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Soil mass attenuation coefficient: Analysis and evaluation

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ABSTRACT

The mass attenuation coefficient (μ) is an important parameter to characterize the penetration and interaction of gamma-rays in the soil. Accurate determinations of μ are important to obtain representative values of soil physical properties by gamma-ray attenuation technique. In this study, the effect of collimator size (2–4 mm diameters) and absorber thickness (2–15 cm) on the experimental μ values of water and soils with different textures were investigated for 59.54 keV (^{241}Am) and 661.1 keV (^{137}Cs) gamma-ray sources. Theoretical results were calculated using the program XCOM. Experimental results were compared with theoretical ones showing a good correlation between methods. It was observed that for the ^{137}Cs the best agreements between theoretical and experimental μ were obtained for sample thickness $\geqslant$10 cm while for the ^{241}Am were those obtained for thickness <5 cm for small collimators.

1. Introduction

The gamma-ray attenuation technique is based on the interaction of radiation with matter. When the photons interact with certain material, they might be scattered or absorbed (Kaplan, 1963). The probability of interaction of this photon per unit of length of a given absorber characterizes its linear attenuation coefficient (κ). However, κ depends on the material physical state and for this reason it is usually substituted by the mass attenuation coefficient (μ), which is the κ divided by the density (Ferraz and Mansell, 1979).

Accurate measurements of μ are of interest in fundamental physics and applied fields such as radiation protection and dosimeter, nuclear diagnostics and medicine, soil science, and engineering. This physical property is used in many applications such as X-ray fluorescence, X-ray tomography, gamma-ray tomography, and gamma-ray attenuation.

Gamma-ray attenuation is employed in soil physics to the measurement of bulk density, soil water content, porosity amongst other properties (Beamish, 2013; Moreira et al., 2001; Pires et al., 2009). One of the first experiments in the area was carried out in 1950 and the transmission of gamma-rays was applied to determine the soil bulk density (Belcher et al., 1950). The gamma-ray attenuation was firstly used in the studies developed by Vomocil (1954) and Bernhard and Chasek (1955), to determine soil bulk density in field conditions.

When a gamma radiation beam reaches some absorber material the attenuation occurs in accordance with the material chemical composition and the photon energy resulting in reduction of its intensity. The beam intensity decrease results from the combination of outright photon absorption and deflection. Therefore, μ presents dependence on the absorber nature as well as on the gamma-ray initial energy.

For a given element, it is well known that μ decreases with the gamma-ray energy increase. Its value also varies from element to element, and this variation is in most cases greater for heavy elements in comparison to light ones (Kaplan, 1963). In the interaction of gamma-rays with the matter three processes are mainly responsible for their attenuation: photoelectric absorption, Compton scattering and production of electron–positron pairs. Therefore, total μ results from the sum of μ in the three different processes.

Regarding the photoelectric absorption, its cross section per atom presents strong dependence on the atomic number (Z^{4-5}) and on the energy of the incident photon ($1/E^{7/2}$). Compton scattering per atom shows linear dependence on Z and pair production on Z^2. A much more slow decrease of μ increasing photon energy is observed for the Compton scattering in relation to the photoelectric absorption.

Total μ can be measured or theoretically predicted by using the mixture rule. Tables of theoretical μ values comprising 40 elements and 45 mixtures and compounds in the energy range of 1 keV–20 MeV were presented by Hubbell (1982). Through these tables it is possible to evaluate the contribution of photoelectric absorption, Compton scattering and pair production to the total μ for different energy ranges.

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However, experimental μ determinations reports found in the literature show its dependence on the geometry variation of the measurement equipment used. Thus, there is some concern about determining the influence of parameters such as the thickness of the absorber and the collimator size on the representativeness of physical properties evaluations using μ data.

Such dependence occurs for both measurements of homogeneous substances (Abdel-Rahman et al., 2000; Gopal and Sanjeevaiah, 1973; Hosseini-Ashrafi, 1998; Singh et al., 2006) and non-homogeneous (Alam et al., 2001; Sidhu et al., 1999a; Sidhu et al., 1999b). For heterogeneous substances such as the soil, few reports are found in the literature.

When μ measurements are carried out with narrow beam geometry, the multiple scattered photons are prevented from reaching the detector. Thus, these photons are not measured. However, the increase in sample thickness and collimator size (half acceptance angle) can improve the probability of multiple scattered photons being detected. The combination of these two effects leads to the variation of μ values affecting the representativeness of their evaluations.

An accurate μ measurement is important for a representative evaluation of physical properties using gamma-ray attenuation. This need is reinforced when the absorber material is the soil, as the more complex the medium is, the higher the difficulty to obtain a representative measured μ value.

The aim of this study was to analyze possible variations of the experimental soil mass attenuation coefficient as a function of the sample thickness and different collimator sizes. To achieve this aim, the gamma radiation sources used were ^{241}Am and ^{137}Cs.

2. Materials and methods

2.1. Samples collection and preparation

The soil samples were collected from the surface layer (0–10 cm) in experimental areas located in Piracicaba, SP, Brazil (22°4′S, 47°34′W, 580 m above sea level). Two different soils with distinct texture were obtained: sandy clay loam (770 g kg^{-1} sand, 50 g kg^{-1} silt, 180 g kg^{-1} clay) and silty-clay (240 g kg^{-1} sand, 330 g kg^{-1} silt, 430 g kg^{-1} clay).

The choice of both soils was based on their extensive use in Brazilian agriculture. The first soil classified as a Red–yellow Latosol is found in vast areas of land throughout Brazil and is widely used to cultivate different types of crops. The second soil classified as a Red Nitosol comprises a soil group with great agriculture relevance due to its high yield potential and good response to the application of fertilizers.

The samples were dried in oven at 105 °C for 2 days and sieved through a 1 mm mesh sieve aiming to obtain a more homogeneous sample. Throughout the experimental analyses, the samples were kept in containers with silica-gel to prevent them from absorbing water from the environment.

2.2. Elemental analysis

The equipment employed in the elemental analysis was a dispersive energy X-ray fluorescence spectrometer (Shimadzu, model EDX-720). This equipment has a Rhodium (Rh) tube and its voltage ranges from 5 to 50 kV and the filament operates with currents from 1 to 1000 μA. It uses an Si(Li) semiconductor as detector, which works with liquid nitrogen cooling at −196 °C. It possesses Zr, Ni, Ti and Al primary filters.

The soil samples were ground in mortar and put into proper containers supplied by the equipment manufacturer and sealed with mylar (6 μm thick). The time used to obtain the spectra was 100 s, in the energy bands from Sodium to Scandium (Na–Sc) (15 kV) and Titanium to Uranium (Ti–U) (50 kV). All the measurements were carried out with pressure under 30 Pa (vacuum).

These results of elemental analysis were used to calculate theoretical values of μ via the program XCOM (Berger and Hubbell, 1987; Hubbell and Seltzer, 1995). XCOM generates the cross sections and attenuation coefficients for any elements, compounds or mixtures, at energies between 1 keV and 100 GeV. For the purpose of interpolation with respect to photon energy, the coherent and incoherent scattering cross sections and the total attenuation coefficients are approximated by log–log cubic-spline fits as functions of energy. The interaction coefficients and total attenuation coefficients of mixtures are obtained from the fractions by weight of the components entered by the user.

2.3. Experimental attenuation coefficient

For μ measurement, the sources ^{137}Cs (661.6 keV; 11.1 GBq) and ^{241}Am (59.54 keV; 7.4 GBq) were used. An NaI(Tl) detector of a plain type (7.62 × 7.62 cm) was employed to detect the gamma photons (Fig. 1). The counting time adopted in the soil mass attenuation coefficient (μ_s) measurements was 600 s (^{137}Cs) and 1200 s (^{241}Am), respectively. The background radiation was monitored daily for the same counting times. A fixed collimator with 4.5 mm diameter was kept at the entrance of the detector in all measurements. The laboratory temperature was kept constant at 19 ± 1 °C.

Radiation spectra were evaluated daily throughout the experimental procedure, which made it possible to adjust the photopeak windows throughout the measurement periods. A 2 mm collimator and counting times of 30 s (^{137}Cs) and 60 s (^{241}Am) were used in the spectra measurements. The spectra were registered for the free beam and for samples with different thickness. The same counting time intervals of the free beam were used for both radioactive gamma-ray sources. The symmetry axis of the gamma-ray equipment arrangement was a horizontal line adjusted by a laser beam. The distance between the source and the detector was kept fixed and equal 23 cm.

The photopeak FWHM (full width at half maximum) was also monitored daily for each soil, thickness and collimator size. This procedure is important in order to verify the influence of the thickness of the samples in the photopeak resolution (Ochbelagh, 2009). With the ^{241}Am gamma source, the photopeak energy resolution remained constant up to the thicknesses of 7 cm (2 mm collimator), 8 cm (3 mm) and 12 cm (4 mm). Beyond these thicknesses it was not possible to evaluate μ due to problems in photopeak definition. On the other hand, there was a slight decrease of about 2.5% (all collimators) in the FWHM with increasing soil thickness for ^{137}Cs when comparing 2 and 15 cm thick samples.

In the gamma photons interaction process with a soil sample, the radiation will be absorbed or deflected by the solid particles,

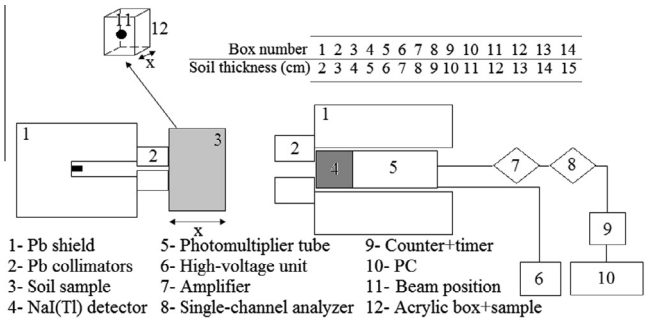

Fig. 1. Scheme of the experimental apparatus.