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COMPUTED TOMOGRAPHIC ANALYSIS OF SOIL STRUCTURE

by

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ABSTRACT

The objective of this study is to investigate the ability and limitation of CT scanner for determination of soil structural properties.

Some researchers have demonstrated the possibility of using X-ray transmission Computed Tomographic (CT) scanning for determination of bulk density and moisture content in soil analysis.

This scanner is an advanced tool in diagnostic radiology used to obtain a nondestructive cross-sectional representation of the human body.
To date no experimental technique has been capable of directly and repetitively measuring spatial variation of soil structure.

Using a third-generation CT scanner, some experiments related to soil structural analysis have been conducted and the result showed that CT Scanner can be used to determine structural properties of soil. The machine was found to respond in a positive linear fashion to increasing bulk density.
The relationship between CT number and moisture content was linear over the range of moisture content evaluated.

PETROVIC et al mentioned that CT scanner is a potentially promising tool for research in the areas of compaction, soil management, and cultivation.
It was concluded that the CT scanner can be used to determine soil physical condition (soil structure) with good three-dimensional spatial resolution.

INTRODUCTION

Soils in their natural condition have at least some of their individual particle, clustered into clods and crumbs, or peds, through them being bonded together by the clay particles present in the

soil; and the size distribution of the pore spaces between them, determine the soil structure.[13]
The structure of a soil implies an arrangement of the particles into a certain structural pattern, including pore space.

Soil structure can be evaluated by determing the extent of aggregation, the stability of the aggregates, and the nature of pore space that can be changed by tillage practice and cropping system.

Soil structural properties have been evaluated by various techniques. The ideal technique for monitoring soil structure is nondestructive, sensitive, rapid, and able to resolve differences within the object in detail.

For instance in the case of bulk density, current methods employ direct sampling by soil cores or clods ; in situ radiation methods e. g. single and dual beam gamma ray attenuation measurements ; neutron scattering analysis, and to a lesser extent by the analysis of shear and compressional wave propagation through column samples.[12]
Core and clod techniques obtain the gross average density value of the sample without or with a little information about internal variation. The discovery of gamma radiation has made it possible to measure bulk density in situ.
However all the current techniques lack the precision to detect three dimensional in a nondestructive manner.
Previous work of PETROVIC et al[11] showed the possibility of using X-ray transmission, computed tomography scanning for bulk density analysis in soil. Presently, studies are underway to determine other application of CT scanner for soil analysis.

The advantage of the CT scanner is providing high quality cross-sectional images of tested sample without destroying it ; facilitates three dimensional observation of internal structure ; inform dimension, shape, internal defects, density, and component distributions.[1],[2],[3],[15]

The objective of the research reported here is to investigate the ability and limitation of CT scanner for determination of soil structural properties.

MATERIALS AND METHODS

Instrumentation

Until 1970 problem existed in diagnostic radiology in seeking to obtain non-destructive three-dimensional representation of human brain. This problem has been essentially overcome by Hounsfield in 1972, who developed the technique known as computer-assisted tomography. Actually the first usable CT scanner system was developed in 1969 by Hounsfield and unit became available commercially in 1972.

The advantage of the CT scanner over other radiographic processes is that a cross section of linear attenuation coefficient (μ) is obtined with a recordable radiation attenuation differences as low as 0.5% and a two-dimensional resolution of 2 ㎟ or less. This system can be used for inspection of such material as ceramics, plastics, rubber, and aluminum.

A sample is placed on either of two tables located between the 140 kV ; 300 mA X-ray tube and 512 channel Xe-gas detector. The diagram of the apparatus of CT scanner schematically shown in **Figure 1** and **Figure 2.** It is exposed to pulsed X-ray from 600 directions while the table is

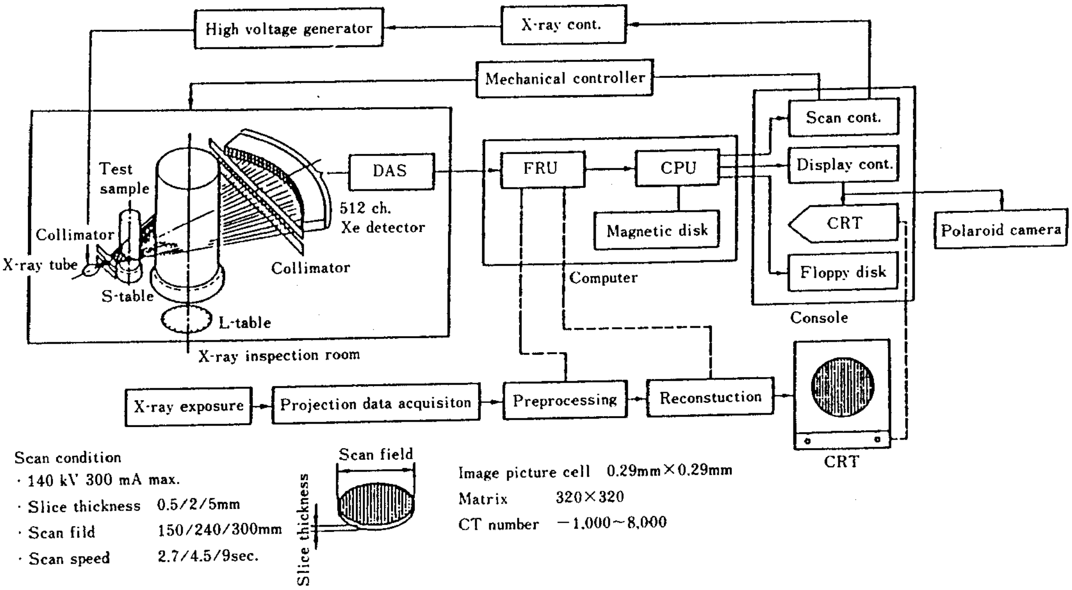

Fig. 1 Principle and System Constitution of CT Scanner

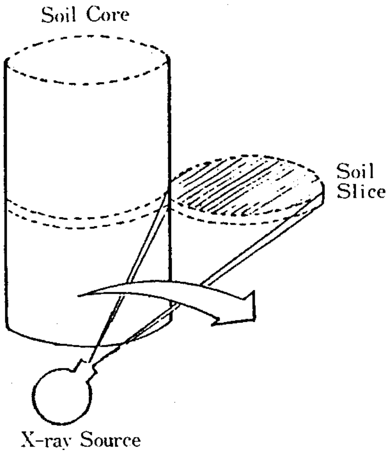

Fig. 2 The X-ray CT Scanner Slices an Object (Soil Core) Using an X-ray.

rotated. The transmitted X-rays are detected by the detector to acquire data. The data are then sent from the data acquisition system (DAS) to the fast reconstruction unit (FRU), where they receive sensitivity correction and logarithmic conversion. The result are then transmitted to CPU and stored in an external memory device. These data are returned from CPU to the FRU where the tomographic image is reconstructed. The reconstructed tomogram displayed on the CRT is in a 320 x 320 matrix configuration.

The system consists of an X-ray tube, a sample table and a detector array installed in an X-ray inspection room, and an image processing unit (computer cabinet), a control and display unit (console), and a polaroid photographic unit.

An industrial type TOSCANER 3200 housed at TOSHIBA CAT center is used for this study. This scanner is a third-generation mode with the specification shown below (**Table. 1**).

Table 1 Specification of TOSCANER−3200

Item	Specification
Scan system	pulsed X-ray 140 kV Xe 512 ch. detector
Penetrability	equivalent to d=150 mm aluminum
Minimum pixel size for scan	300 μm
Inspection time	15 seconds
Scan field	d=150／240／300 mm
Slice thickness	0.5／2／5 mm
Slice position variable	600 mm

Theory

Some articles based on BROOKS and DI CHIRO, 1975, 1976 ; MC CULLOGH and PAYNE, 1977, in ANDERSON[4] explained the theory used by CT Scanner and a brief discussion of the theory is reviewed in this paper.

Basically, the attenuation of a X-ray beam of Intensity Io (initial intensity), as a result of passing through the subject of thickness D, yield a transmitted intensity I is given by

$$I = Io \exp(-\mu D) \qquad \cdots\cdots\cdots\cdots\cdots (1)$$

where μ is the linear attenuation coefficient that mainly depends upon the electron density of the test matertial, the energy of radiation, and the packing density.

As soil are almost not homogeneous then the attenuation coefficient will also be variable.

For the case where μ represent the linaer attenuation coefficient of wet soil, the equation can be expanded to

$$\mu_{wet} = \rho_b \ \mu_s + \theta v \ \mu_w \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

where ρ_b is bulk density of solid soil, μ_s and μ_w are the mass attenuation coefficient ($cm^2 \cdot g^{-1}$) for soil and water respectively and θv is volume fraction of water or volumetric wetness.

For oven-dry soil $\theta v = 0$ and

$$\mu_{dry} = \mu_s \ \rho_b \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Combining equation 2 and 3,

$$\theta v = (\mu_{wet} - \mu_{dry}) / \mu_w \qquad \cdots\cdots\cdots\cdots\cdots (4)$$

As mentioned before the result of image reconstruction initially is to produce an array of numbers representing the value of μ for each pixel. However, in commercial CT Scanner it has been found to be more convenient to express the value of μ as Hounsfield Unit (H) an international standardized number scale or CT number which is defined by

$$H \quad \frac{\mu\ (x,\ y) - \mu_{wa}}{\mu_{wa}} \cdot K \cdots\cdots\cdots\cdots (5)$$

where H = Hounsfield Unit (CT number)
$\mu\ (x,\ y)$ = linear attenuation coefficient of test material
μ_{wa} = linear attenuation coefficient of water
K = constant factor defined 1000

Values of linear attenuation coefficient and CT number of some materials are shown in **Table. 2.**

Table 2 Linear Attenuation Coefficient and CT number of Some Materials*)

Material	μ	$\mu o = \mu \rho$	CT Number
Air	0.155	0.279×10^{-4}	−1000
Water	0.171	$0.171 \times 1 = 0.171$	0
Concrete	0.169	$0.169 \times 2.3 = 0.389$	1275
Aluminum	0.169	$0.169 \times 2.69 = 0.455$	1661
Iron	0.370	$0.370 \times 7.86 = 2.980$	16006
Copper	0.453	$0.453 \times 8.93 = 4.045$	22635
Tin	1.65	$1.65 \times 7.28 = 12.012$	69246
Lead	5.46	$5.46 \times 11.34 = 61.916$	361082

*) X-ray 100KeV

Experimental

1. Moisture Content

For the above case the following work were conducted : (i) the experiment of wetting and (ii) the experiment of drainage using soil column.
A 60 cm tall by 10 cm in diameter PVC (Polyvinyl Chloride) column was uniformly packed with mixtures of sand and clay (10 % by weight). The bottom part of the column was provided with 4 small tubes as water inlet for the experiment of wetting and as water outlet for the experiment of drainage, each connected with a plastic tube. Each end of the plastic tubes were then connected to a water tank.

For the experiment of wetting, the water was expected to flow into the plastic tubing and then into the soil for about 6 days. The column was then placed in the vertical position on the turn table and scanned. Scans were made at every other 1.0 cm slice along the column. As the water was coming from the bottom, the bottom part of the column was expected to have higher moisture content than the top part.

For the experiment of drainage the water was added to the soil and mixed uniformly then put into the column. The water was then drained out through the plastic tubes to water tank which was placed under the column.
The moisture content of the soil in the column after wetting and draining were determined gravimetrically by taking soil from each 1 cm after the scanning process had been completed.

2. Particle size

This experiment consisted of 3 sub experiments. Samples for the first and the second experiment were collected from Ap horizon of Kanto loam.

The first experiment involed 6 samples of known moisture content ranging from 36.5 % db to 38.8 % db. The soil was passed through 5 level sieves of 4.0, 2.0, 1.0, 0.5, 0.1 mm, packed into 50 mm in diameter by 65 mm high plastic containers and scanned. After scanning the samples were then oven-dried at 110 ℃ for about 24 hours then the moisture content and bulk density were measured.

The second experiment involved 24 samples of 4 levels of moisture content. Soils passed through 6 level sieves of 10, 4, 2, 1, 0.5, and 0.25 mm, filled uniformly into 50 mm in diameter by 65 mm tall plastic containers and then scanned. Each sample was equilibrated at a given moisture content before sieving. Scan was made at one cross sectional slice for each sample. After scanning samples were then oven-dried at 110 ℃ for about 24 hours.

In the third experiment, sand was used instead of soil. The sand was sieved at 5 level sieves of 4, 2, 1, 0.5, and 0.25 mm, filled uniformly into 50 mm in diameter by 65 mm high plastic containers. Some amount of water was added to obtain 3 moisture levels, dry, wet, and saturated. The samples were then scanned.

RESULTS AND DISCUSSIONS

Moisture Content

The relationship between CT number and moisture content (volume wetness, θv) for the experiment of wetting is shown in **Figure 3** and for the experiment of drainage is shown in **Figure 4.** Both functions are linear over the range of volume wetness evaluated. The higher the moisture content the higher the CT number.

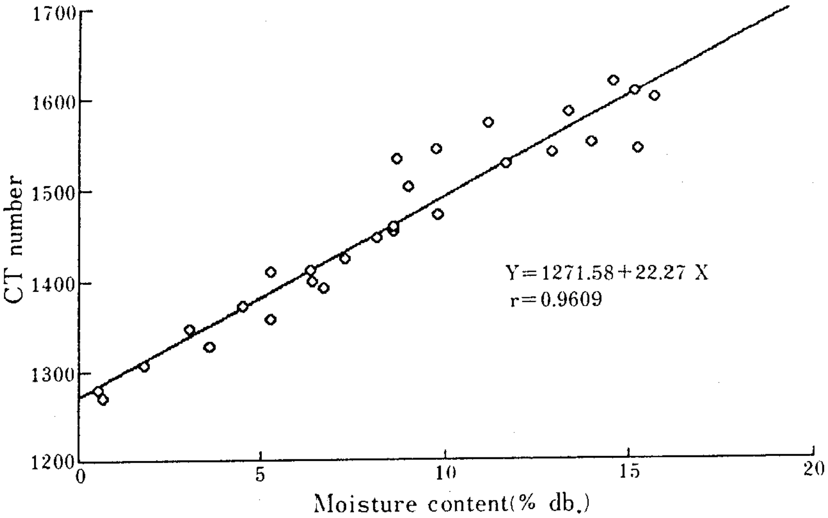

Fig. 3 The Relationship Between CT number and Moisture Content (Sand + 10% Clay ; Wetted)

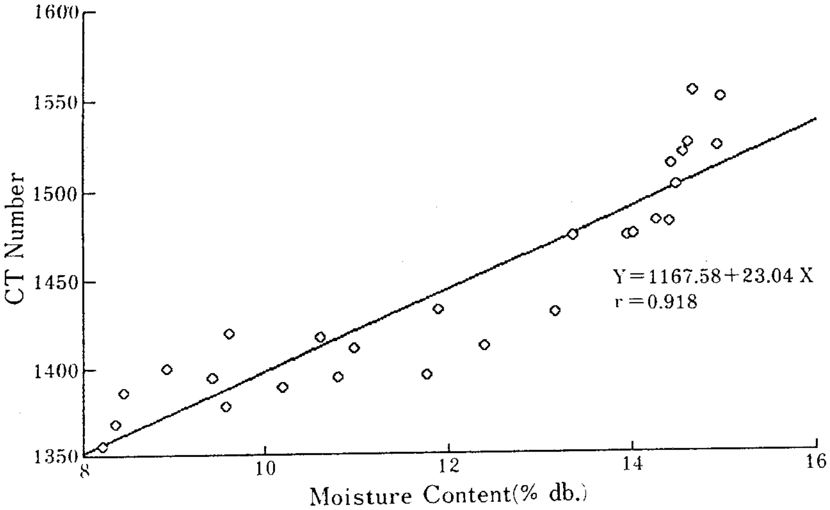

Fig. 4 The Relationship Between CT Number and Moisture Content (Sand + 10% Clay ; drained)

As mentioned in the theory that CT number (X-ray absorption coefficient) primarily depends upon the electron density of test material. The electron density of soil having high moisture content is higher than the electron density of the soil of lower moisture content.

For the wet soil, the pore space between solid particle is occupied by water instead of air, and the water has higher mass attenuation (0. 171) than that of air (0.279×10^{-4}) or as for the unit of CT number, water has CT number 0 while air has CT number -1000. The moisture content of both samples were varied along the 60 cm tall PVC cylinder. For the experiment of wetting, the moisture content ranged from 0. 4 % db. to 15. 7 % db. and CT number ranged from 1272 to 1620. For the experiment of drainage, soil was mixed with water before putting into the cylinder. The minimum moisture content was 8. 2 % db. and the maximum was 15. 0 % db, while the CT number ranged from 1356 to 1554.

Regression analysis for both experiments showed that the relationship between moisture content and CT number was linear and the r value was 0. 961 for the experiment of wetting and 0. 918 for the experiment of drainage. BROWN et al[6] working with 3 porous phenolic foams as test materials instead of soil, showed that CT number of dry foam is significantly different from saturated foam, and the water content distributions were successfully detected with good resolution on the CT image.
CT Image of the soil sample (sand + 10 % clay) in a PVC column for the experiment of wetting is represented in **Figure 5.** The histogram was obtained from 2 mm slice thickness, which reflect water content of the soil. The darker region of the circle in Figure 5 shows lower water content than the surrounding lighter colored region.

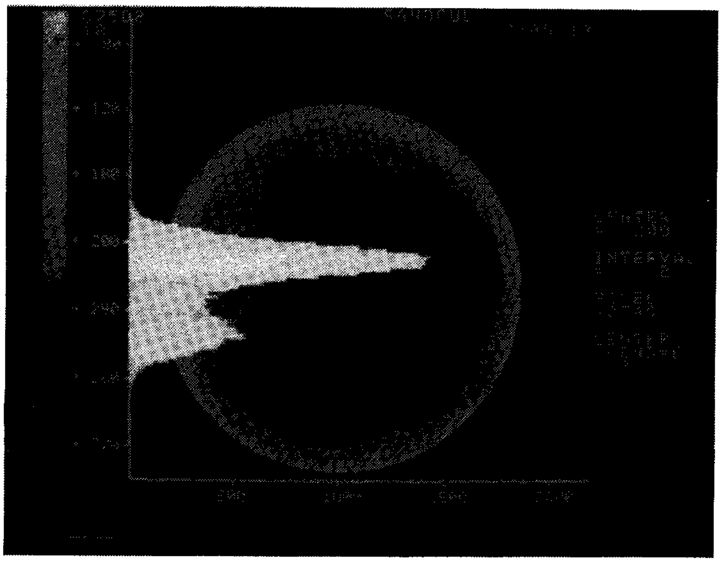

Fig. 5 CT Image of Soil Sample (Sand + 10% Clay). The Grey Scale in CT Number Units, ranges from Black (low moisture content) to White (almost saturated).

Comparisom of CT vs. gravimetric determined moisture content (volume wetness) as a function of depth of column for both treatments are shown in **Figure 6** and **Figure 7**. The mean differences in volume wetness, as measured by the two methods were as great as 0. 038 cm^3/cm^3 for the experiment of wetting and 0. 039 cm^3/cm^3 for the experiment of drainage.

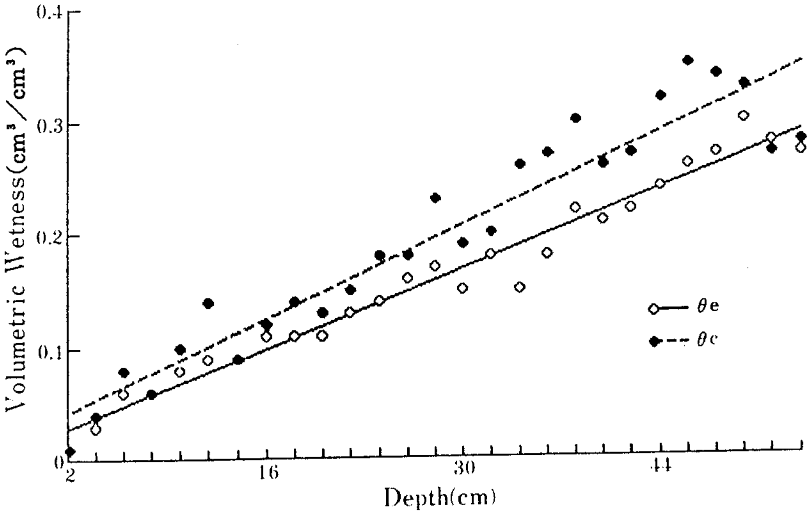

Fig. 6 Volume Wetness Determined Gravimetrically (θe)
and Calculated Using CT Scanner (θc)
(sand + 10% Clay ; wetted)

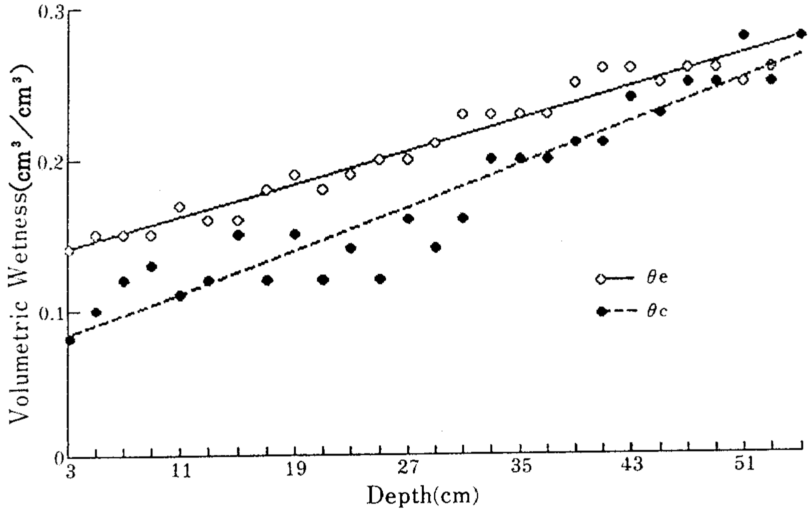

Fig. 7 Volume Wetness Determined Gravimetrically (θe)
and Calculated Using CT Scanner (θc)
(sand + 10% Clay ; drained)

For the experiment of wetting, the CT analysis tended to overestimate the gravimetric values, and the difference increases as the moisture content increases. In contrast with the experiment of drainage, the CT analysis tended to underestimate the gravimetric values and the difference decreases as the moisture content increases.

HAINSWORTH and AYLMORE[10] found a similar tendency with the experiment of wetting that calculated values of θv are higher than measured values for high moisture content and they mentioned that this differences arise from what is known as the Gibbs phenomenon, where large changes in μ from high density to low density areas cause the calculated values in the low density area to be less than the actual μ in that region.
ANDERSON et al[4] found the similar tendency for bulk density in the relationship between μ and volume wetness.

The different tendency of volume wetness observed for the experiment of wetting and the experiment of drainage may be attributed to the sample differences, since we used different kind of sand although the content of clay is 10 % by weight for both.
It is also shown that the slope of the regression line for both experiments are different. It is not known why this occurs because the theory says that the two lines should be parallel.

CRESTANA et al[8]obtained non parallel slopes for two textured soils of the system expressed in Hounsfield Unit (HU) as a function of dry bulk density but obtained parallel slopes in function of volume wetness.
Although there are some difficulties found in this experiment, result from this study indicate that CT Scanner can nondestructively measure volume wetness in soil media.

Particle Size Determination

Linear attenuation coefficient (μ) is function of the effective atomic number of the absorbing material when density and photon energy are held constant.
High contrast resolution is the ability to distinguish two object from one another that differ greatly in density. This is analogous to differentiating between solid particle and air-filled pore. Differentiating among zones of material that have only a small difference in μ (low contrast) is valuable in soil research.

The first experiment of particle size analysis involved 5 samples of known moisture content, passed through 5 level sieves and the smallest size was 0. 25 mm. We found that the CT scanner clearly detected soil particle which passed through 4, and 2 mm opening sieves. Soil particles smaller than 1 mm were slightly visible but not separated. CT numbers of all the samples were almost the same, and ranged from 122 to 148. This may be due to the equality of the porosity and the bulk density of these samples. However, there was a tendency that the larger the particle size the larger the standard deviation.
Measured data for selected physical properties and the CT number of the samples are given in **Table 3**, and the CT image of the test object is represented in Figure 8.

Table 3 Selected Physical Properties and CT Number of Sample

Particle (mm)	Moisture Content (% db.)	Porosity (%)	CT Number –	Standard Deviation
NS < 0.25	36.5	81.1	145.64	28.73
NS < 0.50	36.6	83.7	123.54	55.08
NS < 1.00	38.3	85.3	131.13	95.59
NS < 2.00	38.8	75.1	121.82	264.81
NS < 4.00	37.8	85.9	147.46	561.17

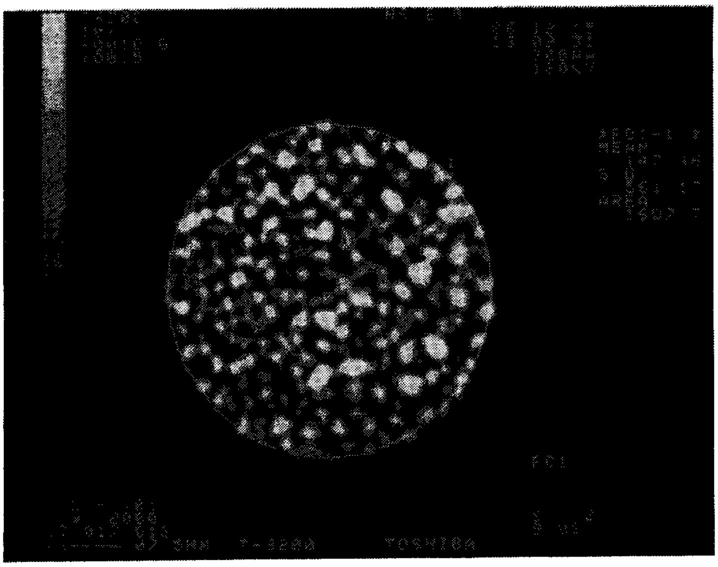

Fig. 8 CT Image of Soil Sample of 2 - 4 mm Particle Diameter

In the second experiment, soils of 4 level moisture contents passed through 6 level sieves. Measured data are shown in **Figure 9**. For the same particle size, the CT number tended to increase as the moisture content increased. As in the previous study, large particle size resulted in high standard deviation.

Standard deviation cited refers to the actual variation in mass attenuation coefficient of the sample. A region of interest (ROI) consists of many pixels. The average CT number of a region was obtained from CT number of pixel. Therefore a great difference in CT pixel and the mean CT of ROI result in larger standard deviation of that ROI.

Basic theory of standard deviation will explain how the particle size influence the standard deviation of the sample evaluated.

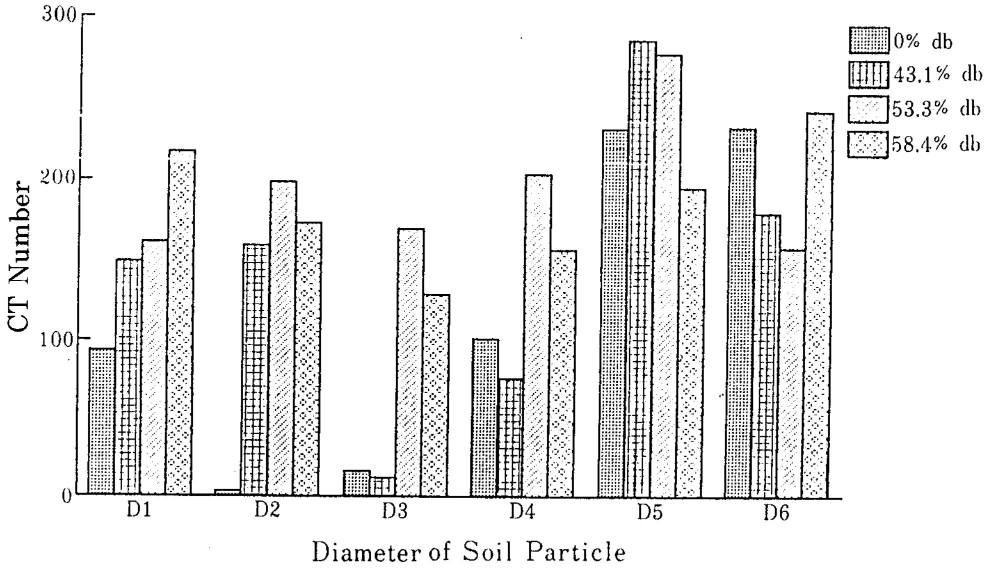

Fig. 9 Relationship Between Soil Particle Size and CT Number of Different Moisture Content D1 (4−10 mm), D2 (2−4 mm), D3 (1−2 mm), D4 (0.5−1 mm), D5 (0.25−0.5 mm), and D6 (0.1−0.25 mm).

Table 4 Moisture Content, CT Number and Standard Deviation of Samples

Treatment	Moisture Content (% db.)	CT Number —	Standard Deviation
DRY			
D1	0.0	1061.88	916.64
D2	0.0	1035.56	412.24
D3	0.0	968.28	172.04
D4	0.0	800.60	69.80
D5	0.0	1025.16	53.32
WET			
D1	31.3	1431.68	743.36
D2	26.4	1475.20	358.92
D3	26.7	1360.00	185.88
D4	23.5	1302.40	110.44
D5	27.5	1417.72	103.00
SAT			
D1	25.1	1528.76	610.96
D2	22.2	1499.84	329.80
D3	22.1	1572.56	167.08
D4	24.0	1519.52	88.16
D5	19.5	1648.48	77.00

D1 (2−4mm), D2 (2−4mm), D3 (0.5−1mm), D4 (0.25−0.5mm), D5 (0.1−0.25mm)

$$SD = \sqrt{\frac{\sum_{k=1}^{n} (X_k - \bar{X})^2}{n}} \quad \cdots\cdots\cdots\cdots (6)$$

where X_k = CT number of pixel
$\bar{X}$ = Mean CT number of Region of Interest (ROI)
n = Number of pixels

By considering the theory, it can simply be understood that sample of large particle size in a certain ROI, the pore space relatively largely occupied by either water or air which have low attenuation coefficient compared to that of solid fraction. This can cause a large difference in CT pixel and mean CT of the region. While for small particle size, in the same ROI, solid particles are close to each other and the pore space is not so wide as in large particle sample. As a result CT pixels are not varied greatly and are close to the mean value of ROI.

Figure 10 shows the tendency of standard deviation due to the particle size of the soil sample.

The third experiment was a comparative study, where sand was used as a test material. Some amount of water was added to obtain 3 moisture levels; dry, wet, and saturated.
Measured data are given in **Table 4** and **Figure 11**. The CT number increases as the moisture content increases. As in the soil sample, the sand sample showed similar tendency in both the CT number and the standard deviation.

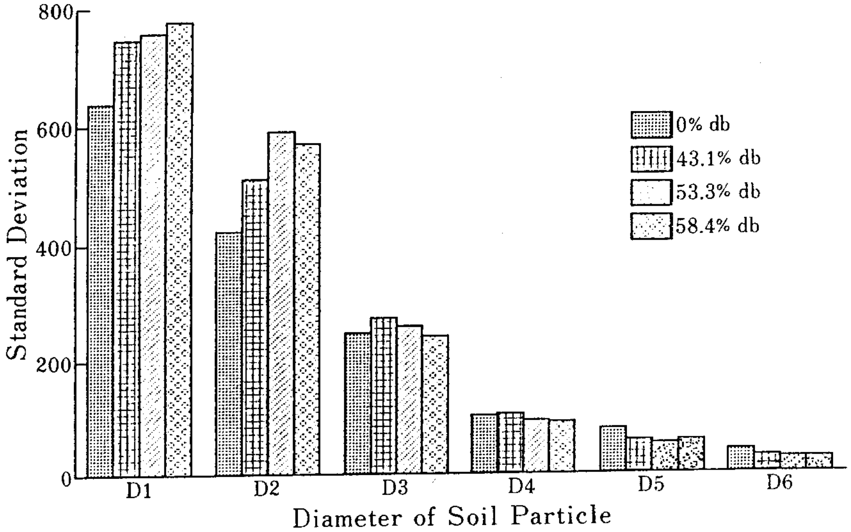

Fig. 10 The Relationship Between Standard Deviation and Diameter of Soil Particle D1 (4−10 mm), D2 (2−4 mm), D3 (1−2 mm), D4 (0.5−1 mm), D5 (0.25−0.5 mm), and D6 (0.1−0.25 mm).

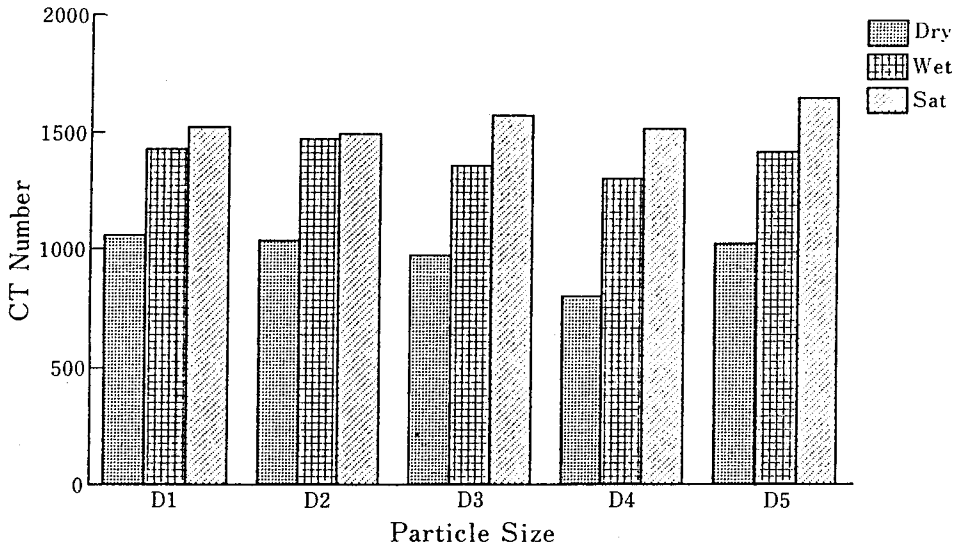

Fig. 11 The Relationship Between CT Number, Moisture Level and Particle Size of Soil D1 (2−4 mm), D2 (1−2 mm), D3 (0.5−1 mm), D4 (0.25−0.5 mm), and D5 (0.1−0.25 mm).

ANDERSON et al[4] found the standard deviation was higher for Fe content greater than 0.05 kg /kg than for those below this value, and they mentioned that it may be due to the difficulty in obtaining a well-mixed sample because of particle size differences between the soil and Fe powder.

Some researchers have conducted the same experiment but the result have not been similar. Since soils are used a test material then the result will be variable.

Despite the above difficulties, these experiments indicate that the application of a CT scanner to soil structural studies is potentially exiting.

Summary

Results from the study showed that CT Scanner can be used to determine structural properties of soil. The machine was found to respond in a positive linear pattern to the increasing moisture content. It was also found that the particle size did not have any influence on CT number but had strong correlation with the standard deviation, over the range of particle size evaluated. The relationship between the CT number and the moisture content was linear over the range of the moisture content evaluated. The mean differences in volume wetness, as determined by gravimetric and CT analysis were as great as 0.038 cm^3/cm^3 for the experiment of wetting and 0.039 cm^3/cm^3 for the experiment of drainage.

Soils are rarely homogeneous, having non uniform bulk densities or large particles of different particle density, that may lead to erroneous interpretations in soil structural determination using CT scanner.

Some researchers reported that errorneous Hounsfield value attributed to size and composition of the sample container.

Further study is needed in order to improve this technique.

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