Soil & Tillage Research 184 (2018) 216–234

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Review

Soil analysis using nuclear techniques: A literature review of the gamma ray attenuation method

Luiz F. Pires*

Laboratory of Physics Applied to Soils and Environmental Sciences, Department of Physics, State University of Ponta Grossa (UEPG), 84.030-900, Ponta Grossa, PR, Brazil

ARTICLE INFO

Keywords:
Attenuation coefficient
Effective atomic number
Radiation interaction
Soil physical properties
Soil porous system
Soil chemical composition

ABSTRACT

The gamma ray attenuation method (GAM) has been used with success in soil science since the fifties of the last century. Several soil properties can be measured directly or indirectly in a fast, non-destructive and accurate way using GAM. This review paper has as main objectives to discuss briefly the first uses of GAM in the soil sciences, to revise the main equations utilized for measuring soil properties, to show some applications to highlight the potential of the technique and to point out possible future studies with GAM.

1. Introduction

The gamma ray attenuation method (GAM) is a nondestructive technique that allows fast measurements of different physical properties. The technique has been frequently used in different fields of knowledge such as medicine, engineering, nuclear sciences, agriculture, geology, etc. In environmental studies GAM enables the analysis of both biological and geological materials and seems to offer many advantages in relation to other traditional methods such as fast and inexpensive analyses, resolution of few millimeters, repeatability, reliability, sensitivity, feasibility and non-invasiveness.

In the soil science area GAM has been widely employed for the determination of the soil bulk density (ρ_s) and soil water content (θ). However, several other soil properties can be evaluated by using this technique directly or indirectly. GAM is applied in both laboratory and field studies and its nondestructive characteristic allows repeated measurements of soil properties in the same position at different times. This is one of the greatest advantages of GAM over other traditional methods.

Normally, two methods can be used for the analysis of soil properties through GAM, which are scattering and transmission. As regards field experiments, the radioactive source in the transmission method is inserted inside the soil profile prior to the measurements. The radiation intensity is measured through a detector placed parallel (horizontal distance) to the radioactive source. In the laboratory the radioactive source is normally assembled inside a lead castle to avoid exposure to the radiation (Colgate, 1952).

One requirement for representative measurements of soil properties using GAM in the laboratory is good narrow beam geometry (Mann, 2017). The narrow beam is obtained through the use of collimators in both detector and radioactive source (Goswami and Chaudhuri, 1973). The detector shielding is also necessary to minimize scattered radiation from entering the detector and background radiation (Conner et al., 1970). When uncollimated beam is used the Beer-Lambert equation needs correction due to the buildup factor (Singh and Chandra, 1977; Mann, 2018; Obaid et al., 2018). In circumstances of appropriate collimation the buildup factor may be equal 1 (scattered radiations screened out of the counting system) and the Beer-Lambert equation can be solved to evaluate, for example, ρ_s or θ.

In soil science the most common radioactive sources employed are the ^{241}Am and ^{137}Cs (Reichardt, 1965; McHenry and Gill, 1970; Corey et al., 1971; de Swart and Groenevelt, 1971; Stroosnijder and de Swart, 1974). The former is a man-made radioactive metal that emits alpha particles (α) and gamma (γ) rays. Its half-life is $\approx$432 years and the γ ray has an energy of $\approx$60 keV. The latter is produced by nuclear fission and emits beta particles (β) and γ rays. Its half-life is $\approx$30 years and the photon emitted has an energy of $\approx$662 keV (Kaplan, 1963). The main reasons for the choice of these radioactive sources are related to the well distinguished primary energy peaks, the half-life of the radioisotopes and the cost for the system assemblage (Wang and Willis, 1965).

Besides the collimation, for accurate measurements of soil physical properties using GAM, an ideal thickness of the sample is also required. Normally this thickness should be less than or equal to one mean free

* Corresponding author at: Departamento de Física, Universidade Estadual de Ponta Grossa, Campus de Uvaranas, Bloco L, Sala 15B, Av. Carlos Cavalcanti, 4748, CEP 84.030-900, Ponta Grossa, PR, Brazil.

E-mail address: lfpires@uepg.br.

https://doi.org/10.1016/j.still.2018.07.015
Received 18 October 2017; Received in revised form 28 June 2018; Accepted 25 July 2018
0167-1987/

Nomenclature

A	Atomic weight
c	Compton scattering
C	Carbon
C*	Concentration
E	Energy
ECD	Equivalent cylindrical diameter
Exp	Experimental
eV	Electron-volt
f	Molar fraction
GAM	Gamma ray attenuation method
HV	High voltage
I	Transmitted beam
I_0	Incident beam
M	Molecular weight
Ma	Macroporosity
MCS	Monte Carlo simulation
mfp	Mean free path
Mi	Microporosity
n	Number of atoms
N_A	Avogadro number
N_{el}	Electronic density
pa	Photoelectric absorption
pp	Pair-production effect
PSD	Pore size distribution
r	Rayleigh (elastic scattering) effect
R_μ	Field capacity factor
R	Coefficient of correlation
R^2	Coefficient of determination
REL	Representative elementary length
SCA	Single channel analyzer
SWRC	Soil water retention curve
TP	Total porosity
w	Weight fraction
WDC	Wetting and drying cycles
x	Material thickness
x*	Optimum thickness
y, D	Thicknesses
Z	Atomic number
Z_{eff}	Effective atomic number
α	Alpha particles
β	Beta particles
γ	Gamma ray
θ	Soil water content
κ	Linear attenuation coefficient
μ	Mass attenuation coefficient
ρ	Material density
σ_a	Atomic cross-section
σ_e	Electronic cross-section
σ_m	Molecular cross-section

path (mfp) to avoid the influence of scattered photons in the experimental results (Varier et al., 1986). This optimum thickness tends to increase with the increase in the γ ray energies. For instance, for the determination of physical properties such as ρ_s or θ, thicknesses smaller than 10 cm are ideal for the ^{241}Am radioactive source while between 10 and 25 cm for the ^{137}Cs (Singh and Chandra, 1977; Ferraz and Mansell, 1979).

Radiation detection is usually carried out using thallium activated sodium iodide (NaI[Tl]) scintillation detectors. The choice of this type of detector is mainly related to its good efficiency. Due to its large area, the probability of γ ray detection is high. Another kind of detector that can be chosen is the semiconductor ones. The high-purity germanium detectors (HPGe) are the most common used in soil science studies. These detectors are characterized by their high resolution (Knoll, 2010).

The application of GAM in soil science and environmental fields is not new (Kirkham and Kunze, 1962). A great development of the technique took place between the fifties and the eighties of the last century (Ferraz and Mansell, 1979). Few years after the first nuclear tests GAM started to be used in experimental measurements of ρ_s in field conditions by Vomocil in 1954 (Vomocil, 1954). In his work the resolution obtained was ≈5.1 cm, which means that ρ_s was measured for layers of at least this thickness. Evaluations of ρ_s carried out ≈7.6 cm below the soil surface were achieved.

A statistical study of the parameters of the equation that relates the correlation between ρ_s and transmitted radiation intensity (I) and the distance between the detector and the radioactive source was presented by Bernhard and Chasek (1955). The authors observed deviations of ρ_s in relation to the methods considered standard of ± 2.3%. The use of ^{137}Cs γ ray source and NaI scintillator detector for measuring ρ_s was proposed by van Bavel et al. (1957). The authors considered only the primary radiation in the measurements, which was accomplished by using suitable electronic circuits and scintillation or proportional counters. The experimental procedures adopted demonstrated the possibility of using the Beer-Lambert equation when applied to soils. Later on, van Bavel (1959) also analyzed aspects related to the counting rate and the distance between the radioactive source and detector and the influence of the material density in the counting rate. Values of ρ_s obtained by that author had a precision of about 0.01 g cm^{-3} with resolutions of the order of 1.5 cm.

Gamma ray collimated beams started to be used in laboratory investigations by Gurr (1962), aiming at determining the unsaturated permeability of soil columns. This work presented a refinement of the method for reliable measurements of θ in water flow experiments considering constant and known ρ_s. In the same year Ferguson and Gardner (1962) also measured the moisture content in small soil samples to an accuracy of approximately ± 0.5% by volume by using a collimated beam. In both works the radioactive source chosen was ^{137}Cs due to the high energy of the γ photon. One year later, Ferguson and Gardner (1963) utilized GAM to evaluate θ with great accuracy aiming at evaluating water flow. Several water distribution curves were measured by them for different times and positions along soil columns. The unsaturated water flow was analyzed with the help of GAM. McHenry and Dendy (1964) carried out measurements of sediment densities using GAM. They collected sediments from small watersheds and measured their densities in silt boxes by using a dual probe. The vertical resolution obtained was ≈2.5 cm. The results indicated considerable material transport within the silt boxes. They observed changes in the depth and sediment densities with storm based on GAM results. Reginato and van Bavel (1964) employed an uncollimated beam to measure θ over a path length of about 30 cm. GAM allowed them to obtain measurements with resolution of the order of 1 cm. The authors pointed out that the greatest advantages of the method were accuracy, resolution, and absence of time lag and site disturbance.

A method based on the attenuation of the radiation was developed by Whisler et al. (1968) to measure the soil water diffusivity through θ evaluations in a horizontal infiltration system as a function of time and at fixed positions. The method allowed the continuous monitoring of θ throughout time with very good resolution. GAM was used by Topp (1969) as an auxiliary technique to evaluate the soil water hysteresis of samples submitted to a series of wetting and drying cycles. The use of tensiometers and pressure transducers and the γ ray system permitted the simultaneous measurements of the degree of saturation, water-phase pressure and hydraulic conductivity. de Vries (1969) carried out