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COLLEGE ON SOIL PHYSICS

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"Eletromagnetic Wave Attenuation in Soil Physics Determinations"

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ELETROMAGNETIC WAVE ATTENUATION IN SOIL PHYSICS DETERMINATIONS[1]

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1. INTRODUCTION

This text is a continuation of Bacchi and Reichardt (1993) and the simbols & definitions there used are also here used. Electromagnetic waves of high energy, like gamma-rays and X-rays, have the property of penetrating into relatively dense materials, and are therefore very useful for "inside" inspections. The attenuation of a beam of this radiation kind of is a function of the "density" of the material, and this fact opens the possibility to stutdy several materials, including the soil. We will here give more emphasis to the measurement of soil water contents and bulk densities, but also extend the technique to soil mechanical analysis.

2. GAMMA AND X RAY PROPERTIES

Gamma and X rays are electromagnetic waves which propagate in vacuum with the speed of light c, and have a characteristic wavelength λ (or frequency f) and, therefore, a characteristic energy E:

$$E = hf \ ; \ c = \lambda . f = \text{constant}$$

h being Plank's constant.

Radiation	wave length λ (μm)
gamma	4×10^{-8}-1×10^{-4}
X	1×10^{-5}-1×10^{-2}
Ultra violet	0.01-0.38
Visible light	0.38-0.78
Infrared	0,78-1.000

Gamma rays are originated from unstable nuclei, while X rays are the consequence of electron energy loss during target bombardmentor due to jumps between different energy levels (orbits). Therefore, gamma-ray beams are obtained from radiactive nuuclei and X-rays from "tubes" in which accelerated electrons loose energywhen interacting with targets, or electrons which are excited and when returning to their original levels, emitt radiation. Table 1 lists radioisotopes used as gamma-radiation sources. From these, the most commonly used are Americium, Cesium and Cobalt.

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Table 1. Radioisotopes suitable for gamma attenuation experiments.

Radioisotopes	Half-life (years)	Main energy peaks (%)	(KeV)	
^{241}Am (Americium)	458	86	60	
^{109}Cd (Cadium)	1.24	100	88	
^{144}Ce (Cerium)	0.78	11	134	
^{134}Cs (Cesium)	2.50	23	570	
^{137}Cs (Cesium)	30	85	662	
^{60}Co (Cobalt)	5.3	100	1173	
^{192}Ir (Iridium)	0.2	29	296	
			20	308
			81	317
			49	468
^{22}Na (sodium)	2.6	100	511	
		100	1275	

When gamma radiation interacts with matter, mainly three processes occur, which are responsible for the attenuation of the beam. For low energy radiation the photo-electric process is very probable. By this process, the photon (or gamma ray) colides with an inner shell electron, is completely absorbed, and as a consequence the electron is ejected from the atom. For medium energy photons the Compton-effect is the most probable. Here a photon also colides with an electron, but there is only partial energy loss and the ray is deviated from its original trajetory. Through this process gamma and X radiation is scattered. Only for energies higher than 1.02 MeV, photons may interact with target nuclei and become transformed in an electron and a positron. This process is called pair-production.

Due to these and other less probable processes, a gamma-ray beam of a given intensity becomes attenuated when passing through matter. The attenuation process depends on the energy of the photons, on the nature and density of the target matter and on the length of the travel path of the radiation through this matter. For a mono-energetic radiation bean, Beer's law is valid:

$$I = I_o \exp(-k\rho x) \tag{1}$$

where I_o is the incident beam intensity [number of photons per cm^2 per s, or counts per s (cps), or counts per minute (cpm)]; I the transmitted beam intensity; k the mass attenuation coefficient (cm^2/g); ρ the density of the absorbing material (g/cm^3); x the absorbtion length (cm). Figure 1 ilustrates the process.

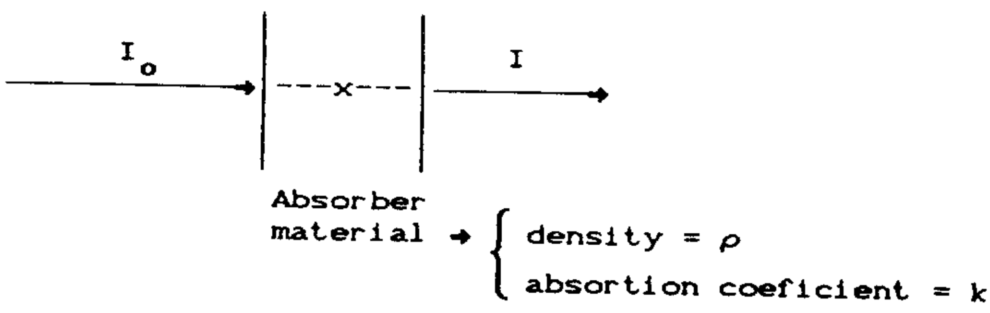

Figure 1. Schematic diagram of the attenuation process of a monoenergetic radiation beam by an homogeneons material

The absorption coefficient k is a function of the absorbing material and of the energy of the gamma or X rays. Knowing k and measuring I_o and I, the attenuation process can be used to measure ρ if x is known, or to measure x if ρ isknown, using equation (1). This is the principle of the process.

Very important details, which will not be treatet here, are i. source intensity; ii. beam colimation; iii. counting equipment; iv. peak definition, etc. Radiation safety has also to be mentioned. In general, to colimate radiation beams, gamma sources or X-ray tubes, are involved in lead (Pb) shields, calculated to protect the opperator. Radiation is only alowed to pass through a colimation whole, which defines the cross section of the beam (circular, rectangular, generally with less than 1 cm^2). At the beam, radiation levels are high and care showld be taken in order not to expose hands and other parts of the body to radiation. When manipulating samples within the beam path, the colimation whole should be closed with a lead shield.

3. ATTENUATION IN SOILS

Soils are not homogeneous and equation (1) must be extended for heterogenous materials. We will assume that the solid fraction of one given soil is homogeneous and so a moist soil sample of thickness x can be represented by:

$$x = x_s + x_w + x_a \tag{2}$$

where $x_s + x_w + x_a$ are the equivalent thicknesses of solids, water and air, within x.

Since a soil sample generally comes in a container, and the radiation source is located at a "fair" distance from the radiation detector the total radiation absorbing distance X from source to detector will be:

$$X = x_{a1} + 2x_c + x_s + x_w + x_a + x_{a2} \tag{3}$$

Figure 2 ilustrates schematially these distances. Considering the attenuation process as additive, equation (1) for the sistem described in Figure 2, is extended to:

$$I = I_o \exp\{-[k_a\rho_a(x_{a1} + x_a + x_{a2}) + 2k_c\rho_c x_c + k_s\rho_s x_s + k_w\rho_w x_w]\} \tag{4}$$

where k_i, ρ_i and x_i correspond to material i.

If I_o is measured with the empty container, the constant attenuation of air and container is already taken care of, and recognizing that:

$$\rho_s x_s = d_b x \quad andl \quad \rho_w x_w = \theta x$$

where: ρ_s = density of soil particles
d_b = soil bulk density
ρ_w = density of water
θ = soil water content

equatio (4) reduces to:

$$I = I_o \exp[-x(k_s d_b + k_w \theta)] \tag{5}$$

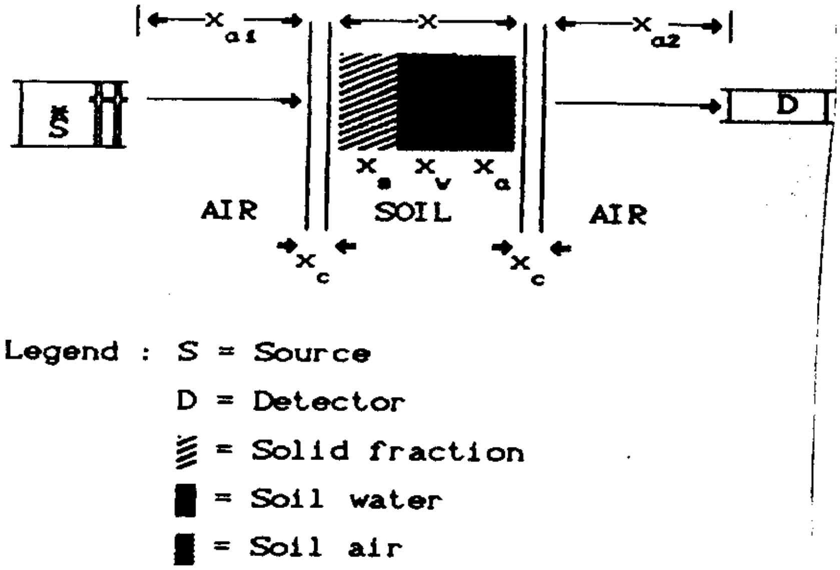

Figure 2. Schematic diagram of attenuation distances for a soil sample packed in a container.

Using carefully measured values of I_o, I, x, k_s and k_w, soil bulk density d_b and soil water content θ, can be estimated, at the position of the path of the radiation beam. Rearranging equation (5) we have:

$$d_b = \frac{1}{xk_s}\left[\ln\left(\frac{I_o}{I}\right) + xk_w\theta\right] \quad (6)$$

and

$$\theta = \frac{1}{xk_w}\left[\ln\left(\frac{I_o}{I}\right) + xk_s d_b\right] \quad (7)$$

The great difficulty in uing equations (6) and (7) is that to measure d_b one needs to know θ and to measure θ one needs know d_b. For monoenergetic gamma or X-ray beams, the only possibilities are the measurement of d_b in dry soils (θ = 0) and the measurement of θ in soil with d_b invariant in time and in θ, with previons measurement of d_b.

Since k_s and k_w are a function of the energy of the radiation, if a convenient choice of a double-energy (E_1 and E_2) radiation beam is made, which determine different values of k_s and k_w, soil bulk density d_b and soil water content θ can be measured simultaneonsly solving the set of equations:

$$\text{For } E_1\text{: } I_1 = I_{01} \exp\left[-x(k_{s1}db + k_{w1}\theta)\right] \quad (5a)$$

$$\text{For } E_2\text{: } I_2 = I_{02} \exp\left[-x(k_{s2}db + k_{w2}\theta)\right] \quad (5b)$$

The solution is:

$$d_b = \frac{\left[k_{w1}\ln\left(\frac{I_2}{I_{02}}\right) - k_{w2}\ln\left(\frac{I_1}{I_{01}}\right)\right]}{x(k_{s1}k_{w2} - k_{s2}k_{w1})} \qquad (8)$$

$$\theta = \frac{-\left[k_{s1}\ln\left(\frac{I_2}{I_{02}}\right) - k_{s2}\ln\left(\frac{I_1}{I_{01}}\right)\right]}{x(k_{s1}k_{w2} - k_{s2}k_{w1})} \qquad (9)$$

The use of equations (6), (7), (8) and (9) implies in the knowledge of the attenuation coefficients k_i. Ferraz and Mansel (1979) present values for several soils and for water, for several radiation energies. Some of them are reproduced in table 2. As can be seen from the k_i values of soils, for Americium and for Cesium, these two sources are a very good choice for a double energy beam. Since k_i values vary from soil to soil, they have to be determined for each soil. This is easily done through equation (1), using an artificially packed dry soil sample of known bulk density d_b.

Table 2. Soil and other absorber materials mass attenuation coefficients k_i for 60 (^{241}Am) and 662 (^{137}Cs) KeV gamma photons.

Material	Clay	Silt	Sand	k_i (cm^2.g^{-1})	
	%			60 Kev	662 Kev
Dark red latosol	48	31	21	0.31647	0.07424
Yellow red latosol	17	10	73	0.27501	0.07834
Red yellow podsol	8	10	82	0.26411	0.07755
Alluvial soil	33	43	24	0.30440	0.07837
Regosol	16	9	75	0.25518	0.07724
Washed sand	-	-	100	0.25008	0.07666
Water (distilled)	-	-	-	0.20015	0.08535

Example 1: To measure the mass absorbtion coefficient of a soil for the gamma radiation of ^{137}Cs (622 KeV)), a dry soil sample was used, of thickness 5.7 cm and a bulk density of 1.473 g.cm^{-3}. The measured gamma intensities were I_o = 102525 cpm (container without soil) and , = 53575 cpm (container with homogeneously packet dry soil). In this case:

$$53575 = 102525 \exp(-k_s \times 1.473 \times 5.7)$$

and

$$k_s = 0.0773\ cm^2.g^{-1}$$

Example 2: Using the same container filled with distilled water, the attenuated gamma intensity changed to I = 63156 cpm. Therefore:

$$63156 = 102525 \exp(-k_w \times 1.000 \times 5.7)$$

and

$$k_w = 0.085\ cm^2.g^{-1}$$

Example 3: A soil sample of thickness 6.62 cm is submitted to a double gamma ray beam and the following data was obtained:

Radiation 1:
I_{01} = 253.428 cpm
I_1 = 4.776 cpm
k_{s1} = 0.40139 $cm^2.g^{-1}$
k_{w1} = 0.20015 $cm^2.g^{-1}$

Radiation 2:
I_{02} = 116.438 cpm
I_2 = 48.574 cpm
k_{s2} = 0.07881 $cm^2.g^{-1}$
k_{w2} = 0.08535 $cm^2.g^{-1}$

Using equations (5a) and (5b) we have:

$$4.776 = 253.428 \exp[-6.62(0.40139 d_b + 0.20015\theta)]$$

$$48.574 = 116.438 \exp[-6.62(0.07881 d_b + 0.08535\theta)]$$

and solving this set of equations we obtain:

$$d_b = 1.340\ g.cm^{-3} \quad andl \quad \theta = 0.310\ cm^3.cm^{-3}$$

4. EXPERIMENTAL ERRORS ASSOCIATED IN d_b AND θ MEASUREMENTS

4.1. Sample Thickness x

Sample tickness x is critical and has to be measured carefully, with minimal errors. In example 3 (above) if x would be 6.52 insted of 6.62 cm, i.e. with an error 1.5 of %, the values of d_b and θ would be 1.361 and 0.3:4, respectively.

Since the radiation attenuation process is exponential, the reduction of I_o is very high, and directly related to the sample thickness x. In Example (3) we observe a reduction of I_o of 98% for radiation 1 (low energy) and of 58% for radiation 2 (high energy). If x is increased excessively the values of I become too small, compromising counting statistics. Ferraz and Mansel (1979) show there is an optimum thickness x^*, which depends on the type of radiation and of the values of d_b and θ. Too thin samples or too large samples introduce great errors in the measurements. They show that x^* is given by:

$$x^* = \frac{2}{k_s d_b + k_w \theta} \tag{10}$$

For example 3 we have:

$$\textit{Radiation } 1: \; x_1^* = \frac{2}{0.40139 \times 1.34 + 0{,}20015 \times 0.31} = 3.3 \; cm$$

$$\textit{Radiation } 2: \; x_2^* = \frac{2}{0.07881 \times 1.34 + 0{,}08535 \times 0.31} = 15.1 \; cm$$

Since x is more critical for the low energy, when using double beams, x has to be closer to x^* for the low energy. For the above example, x = 6.62 is a good choice. More details for the choice of x are found in Ferraz and Mansel (1979).

4.2. Errors in d_b and θ Measurements

Ferraz and Mansel (1979) show that the mininum resolvable changes σ of d_b and θ, when using a monoenergetic beam, are:

$$\sigma_{d_b} = \frac{1}{x k_s \sqrt{I_o}} \exp \left[\frac{x}{2} \left(k_s d_b + k_w \theta \right) \right] \tag{11}$$

$$\sigma_{\theta} = \frac{1}{x k_w \sqrt{I_o}} \exp \left[\frac{x}{2} \left(k_s d_b + k_w \theta \right) \right] \tag{12}$$

As can be seen, the mininum resolvable changes σ depend on all parameters and measurements of the attenuation process: I_o, x, k_s, k_w, d_b and θ. For example 3 analysing separately the case of each radiation, we have,

Radiation 1:

$$\sigma_{d_{b1}} = \frac{1}{6.62 x 0.40139 (253428)^{1/2}} \exp \left[\frac{6.62}{2} (0.40139 x 1.43 + 0.20015 x 0.31) \right]$$

$$\sigma_{\theta_1} = \frac{1}{6.62 x 0.20015 (253428)^{1/2}} \exp \left[\frac{6.62}{2} (0.40139 x 1.43 + 0.20015 x 0.31) \right]$$

and

$$\sigma_{d_{b1}} = 0{,}006\ g.cm^{-3} \quad ; \quad \sigma_{\theta_1} = 0{,}012\ cm^3.cm^{-3}$$

Radiation 2:

$$\sigma_{d_{b2}} = \frac{1}{6.62x0.07881(116438)^{1/2}} \exp \left[\frac{6.62}{2}(0.07881x1.43 + 0.08535x0.31)\right]$$

$$\sigma_{\theta_2} = \frac{1}{6.62x0.08535(116438)^{1/2}} \exp \left[\frac{6.62}{2}(0.07881x1.43 + 0.08535x0.31)\right]$$

and

$$\sigma_{d_{b2}} = 0{,}009\ g/cm^3 \quad ; \quad \sigma_{\theta_2} = 0{,}008\ cm^3/cm^3$$

indicating errors of about 0.5% for bulk density and 3.2% for water content measurements.

When using the double beam, a system of equations is solved and parameters of both radiations interfere in the measurements of d_b and θ. For this case:

$$\sigma_{d_b} = \frac{\left[\frac{(k_{w1})^2}{I_2} + \frac{(k_{w2})^2}{I_1}\right]^{1/2}}{x(k_{s1}k_{w2} - k_{s2}k_{w1})} \qquad (13)$$

$$\sigma_{\theta} = \frac{\left[\frac{(k_{s1})^2}{I_2} + \frac{(k_{s2})^2}{I_1}\right]^{1/2}}{x(k_{s1}k_{w2} - k_{s2}k_{w1})} \qquad (14)$$

For example 3, using the double beam, we have:

$$\sigma_{d_b} = \frac{\left(\frac{0.20015^2}{48574} + \frac{0.08535^2}{4776}\right)^{1/2}}{6.61(0.40139x0.08535 - 0.20015x0.07881)} = 0.012\ g/cm^3$$

$$\sigma_\theta = \frac{\left(\frac{0.40139^2}{48574} + \frac{0.07881^2}{4776}\right)^{1/2}}{6.61(0.40139x0.08535 - 0.20015x0.07881)} = 0.018\ cm^3.cm^{-3}$$

indicating errors of 0.8% and 5.8% for d_b and θ respectively. As can be seen, although the double gamma technique is an improvement, the measurements have greater errors as compared to the mono gamma technique.

5. FURTHER IMPROVEMENTS OF THE TECHNIQUE

One shortcomming of the gamma or X-ray attenuation technique is the measurement of x, which is critical for the estimation of d_b and θ, and difficult to be measured accurately. It is only easy to be measured for cases of soil samples packed in rectangular or cylindric acrilic containers, precisely manufactured. In other cases, like plants growing in commercial soil pots or even soil clods, it is very difficult to measure x, which varies for each measurement point.

Why not use a triple energy beam and leave x also as an unknown? This is not possible because x multiplies d_b and θ in equation (5) and the resulting simultaneous equations will not be independent.

So, as things stand today, x has to be meaured as precisely as possible for mono-and double beam attenuation measurement. One improvement has, however, been introduced through the computed tomography. This technique, first introduced into Soil Science by Crestana et al (1985) gives d_b and θ distributions in irregularly shaped soil samples, without the need of measuring x. In a tomograph the sample rotates around an axis and a very high number of attenuation measurements is made within the rotation plane, which envolve different beam paths, each having its x, d_b and θ. Solving all these unknowns through computation one obtains the d_b or θ distribution over the rotation plane, i.e., a cross section "picture" is obtained, indicating the d_b or θ distribution, with a resolution (pixel) that can go down to 1 mm^2. Vaz et al (1992) gives more details of the technique.

6. APPLICATIONS IN SOIL PHYSICS

6.1. Infiltration tests in homogeneous soils

The gamma-attenuation techniques is very suitable for laboratory studies that envolve water movement in soils. The main advantage of the methodology is its non-destructive character. As water moves thorough the soil, the changing water content can be monitored at different positions and times, with measurement times of less than 1 minute per point. Infiltration tests are examples for which gamma-attenuation has contributed singnificantly. These tests are normally performed on homogeneous soil columns, as shown in Figure (3). The colunns are packet carefully with dry soil and before submitting to water infiltration are tested for homogeneity through bulk-density distributions. This can be performed by gamma-attenuation and, when the colimation beam is of the order of mm, d_b can be measured mm by mm. Columns presenting undesired d_b descontinuities can be descarted and repacked.

During infiltration tests the position of the water wetting front x_f advances and it is important to know the θ distribution between $x = 0$ and $x = x_f$. Therefore, from time to time attenuation measurements are performed at points x, $0 < x < x_f$, since for $x > x_f$ we have only dry doil. This can be done in two ways. One is making quick θ measurements at several positions, starting close to x_f, because there θ changes rapidly, and then making measurements at increments Δx, approaching $x = 0$. In this case we obtain a x versus θ profile at a given time t^*, as shoun in figure 4.

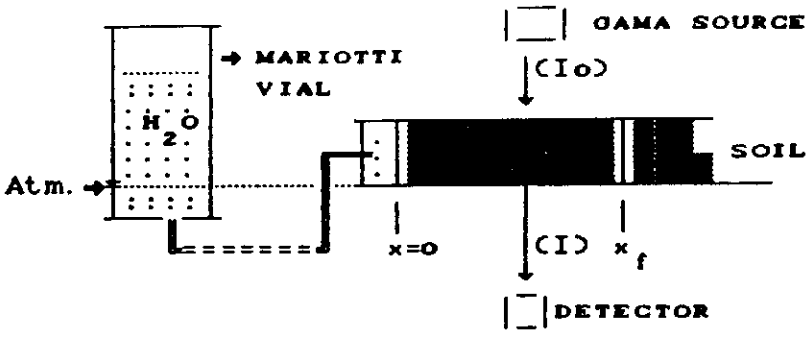

Figure 3. Schematic diagram of an infiltration test.

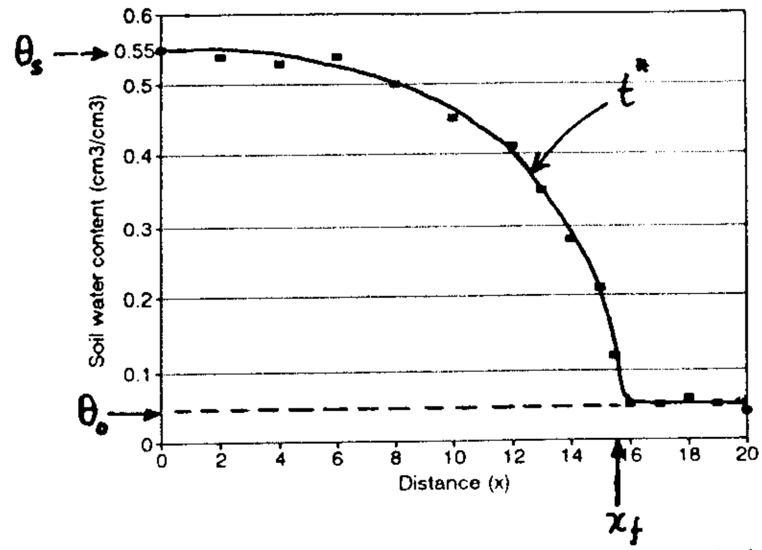

Figure 4. Soil water content at t^*; θ_s is the saturated water content and θ_o is the initial soil water content, in this case the water content of air-dry soil.

This procedure is only possible for soils with low infiltration rate, since the profile changes in time. If the wetting front position x_f does not change significantly in, let's say, 15 minutes, there is plenty of time to obtain the profile. Any way, allways starting at x_f and going backwords toward $x = 0$, where θ changes are slow. Even for soils of relatively fast infiltration rates this procedure is possible if the profile is measured for large times t^*, at which the infiltration rate has decreased significantly.

The other way, in cases of rapid changes in θ at measurement poitions, it is recomended to make several measurements at a fixed point x_i, then move to another point x_j and make another set of measurements, move to x_k and ..., and then return to x_i to make another set ... As a result one obtains θ versus t graphs, at choosen posions x (Figure 5). With this set of data it is possible to construct θ versus x profiles like Figure 4, for fixed times. In Figure 5, for example, we have θ values at positions x_i, x_j and x_k at exactly t_k.

The gamma-attenuation technique has been widely used in studies similar to the above. Just to mention some, the reader is reffered to Davidson et al (1963) and Reichardt et al (1972).

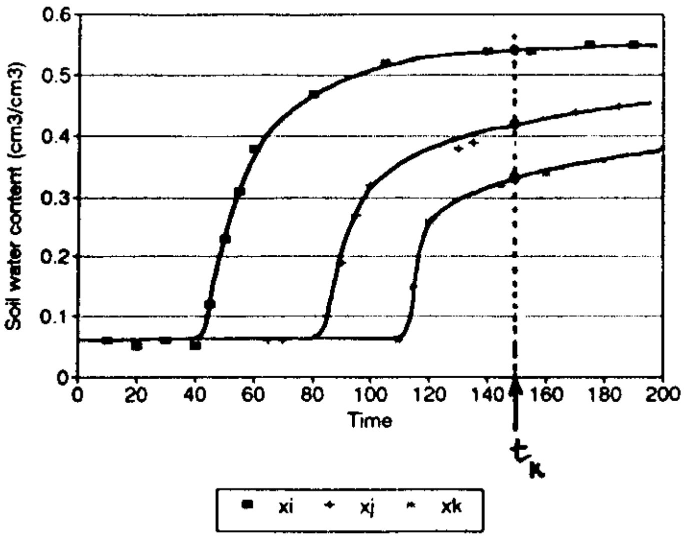

Figure 5. Soil water content as a function of time at three fixed positions.

6.2. Soil Mechanical analysis

The intensity of a gamma beam passing through a soil suspension at a given depth is related to the concentration of the suspension as it varies with time. From the changes in the attenuation of the beam intensity it is possible to calculate particle fractions. The attenuation equation for a gamma beam passing through the sedimentation system composed of an acrylic plastic container, soil particles, water and sodium hydroxide (shown in Figure 5) can be written as:

$$I = I_0 e^{-(k_w x_w + k_s d_p x_p)} \tag{15}$$

where I_0 is the attenuated radiation beam (cps) from the system without the soil, I the attenuated radiation beam (cps) from the system with soil under sedimentation, k_w and k_s ($cm^2 g^{-1}$) the mass attenuation coeficients for water and soil, respectively; x_p (cm) the absortion thickness due to soil particles; and d_p ($g.cm^{-3}$) the particle density. Equation (15) neglects the absortion thickness of sodium hidroxide, assumes that the density of the solution is 1 $g.cm^{-3}$ and assumes that all particles have the same density.

Relating the suspension concentration C ($g.l^{-1}$) to the particle density and to the container internal thicknees $\underline{X}$ (cm), we have:

$$x_p = \frac{C \cdot X}{d_p} 10^{-3} \tag{16}$$

Substituting (16) into (15) we obtain:

$$C = \frac{\ln(I_o/I)}{X\,(k_s - k_w/d_p)} \qquad (17)$$

Equation (15) is obtained as follows:

$d_p = m_p/v_p$ (a)

$C = m_p/v$ (b)

$d_p.v_p = C.v.$ (c)

$d_p/C = v/v_p$ (d)

$\frac{d_p}{C} = \frac{A\,.\,X}{A\,.\,x_p}$ (e) $\qquad \frac{d_p}{C} = \frac{X}{x_p}$ (15)

From the measurement of I as a function of the sedimentation time at a chosen depth <u>h</u> (equivalent to the pipette depth) the suspension concentration is obtained by equation (17). Knowing the initial suspension concentration the percentage of each particle size fraction can be calculated. Since the measurements of I are performed in definite time intervals (Δ_t = 3 seconds), it is difficult to measure the initial concentration (corresponding to the start of the sedimentation process, t = 0) through beam attenuation. Therefore, the initial concentration is calculated from soil mass and solution volume.

A radiactive source ^{241}Am of 300 mCi is used to produce the gamma-ray beam, using the energy peak of 59.6 Kev. The detection system is composed of a NaI(Tl) crystal scintilator, photomultiplier cell, power supply, amplifier, monochannel analyser and counter timer. To improve the sensibility of the method, the beam colimator can be a horizontal rectangular slot (1 mm x 15 mm) instead of the traditionaly used cirular colimator. More details can be found in Vaz et al (1992).

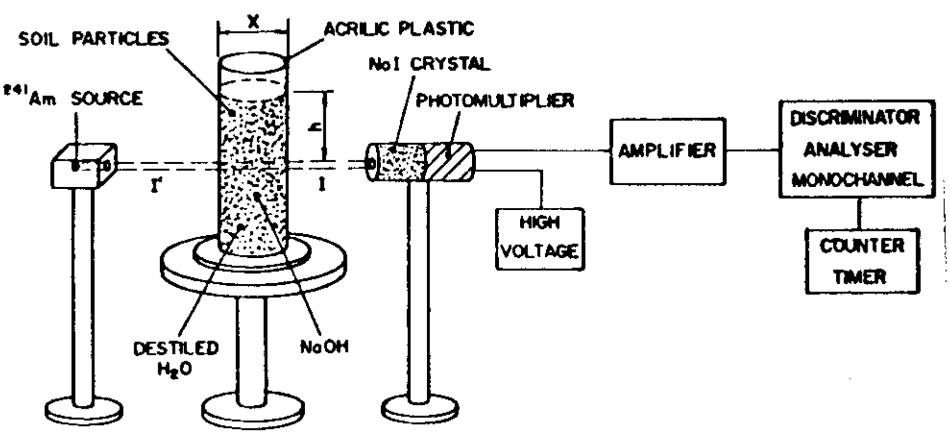

Figure 6. Scheme of the gamma ray attenuation system.

7. REFERENCES

BACCHI, O.O.S. and REICHARDT, K. 1993. Neutron probes and their use in gronomy. CENA, P.O. Box 96, 13418-900. Piracicaba, S.P., Brazil. 54p.

CRESTANA, S.; MASCARENHAS, S. and PAZZI-MUCELLI, R.S. 1985. Static and dynamic three dimensional studies of water in soil using tomographic scanning. Soil Science, Baltimore, 140(5): 326-332.

DAVIDSON, J.M.; NIELSEN, D.R. and BIGGAR, J.W. 1963. The measurement and description of water flow through Columbia Silt Loam and Hesperia Sandy Loam. Hilgardia, Davis, 34: 601-617.

FERRAZ, E.S.B. and MANSELL, R.S. 1979. Determining Water Content an Bulk Density of Soil by Gamma Ray. Attenuation Methods. Bull 807 (Tech.) Univ. of Florida, Gainsville, USA, 43p.

REICHARDT, K.; NIELSEN, D.R. and BIGGAR, J.W. 1972. Scaling of horizontal infiltration into homogeneous soils. Soil Sci. Soc. Am. Proc., Madison, 36: 241-245.

VAZ, C.M.P.; CRESTANA, S.; MASCARENHAS, S.; CRUVINEL, P.E.; REICHARDT, K. and STOLF, R. 1989. Using a computed tomography miniscaner for studying tillage induced soil compaction. Soil Technology, Cremlingen, 2: 313-321.

VAZ, C.M.P.; MARTINS, J.C.O.; REICHARDT, K.; CRESTANA S. and CRUVINEL, P.E. 1992. Soil mechanical analysis through gamma-ray attenuation. Soil Technology, Cremlingen, 5(4): 314-325.