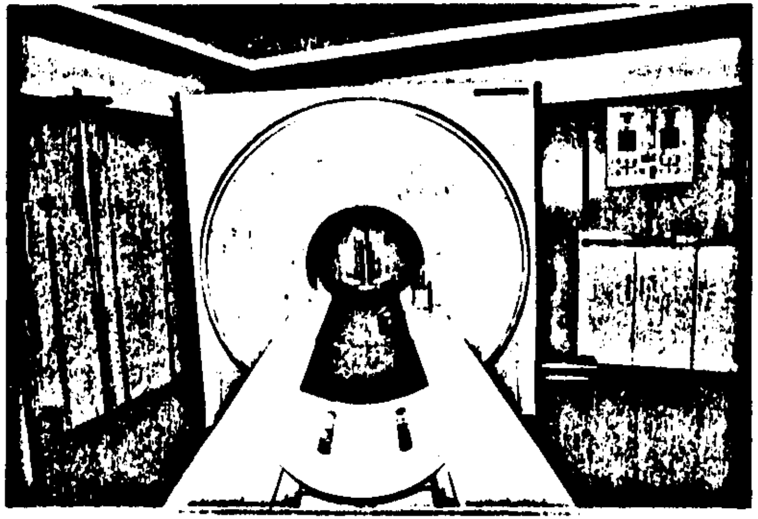
Though CT scanners are expensive, they are now commonly found in most large hospitals and may eventually be used for such other applications as the one we propose in this text (Crestana et al, 1984, 1985). We also proposed and built a small mini-CT scanner to be used for special purposes, such as in 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).

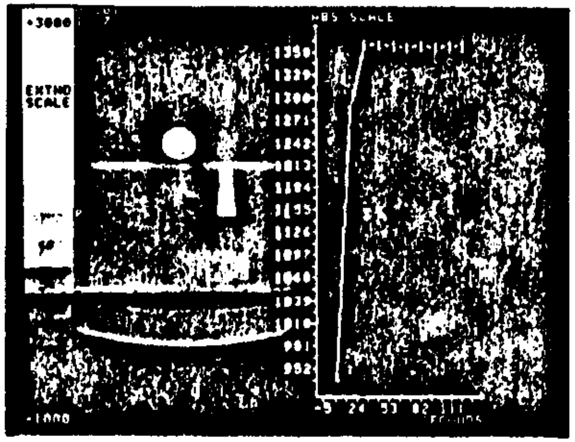


Fig. 4. Dynamic experiment made after introducing water into a horizontal column showing a fixed slice. Ten sequential scans (right-side curve) in HU (absolute scale) as a function of time are shown. The number 1 represents points at the chosen slice.

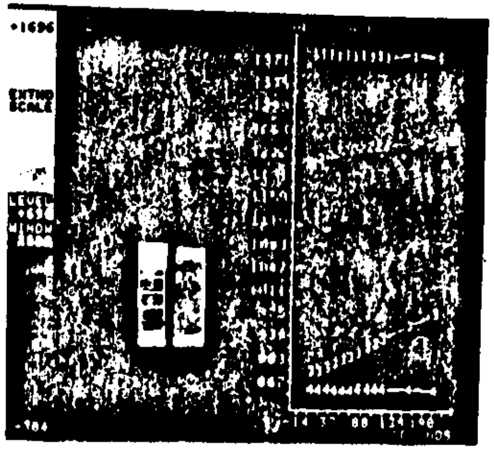


Fig. 5. Spatial and real-time (dynamic) measurement made with a vertical column (left side) at different time intervals. The attenuation was measured in different regions with the ROI (region of interest) boxes indicated by numbers 1, 2, 3 and 4 from top to bottom of the column. On the right side we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

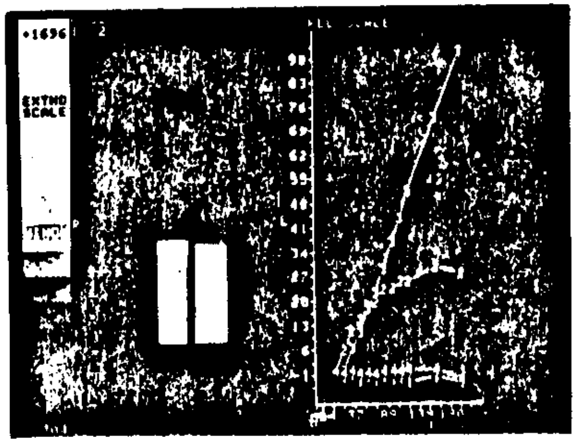


Fig. 6. With the same system described in Fig.5, we plotted the differences of water content for different regions 1, 2, 3 and 4 as a function of time. In region 3, for instance, we see a continual increase in water content with a more drastic relative change.

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.

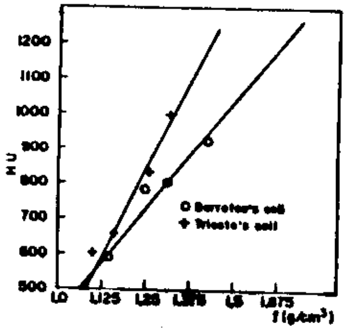


Fig.7. Linear calibration curve of Hounsfield Units (HU) as a function of dry bulk density (mass of dried soil per volume of dried soil). The average value of standard deviation is 32,5 HU.

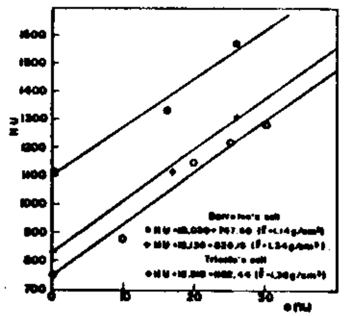


Fig.8. Linear calibration curve of Hounsfield Units (HU) as a function of water content (θ) (volume of water per volume of soil). The average bulk density was obtained from fig. 7, and the average standard deviation is 63,2 HU.

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$ 2×10^4, which is a factor of 10^2 lower than the commercial medical scanner. With the X-ray tube the cost increases to about US$ 5×10^4.

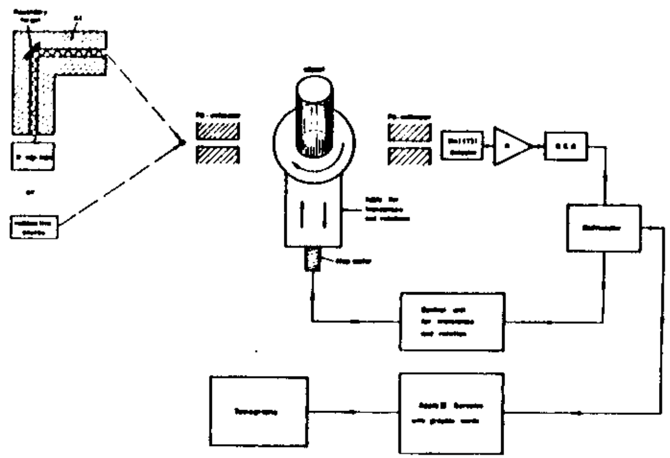


Fig. 9. Complete diagram of the CT miniscanner used to obtain tomographies of soil samples

(*) Cesareo et al, 1983

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 0,01g/cm^3 (Crestana et al, 1988).

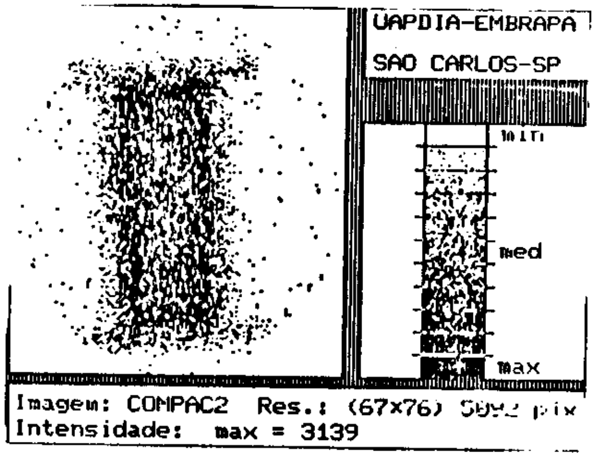


Fig. 10. Tomografic scanning of a retangular column of acrylic (26mm x 51mm) with soil inside not compacted

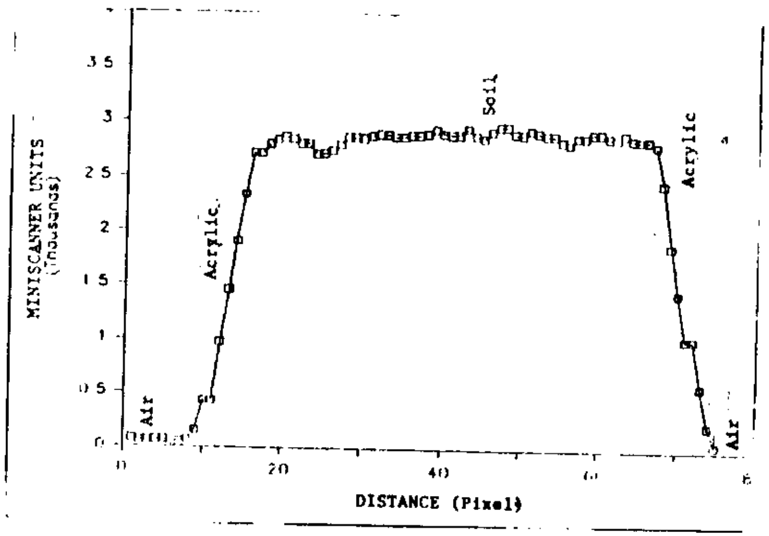


Fig. 11. Vertical profile of the column of Fig. 10, showing quantitativelly the densities of air, acrylic and soil

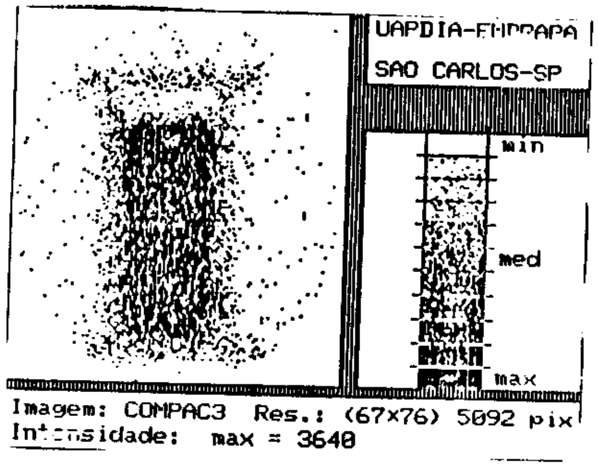


Fig. 12. The same column scanning of Fig. 10, after compaction of the soil on the top. The displacement of the top soil was about 4mm

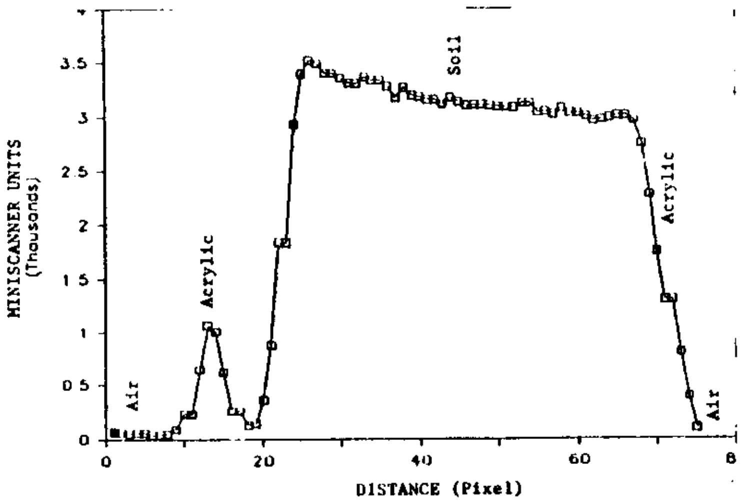


Fig. 13. Vertical Profile ofthe compacted column showed at Fig. 12. The gradient of soil distribution can be observed

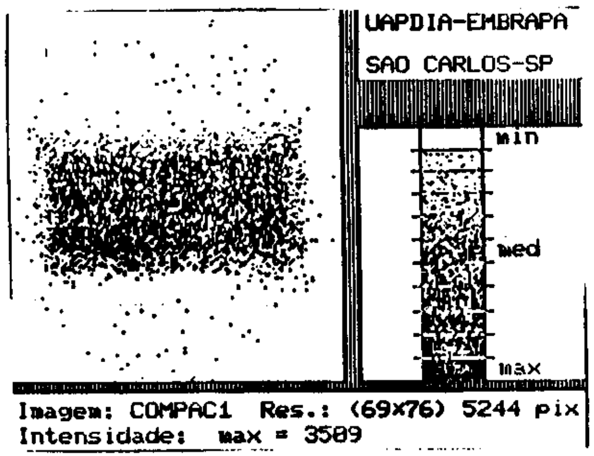


Fig. 14. Column scanning of soil,performed in lab simulating a "blade" of 3mm of dry compacted soil (density about 1.4g/cm³,near the center of the column) with a bulk density about 1.1g/cm³.

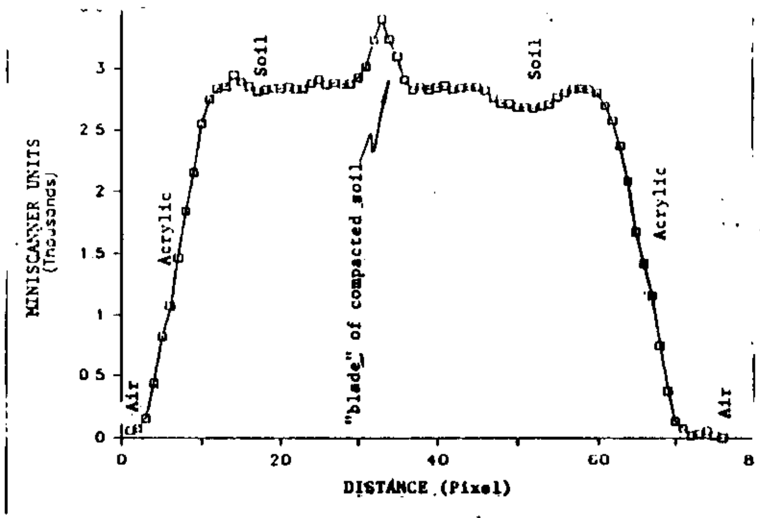


Fig. 15. Vertical Profile of the column of Fig. 14 clearly showing the "blade" of compacted soil near the center of the column.

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.

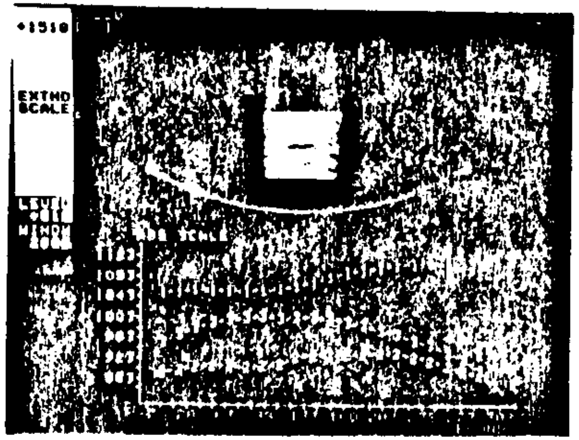


Fig. 16. Cylindrical column of 7,5cm height, 8,3cm of internal diameter submitted to a constant dripping flux of water equal to 4,8cm³/min. It is possible to observe from the indicated points 1, 2 and 3 the distribution of water in the horizontal plane in function of time, measured in H.U. and seconds.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

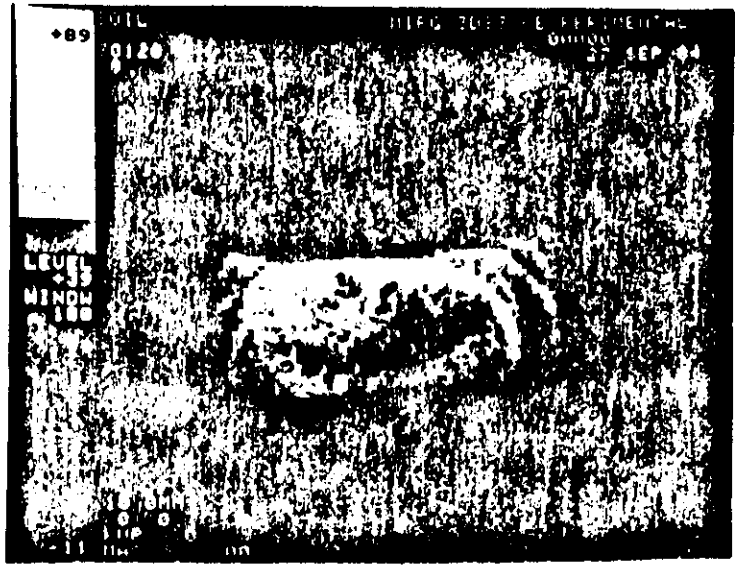


Fig. 17. View of tri-dimensional image reconstruction of water drainning in soil, simulating drip irrigation (horizontal and vertical infiltration) of the wetting front. It is possible to observe details of the boundaries (frontiers) of the water in the soil.

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.

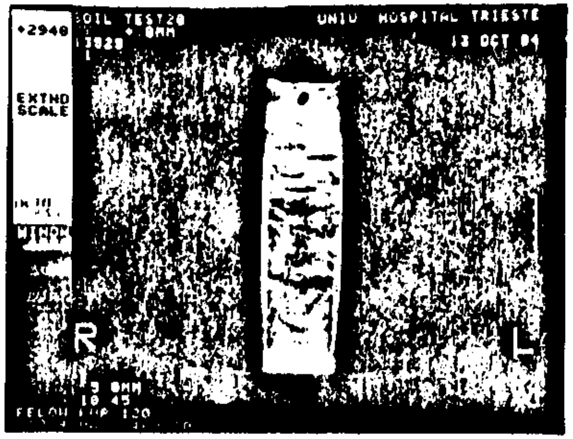


Fig. 18. Tomographic view of a cylindrical column of soil of 25cm height and 57cm internal diameter containning a grain of corn before germination. Notice the presence of inhomogeneities in the distribution of density of the column and the presence of water on the top and bottom of it.

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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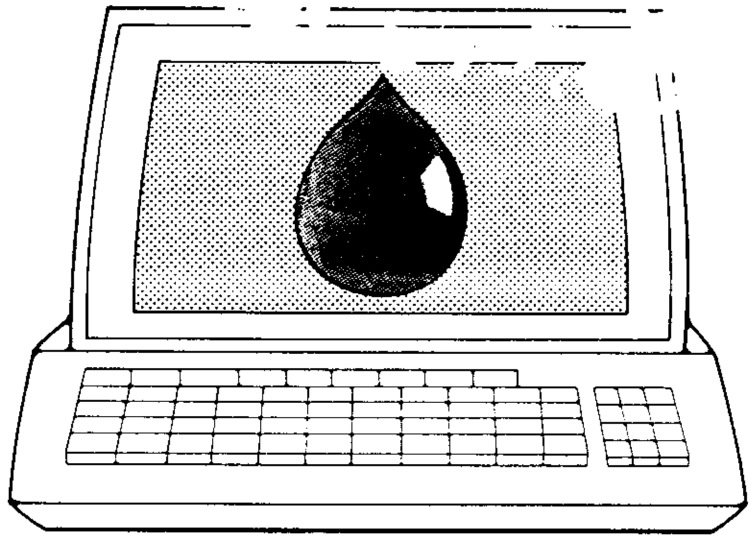

Inn of the Mountain Gods
Ruidoso NM May 22-25, 1988

College of Agriculture and Home Economics

SOIL RESEARCH OPPORTUNITIES USING X- AND γ-RAY COMPUTED TOMOGRAPHY TECHNIQUES[1]

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ABSTRACT

Some measurements with an inexpensive computed tomography (CT) miniscanner allowing the use of different radiation sources (isotopes or x-ray fluorescence) are presented. The use of differential CT technique as well as the use of tracers like iodine and thulium are introduced to improve the image resolution and contrast. As a preliminary study, a 2-dimensional image of a germinated seed of corn with roots and a 3-dimensional image of water draining in a column of soil, performed with a commercial medical CT, are also presented.

INTRODUCTION

The technique of computed-assisted tomography (CAT or only CT) has been successfully used as a new method for physical studies of soil water (Petrovic et al., 1982; Hainsworth and Aylmore, 1983; Crestana et al., 1985; Anderson et al., 1988). Using a third generation commercial medical CT belonging to the University of Trieste, Italy, we performed several scans and tomographies of soil samples. Essentially in the video of a CT scanner a plot of the attenuation coefficient (map of linear attenuation coefficients) is shown on a gray-level viewing system in Hounsfield Units (HU), defined as:

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

where μ_w and μ are respectively the linear attenuation coefficients of water and soil.

For the plotting, a relative scale is sometimes used, where μ_w is taken a reference level arbitrarily considered as zero. We demonstrated the appropriateness of CT to dynamic (real-time) studies of water motion in soil including measuring water velocities as high as 1.6 mm/s. Information on heterogeneities of bulk density, water content and related 3-D information as well as simultaneous spatial and time distributions was obtained using the appropriate CT techniques (Crestana et al., 1985).

Some semi-quantitative images simulating drip irrigation and seed germination, growth and water uptake by roots in a column of soil were also performed and are shown in Figures 2 and 3.

Simultaneously, it was also possible to design, build, and use in our laboratory an inexpensive CT miniscanner dedicated to soil science research (Crestana et al, 1986).

The miniscanner (Cruvinel, 1987), built at UAPDIA-EMBRAPA has similar characteristics of the miniscanner constructed at the University of Rome (Cesareo et al., 1983). The characteristics of the miniscanner are (Fig. 1):

- monoenergetic sources obtained both with radioisotopes and an x-ray tube with secondary target.
- an NaI (Tℓ)-x-ray detector - 1
- a rotation-translation system - 4,5,6,7
- a multichannel analyzer employed as multi-scaler or a quad counter-timer - 2,3
- a personal computer - Apple II with a reconstruction algorithm working in PASCAL 8,9.

The cost of 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. One of the main advantages of the miniscanner is the possibility of varying the monoenergetic

[1]Some partial results presented here were presented by one of the authors (SC) in Trieste, Italy, at ICTP, during the realization of the "College on Soil Physics" (November, 1987) and in São Carlos, Brazil at UAPDIA-EMBRAPA, during the realization of the "First Latin American College on Soil Physics" (January, 1988).

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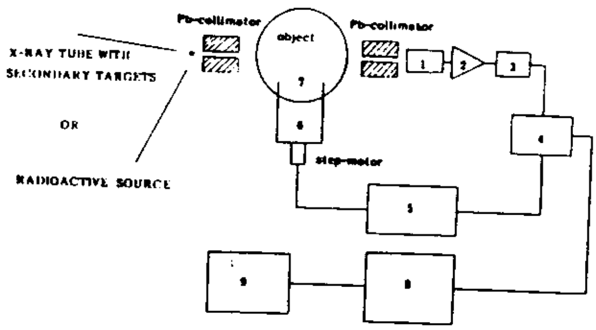

Figure 1. Complete diagram of the CT miniscanner used to obtain tomographies of soil samples.

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 30 Kev. 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 in several experiments with many soil samples having different bulk densities (ρ) and water contents (θ), we obtained the same linear behavior using the medical CT scanner that relates Hounsfield Units, ρ and θ (Crestana et al., 1986 and Cesareo et al, 1988).

SOME RESULTS FROM CT POSSIBILITING APPLICATIONS IN SOIL RESEARCH

We briefly present some 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 a 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 in the medical CT and differential CT (DCAT) in the miniscanner CT.

Dynamical and Tri-Dimensional Simulation of Drip Irrigation in a Column of Soil

The study of drip irrigation has a large practical interest. On the other hand, it is impossible to solve analytically Darcy's equation in three dimensions considering the specific boundary conditions of this problem (a complicating factor is the discrete source of water). Experimentally, using the usual techniques of soil physics, such as γ-ray absorption, it is not possible to assay the three dimensional nature of the wetting front, much less the two-dimensional horizontal plane. Due to these limitations we used a medical CT scanner to make the tomography of Figure 2 (Crestana, 1985). The image is a tri-dimensional instantaneous (transient state) slice reconstruction from a cylindrical

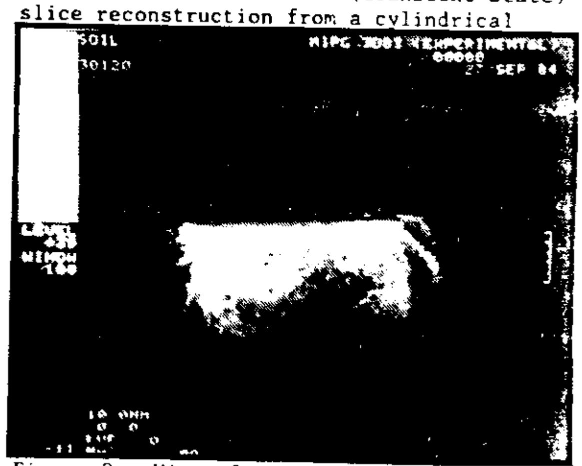

Figure 2. View of tri-dimensional image reconstruction of water draining in soil, simulating drip irrigation (horizontal and vertical infiltration) of the wetting front. It is possible to observe details of the wetting front in the soil.

column of soil (sandy loam soil) 7.5 cm high, 8.3 cm of internal diameter submitted to a constant dripping flux of pure water equal to 4.8 cm^3/min. Water distribution measurements in HU (as a function of time) was performed in both planes: horizontal and vertical.

From Figure 2 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, etc.

Other tomographies in addition to that given in Figure 2 for other views (angles, planes or positions) in a certain instant of time have been reconstructed.

Seed Germination, Growth and Uptake of Water by Roots

Figure 3 shows a partial bi-dimensional image of a cylindrical column of soil 25 cm height and 5.7 cm internal diameter. The presence of a germinated corn seed with roots as well as 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 as the uptake process of water and nutrients, the distribution and redistribution of water in the column (Crestana, 1985).

More recently, Hainsworth and Aylmore, 1986, studied quantitatively the water absorption from a radish root as a function of the water-root distance. Tollner et al., 1987, presented several results involving soil systems like plant, seeds and insects.

The fact that the CT method is noninvasive has advantages, allowing studies involving genetic selection of best seeds and plants, statistics of germination, evapotranspiration, motion of solutes, i.e., studies relating the soil-plant-water continuum.

Although the tomography shown in Figure 3 is in two dimensions, 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 (Crestana et al. 1985) or by means of several bi-dimensional tomographies taken at different times and angles.

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 HU to -15.97 HU. The standard deviation changed from 102.86 to 212.92 respectively. After germination, the seed manifests at least two distinct regions: one of mean density equal 115.53 HU and the other of mean density equal -186.04 HU. We know that negatives values imply the presence of air. In conclusion it is evident that the process of

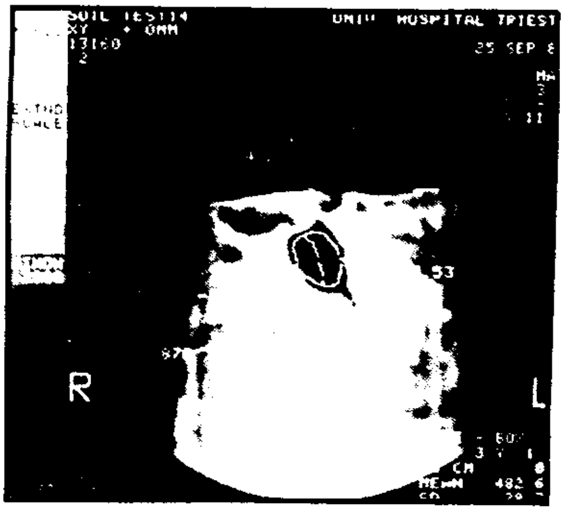

Figure 3. Tomographic bi-dimensional view of a corn seed germinated, where it is possible to observe clearly the measurements of soil water content (1112.38 HU), the densities of the roots (819 HU and 870 HU), the densities of the seed (115.53 HU and -186 HU) as well as that of the plant (482 HU).

germination of a seed occurs from a larger consumption of nutrients of a certain region of the seed, leading finally to a void filled with air. The high value of the standard deviation (higher than the value of itself measurement) is a demonstration of the high nonuniformity of the measured region, which is the case when an air-filled void exists. More detailed studies are needed to realize the great potential of the method.

Compaction and Distribution of Soil Using the CT miniscanner

The quantification of the physical parameters bulk density, water content and resistance of the soil to the penetration of plant roots (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 successive plowing.

We have recently applied the CT miniscanner to the study of samples collected from a soil submitted to successive plowing and heavy machinery in a sugar cane plantation.

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 possibiliting the accurate measurement of a "blade" about 3 millimeter-thick and density variations of about 0.01 g/cm^3 as can be seen in Figures 4 and 5.

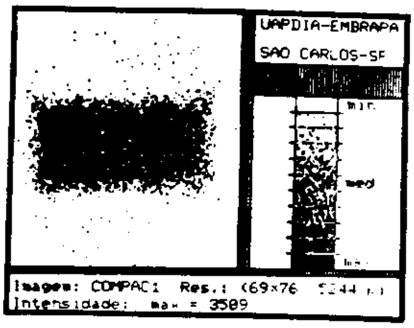

Figure 4. Column scanning of soil performed in lab simulating a "blade" of 3 mm of dry compacted soil (density about 1.4 g/cm^3, close to the center of the column) with a mean bulk density equal to 1.1 g/cm^3.

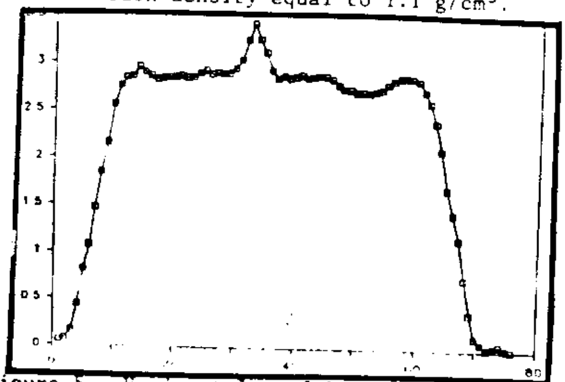

Figure 5. Horizontal profile of the column shown in Figure 4. The position of the "blade" of compacted soil is clearly evident from the magnitude of the peak having a value of 3.4 corresponding to the bulk density of 1.4 g/cm^3.

Using a calibration curve (HU as a function of density) for this soil it was possible to accurately calculate the density distribution in the profile and the position of the "blade". Non-disturbed soil samples (clods) collected in the field have been analyzed in our laboratory with the miniscanner (Vaz et al., 1988).

One of the advantages of the CT miniscanner over the γ-ray absorption apparatus is the possibility to perform 2- and 3-dimensional scans of soil samples (non-disturbed) independently of the geometry and the shape of each sample. More details can be seen in Figures 6 and 7.

Certainly, these results open new frontiers in research regarding compaction phenomena. Another application is analyzing and constructing homogeneous soil columns in the laboratory.

DCAT Measurements as a New Possibility in Soil Research

As can be seen in Figure 8, the attenuation coefficient of iodine versus energy exhibits a sharp discontinuity (K-photoelectric edge at

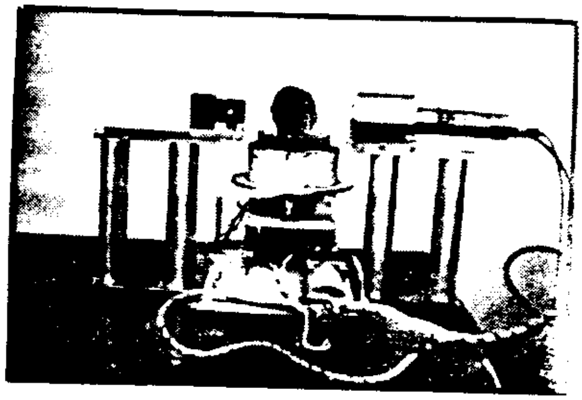

Figure 6. View of the CT miniscanner tomographic table. It is possible to observe a clod of soil (mean diameter about 15 cm) positioned between the columns (bearing the source and the detector system) and ready to be scanned.

Figure 7. Partial view of the image reconstruction system. In the microcomputer screen, a bi-dimensional image of the soil clod shown in Figure 6 can be observed.

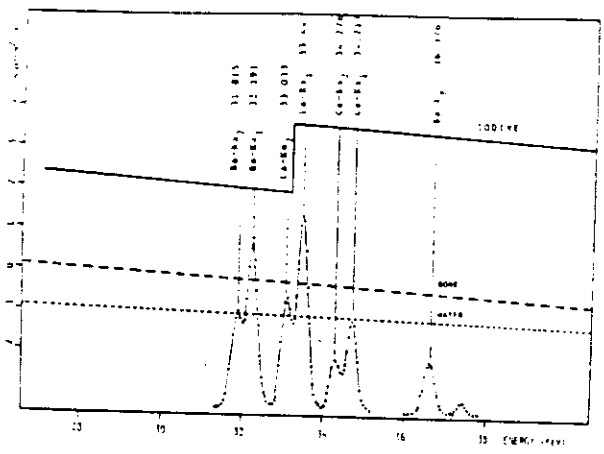

Figure 8. Mass attenuation coefficient of several elements plotted logarithmically as a function of energy. Particularly the sharp discontinuity of iodine at 33.17 Kev can be observed.

33.17 Kev). That discontinuity can be used for "amplifying" the presence of an element in any sample, when monoenergetic radiation is employed as close as possible to the referred discontinuity. That is the case of barium and cerium when used as secondary targets irradiated by the x-ray tube (Bremsstrahlung radiation) of the miniscanner. The lines K_{α} of barium units mean x-ray monoenergetic radiation equal to 32 Kev (just below the I discontinuity) and cerium units mean x-ray monoenergetic radiation equal to 34.5 Kev (just above the I discontinuity).

If two tomographies (or attenuation measurements) are carried out, then the difference between the two measurements is only sensitive to the presence of the iodine, which can be considered as a tracer. With this technique, called differential CAT (DCAT), the final image can be enhanced, improving, e.g. the contrast soil-water, seed-soil-water and possibiliting sensitive measurements and kinetic studies.

The principles of differential attenuation and DCAT have been tested several times in other areas, by using various "tracers" and therefore, various pairs of secondary targets (Fryar et al., 1987 and Cesareo, 1988).

Recent measurements carried out in our lab at EMBRAPA-Saõ Carlos, Brazil and Rome, Italy, at C.E.B. demonstrated the appropriateness of the use of DCAT for soil research.

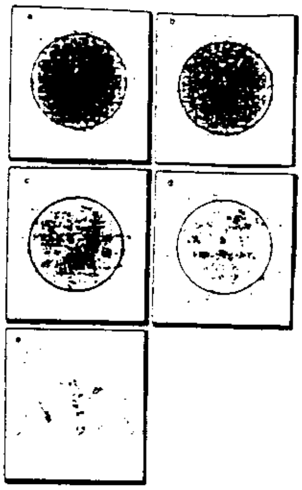

Figure 9. Tomographs at 34.5 Kev of a plexiglass cylinder containing air-dried soil (a) and soil plus 1 ml water with 8% iodine (b) and difference between tomograph (b) and tomograph (a) (c). Tomographs (d) and (e) refer to the differential tomographs of soil plus water-iodine distribution at time equals 80 minutes and time equals 24 hours after the injection of the solution in the soil sample.

As an example, Figure 9 shows five tomographies from successive scans. The scans were carried out in a plexiglass cylinder of 3 mm diameter filled with soil from Barretos-Brazil (fine sandy-loam soil), using Cerium (34.5 Kev) assecondary target after 1 ml of 8% I-solution was introduced into the air-dried soil.

Figure 9a is a tomographic image of the air-dried cylindrical soil sample. Figure 9b is a tomographic image scanned 15 minutes after the injection of iodine into the soil. Figure 9c shows the DCAT between Figures 9a and 9b at a mean time equal to 15 minutes. Figure 9d and 9e show the DCAT at 80 minutes and 24 hours, respectively.

As a consequence, the distribution of iodine can be observed and measured as a function of time. Furthermore, employing a radioactive source of americium (59.6 Kev energy) it was possible to find an element whose photoelectric edge lies just below the americium. This element is thulium which has a K-edge of 59.3 Kev. Several tomographies at different concentrations of thulium in the soil and water contents were performed, demonstrating the possibility of using thulium as a tracer, when an americium source is employed.

CONCLUSION

Though more detailed studies are needed, we can briefly conclude that the use of appropriate CT scanners, sources, tracers and the DCAT technique provide unexcelled opportunities to study in 2- and 3-D basic and applied steady and time dependent soil processes. Soil compaction, absorption and distribution of soil water, movement of solutes in the soil and water uptake by plants as well as related problems involving seed germination, growth of roots and soil crusting are all capable of being studied inexpensively with the use of a CT miniscanner.

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X- AND γ-RAY, NMR AND ULTRASONIC TOMOGRAPHY: ITS CAPABILITIES AND LIMITATIONS FOR STUDYING SOIL-WATER-PLANT RELATED PHYSICAL PROCESSES

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Important and challenging research problems such as ground-water contamination, miscible and immiscible displacement of nutrients in the presence of roots, preferential flow of pollutants in fractured porous media, seedling in cracking and swelling soils, raindrop impact, soil tillage, wetting-drying or freezing-thawing cycles are some real examples of many coupled and time-dependent processes occurring in the soil (Nielsen et al., 1986). Considering these processes by employing the conventional techniques such as neutron-probe, gravimetry, direct γ-ray transmission, tracers and others is practically impossible in either the laboratory or the field.

In the last few years, with the advent of new methodologies coming from different areas like Physics, Space Science, Cybernetics, Geophysics and Medicine, some experimental techniques have been improved or proposed for the first time in the domain of soil or water resources research. Among them we can cite: neutron radiography (Brenizer et al., 1987), seismography (Birkelo et al., 1987), remote sensing (Froidevaux, 1986), magnetic susceptibility (Martin et al., 1987) dielectric conductivity (Topp, 1987), resistivity (Kean et al., 1987), and laser (Huang et al., 1988).

In our laboratory we have already successfully employed the X- and γ-ray computerized tomography (CT) and recently started to apply nuclear magnetic resonance (NMR) and ultra-sound imaging in soil investigations.

1) Soil-water ultrasonic tomography: preliminary experiments

Using a medical image ultra-sound equipment (Ultramark-8-ATL), the penetration of ultra-sound waves in different soil samples at several water contents were tested. Four probes (transducers) available from the equipment employing 3,5; 5; 7, 5 and 10 MHZ frequency were experimented. As the results have been demonstrated the ultra-sound penetration in the soil in the employed frequency range is practically zero. The ideal frequency to perform ultra-sound images in soil samples is in the range of a few Kilohertz. Nevertheless the spatial image resolution is very poor, as recently confirmed by Lo et al., 1988 using a laboratory ultra-sound miniscanner.

2) Soil-water-plant magnetic resonance imaging

The ideal potential technique to measure water content in the soil and to observe soil systems (plants, roots, and organisms) would be NMR due to the high concentration of H+ protons in these systems. Recently using the UCD-NMR-CSI-2

spectrometer we have achieved some encouraging results employing sand samples. It was possible to qualitatively observe the water content distribution in a saturated sand sample and to observe the root distribution of a bean seedling.

Our preliminary results using soil samples (sand, silt loam and clay soils) yielded images sufficiently poor (broad peak signals) to render inconclusive interpretations. Bottomley et al., 1986; Anderson and Gantzer, 1987; and Tollner et al., 1987 also reported problems concerning consistent results analyzing real soil NMR imaging. The presence of paramagnetic and ferromagnetic materials in the soil (or porous medium), producing local heterogeneities, disturbing the image and limiting its spatial resolution is one of the constraints of the soil-water-plant NMR imaging. Another limitation is the short NMR decay time (and complex Free Induction Decay-FID) not allowing its detection by the NMR spectrometer when the conventionals spin-echo image sequences are employed (spin-echo time equal to or less than 15 ms. Moreover, the NMR signal is not only sensitive to the water content of the sample but it is also sensitive to the porosity of the sample. Because of this fact, we can anticipate that a simple relationship involving NMR signal and the soil-water content of the sample is practically difficult or even impossible.

3) Soil-water-plant X- and γ-ray CT imaging

We have obtained results showing the appropriateness of CT to measure soil bulk density, soil water content in 2- and 3-dimensions, as well as related measurements for transient flow (Crestana, 1985; Crestana et al., 1985, 1988a). Three-dimensional measurement of transient flow from drip irrigation in a soil column and seed germination growth and uptake of water by roots (Crestana, 1985; Hainsworth and Aylmore, 1986; and Crestana et al., 1988a) has been achieved. Several results involving soil systems like plant, seeds, insects and cone penetrometer interactions have also been presented (Tollner et al., 1987). Using a third-generation commercial X-ray computerized tomograph, several non-swelling soil columns of different initial water contents and bulk densities were scanned to obtain 2-dimensional images (Crestana et al., 1988b). The infiltration process was capable of being monitored every 6·7s. Water content distribution as a function of position and time allowed the calculation of the soil-water diffusivity. A comparison of the data from infiltration and the solution of Richards' equation has demonstrated the utility of the method.

Two limitations of the CT technique exist: the complexity and the high cost of commercial tomographs. We were able to design and build for the first time a simple and inexpensive X- and γ-ray CT micro-scanner dedicated to soil science investigations (Crestana, 1985; Crestana et al., 1986, 1988a; Cruvinel, 1987; and Cesareo et al., 1988). Subsequently, we have successfully used the instrument in a variety of measurements described briefly in the following paragraph.

Undisturbed soil clods submitted to successive plowing processes in the field were scanned using the CT micro-scanner (Vaz et al., 1988). It was possible to observe and measure a thin compacted layer present in the clods. One of the advantages of the CT micro-scanner over the γ-ray absorption apparatus is the possibility to perform 2- and 3-dimensional scans of soil samples (non-disturbed) independent of the geometry and the shape of each sample.

Our CT micro-scanner allows the use of several beam energies and different radiation sources stemming from different isotopes or X-ray fluorescence. We have demonstrated that the use of 30 to 40 Kev is the best energy for water-content resolution rather than that of 60 Kev supplied commercially. The technique of differential tomography (DCAT) was also employed to quantify water draining in soil, taking advantage of the photoelectric discontinuity of Iodine when we employed the radiation of Barium (32 Kev) or Cerium (34.5 Kev) as secondary targets of an X-ray source. The use of Thulium (59.3 Kev) in the soil as a tracer allows us to enhance the soil-water images when we employed a source of Americium (59.6 Kev).

Briefly concluding, we can affirm that some techniques using ultra-sound, neutrons, microwaves, laser and others mentioned above are encouraging new experimental possibilities in soil-water-plant investigations, still depend upon future improvements. On the other hand, though more X- and γ-ray CT research is necessary (Anderson et al., 1988) we can also affirm that fluorescent radiation, differential tomography and new tracers are already an available opportunity for imaging real soils. Undisturbed, and high resolution two- and three-dimensional analyses of a 2- or 3-phase system in a porous material such as transport of water and solutes within the soil is a particular example.

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