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Different methods of mass attenuation coefficient evaluation: Influences in the measurement of some soil physical properties

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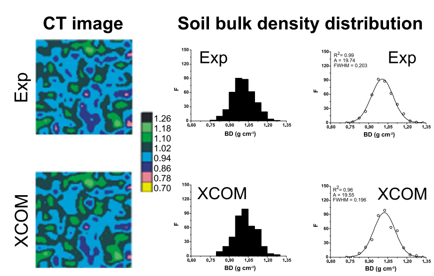
HIGHLIGHTS

- XCOM, GEANT4, FLUKA and MCNP codes were used in this study.
- Experimental and computational evaluations of attenuation coefficient (μ) were performed.
- Soil bulk density (BD) and water content (θ) was measured by computed tomography.
- 2D images allowed a detailed analysis of BD and θ distributions.
- Different methods of μ evaluation affect the measurements of BD and θ.

GRAPHICAL ABSTRACT



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ABSTRACT

The mass attenuation coefficients of Brazilian soils (μ_s) and water (μ_w) were measured and calculated at 59.5 keV (^{241}Am) photon energy. The μ_s and μ_w experimental values were compared using XCOM and Monte Carlo computer codes (FLUKA, GEANT4 and MCNP). The influence of different methods of μ evaluation on the measurement of soil bulk density (ρ_s) and soil water content (θ) distributions and soil water retention (SWRC) was investigated. ρ_s and θ distributions were analyzed by using computed tomography (CT). Distinct ρ_s distributions were obtained even for similar μ_s values measured among methods. θ distributions were also greatly influenced by the different methods of μ_w evaluation. Regarding the SWRC, the results exhibited great differences in the region of structural pores, which directly affected the pore size distribution.

1. Introduction

Understanding the X- and γ-rays mechanisms of interaction with the matter is important in different fields of applied sciences (engineering, agronomy, biology, medicine, etc.). Photon attenuation measurements and calculations have been carried out for different materials and the mass attenuation coefficient (μ) has been studied as a function of different physical parameters. Mass attenuation coefficient, atomic and electronic cross-section, effective atomic number and electron density are the basic parameters used to evaluate the penetration of X- and γ-rays through the matter (Medhat et al., 2014).

In the scientific literature, a great number of publications dealing with the experimental measurement of μ and other

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parameters for elements, compounds and mixtures can be found. The experimental data obtained are compared with the theoretical tabulations used by XCOM computer code (Esfandiari et al., 2014; Trunova et al., 2015; Elmahroug et al., 2015).

There are also some attempts to apply Monte Carlo simulation (MCS) to calculate photon attenuation. Modeling μ through materials in a computer environment represents a more useful and flexible method than its analysis by experimental measurements. It can provide the highest achievable accuracy and precision in the modeling of physical interactions in the matter. The use of this method requires knowledge of the material elemental composition and its density and physical characteristics as input information to perform these calculations (Medhat, 2015).

Amongst the physical properties of the soil, its bulk density (ρ_s) and soil water content (θ) are the ones of greatest interest. ρ_s presents environmental interest mainly because it can be used as an indicator of damages in the soil structure. The ρ_s evaluation provides information about the soil structure and its ability to transport and retain water, solutes and gases inside this porous media (Hillel, 2004). In general, this soil physical property is useful from the biological, chemical and physical points of view due to its possible use to convert properties into volumetric basis for soil health analysis.

Soil water content distribution and water retention are directly related to the structure of this porous media. The evaluation of θ distribution presents great interest due to its importance as a source of water for plant use. The water retention, classically determined through the soil water retention curve (SWRC), represents an important soil physical property (Klute, 1986). The SWRC can be used to measure the available water capacity, field capacity, wilting point and pore size distribution of the soil (Hillel, 2004). By using mathematical models, it is also possible to infer about the soil hydraulic conductivity based on SWRC information.

Non-invasive inspection techniques such as computed tomography (CT) and gamma-ray attenuation (GAT) can be used to evaluate ρ_s and θ. The former is utilized to convert the attenuation of the radiation by the matter into CT numbers called tomographic units (TU). From a TU matrix, utilized to generate the CT image, it is possible to generate ρ_s and θ maps. However, to convert the TU into ρ_s and θ maps good evaluation of the soil μ is necessary (Costa et al., 2013).

CT and GAT represent extremely useful methods to obtain detailed analysis of porous media structures with spatial resolutions from millimeters to micrometers (Pires et al., 2010). The greatest advantage of these methods over the traditional ones is the possibility of ρ_s and θ distribution detailed measurements in cross-section images of a sample.

The aim of this study was to evaluate the influence of the use of different methods to determine the mass attenuation coefficient of the soil in the measurement of bulk density and water content distributions, and soil water retention. To achieve this aim, experimental and theoretical (XCOM, GEANT4, FLUKA and MCNP) measurements of soil and water μ were carried out. ρ_s and θ variations were analyzed through cross-sectional images (2-D) of the soil samples obtained through a first generation low cost CT scanner exclusively used for soil science studies. SWRC was evaluated by using GAT.

2. Computational methods

For narrow beam geometry experimental arrangements, μ of different materials is evaluated by the transmission method according to Beer-Lambert's law. For soil samples, two phases are considered: the solid material and water (Ferraz and Mansell, 1979). Besides the experimental (EXP) method, μ can be calculated by XCOM or by MCS codes.

XCOM can generate cross-sections and attenuation coefficients for pure elements ($Z = 1 - 100$), mixtures and compounds at different energy ranges (1–100 GeV). With the help of this software, it is also possible to obtain partial cross-sections for photoelectric absorption, scattering (incoherent and coherent) and pair production (Berger et al., 2010).

MCS has been used to model irradiation facilities in order to predict photon attenuations. Modeling the experimental setup of detecting attenuation through soil samples in a computational environment makes it flexible and easy to use, instead of having to perform measurements for different soil types. There are many MCS codes, which can be used in the soil physics field. The most widespread are GEANT4, FLUKA and MCNP (Taleei and Shahriari, 2009; Singh et al., 2013; Bohlen et al., 2014; Dababneh et al., 2014).

GEANT4 is a computer code used to simulate the passage of particles through the matter by utilizing MCS. Simulation through GEANT4 depends on narrow beam geometry, with the mono-energetic photon beam interacting with the material analyzed in the experimental set-up simulated. The Beer Lambert law is utilized to evaluate μ. The material thickness is optimized based on the incident photon energy. This procedure is carried out to avoid the total beam absorption by the material or lack of interaction with it. Therefore, the primary photons transmitted from the material are taken into account. All relevant physical processes and interactions with and without the material analyzed are used to calculate photon attenuation (Medhat, 2015).

FLUKA is a computer code for a variety of models of particle transport and interaction with the matter through MCS. FLUKA can simulate the interaction and propagation in the matter of more than 60 different particles such as: heavy ions, electrons, neutrons, photons, neutrinos and muons. The code has been used in several research fields such as: shielding design, detector-response studies, cosmic-ray studies, medical physics and dosimetry calculations. The chemical and elemental composition of the material combined with its physical characteristics and density are needed as input information (Bohlen et al., 2014).

MCNP is a general-purpose, continuous-energy, generalized geometry, time-dependent, coupled neutron-photon-electron MCS transport code system. Physical models for particle interactions and nuclear cross section libraries are required by MCNP-4C. The code can consider neutrons, photons and electrons, or in pairs neutron-photon-electron together. Radiation sources of different shapes (point, surface or volume) can be utilized, from which the mentioned particles are emitted with user specified probability distributions for energy and direction. The code then simulates the particle tracks and interactions with the materials, according to probability density distribution (Esfandiari et al., 2014).

3. Material and methods

3.1. Soil samples

Disturbed samples of a Red Nitosol and undisturbed samples of a Red-Yellow Latosol were collected in the Southeast region of Brazil (22°40′S; 47°38′W; 580 m a.s.l.).The term disturbed is used when the natural conditions of the sample such as: its structure, bulk density, porosity, etc are disturbed. Samples that keep the soil natural conditions as well as its original attributes as much as possible are considered undisturbed (Hillel, 2004).

After sampling, the Red Nitosol samples were air dried (12 weeks) and sieved finer than 2 mm. The sieved samples were then carefully placed into PVC cylinders of 5.0 cm diameter and 5.0 cm height.

The Red-Yellow Latosol samples were collected at the soil surface with PVC cylinders ($h = 30$ cm, $D = 10$ cm, $V \approx 2355$ cm^3).