Revista Brasileira de Ensino de Física, vol. 42, e20190340 (2020)
www.scielo.br/rbef
DOI: https://doi.org/10.1590/1806-9126-RBEF-2019-0340

Physics Education Research

Gamma ray attenuation for determining soil density: laboratory experiments for Environmental Physics and Engineering courses

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Received on December 9, 2019. Accepted on January 22, 2020.

In this paper, we present in details a method for determining the soil density of disturbed samples. The mass attenuation coefficient was also evaluated by using the relation between the number of photon counts and the path length (soil density ×thickness). A typical student laboratory setup (PASCO) was utilized in the measurements. A gamma ray source of ^{137}Cs and soils with four different textural classes were employed. The experimental apparatus here proposed, that uses an educational gamma ray attenuation system, permitted measuring, with very good agreement with the traditional method, the density of soil samples. The experiment can be somehow extended by proposing the investigation of soil bulk variations due, for instance, to soil compaction, a subject of interest for engineering and environmental physics students.
Keywords: ^{137}Cs gamma ray photons, Soil mass attenuation coefficient, XCOM, Soil chemical composition.

1. Introduction

The gamma ray attenuation (GRA) technique has been applied with success in many areas of knowledge such as medicine, engineering, geology, environmental and soil sciences. The technique is based on the absorption of gamma radiation by chemical elements from pure or composite materials [1,2]. GRA is considered a nondestructive method that allows accurate and precise measurements of physical properties of selected materials [3].

Gamma ray beams interact with the matter according to the Beer-Lambert attenuation law ($\mathrm{I} = \mathrm{I_o e^{-\mu\rho x}}$) where the mass attenuation coefficient () is related to the capacity of a material for attenuating the incident radiation. This coefficient is dependent on the elemental composition of the absorber as well as the energy of the incident gamma radiation [2]. The soil mass attenuation coefficient is also described as a measurement of the probability of the interaction between the gamma ray photons and the atoms that compose the absorber.

GRA has been widely utilized for the determination of different properties of porous media such as density, water content, water retention and water movement [4-6]. The use of GAR in environmental studies of porous media is well reported in the literature. The first applications took place in the middle of the last century [7]. In the areas of soil and environmental physics GRA allows evaluating the effect of natural and anthropogenic actions in the porous media [8]. One important property for monitoring changes in the porous media condition is its density (ρ). Bulk density has been frequently used as an indicator of the health and quality of pore systems such as rocks and soils [9].

One of the possibilities of GRA is monitoring changes in ρ induced by anthropogenic interventions in porous media. Increases in ρ caused by compaction is frequently related to environmental issues such as soil erosion [10]. This article introduces procedures for measuring ρ of soils based on calibration curves. The study is mainly directed for students of experimental physics courses of engineering, environmental and soil physics. The experiment involves the use of a GRA apparatus usually existing in teaching laboratories of Modern Physics around the world.

2. Basic theory

The intensity variation (dI) of a monoenergetic gamma ray beam transposing a material of thickness x (cm) is described by the expression [2]:

$$\mathrm{dI} = -\mathrm{kIdx}\,, \tag{1}$$

where k ($\mathrm{cm^{-1}}$) is the linear attenuation coefficient, I is the intensity of the incident radiation ($\mathrm{I_0}$), and dx is the infinitesimal thickness of the absorber (Fig. 1). The integration of Eq. (1) allows obtaining the Beer-Lambert attenuation equation:

$$\int_{\mathrm{I_0}}^{\mathrm{I}} \frac{\mathrm{dI}}{\mathrm{I}} = -\mathrm{k}\int_0^{\mathrm{x}} \mathrm{dx}\,, \tag{2}$$

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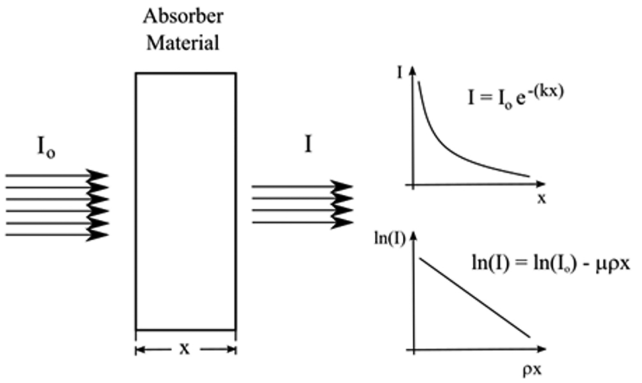

Figure 1: Beer-Lambert attenuation law for a monoenergetic gamma ray beam of intensity I passing through an absorber of thickness x. Exponential decay representation of I versus x and of ln (I) versus path length (ρx).

$$\mathrm{I} = \mathrm{I}_0 \exp\left(-\mathrm{kx}\right) . \quad (3)$$

When applied to materials composed by different phases (solid, liquid and gas) such as soils or rocks, k is replaced by the mass attenuation coefficient and Eq. (3) becomes:

$$\mathrm{I} = \mathrm{I}_0 \exp\left(-\mu\rho\mathrm{x}\right) , \quad (4)$$

where μ (cm^2 g^{-1}) is the mass attenuation coefficient (k/ρ) and ρ is the density or bulk density of the absorber material.

The plot of ln (I) versus ρx (g cm^{-2}) represents a straight decreasing line whose slope gives a direct measurement of μ (Fig. 1).

3. Experimental design

The gamma ray source used in this experiment was a ^{137}Cs PASCO radioactive source whose activity was c. 3 μCi (Fig. 2a). The half-life of this radionuclide is 30.2 years. To increase the signal/noise ratio, three equal Cesium sources, one above the other, were assembled together to form a single gamma ray source. Then, the total activity of this "single" source was c. 9 μCi.

The gamma ray photon detection system consisted of a Student Geiger-Müller (GM) Tube (PASCO) with a 35 mm diameter window made of mica (2 mg cm^{-2}), which provided a good photon efficiency for low activity gamma ray sources (Fig. 2b). The dead time of the GM tube is around 200 μs. The operating voltage selected for the experiments was 920 V. The GM holder is composed of 10 shelf positions that allow accommodating the samples and the sources for the experimental measurements.

The counts were registered in a radiation counter system (PASCO) composed by a timer, preset counter, and a digital rate meter (Fig. 2c). The time interval selected for each measurement was 10 minutes. It was chosen for reducing the uncertainty in the measurements ($\sqrt{\mathrm{I}}$) to c. 1% of the total counts recorded. This time interval was also selected to permit the measurements in a two to three hours experimental class.

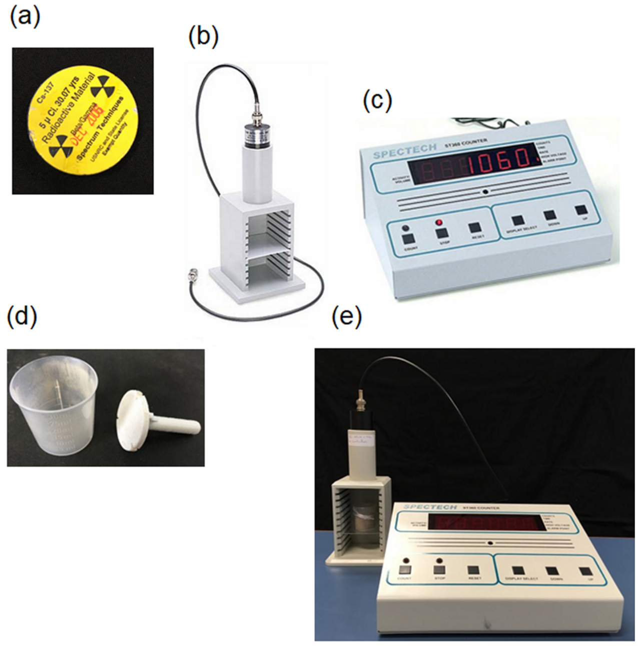

Figure 2: (a) ^{137}Cs educational radioactive source. (b) Student Geiger-Müller (GM) tube. (c) Radiation counter system. (d) Sample container and pestle. (e) View of the experimental setting up.

Soils of different textural classes (F-SAND, S-LOAM, S-C-LOAM, CLAY) were selected for conduct this work. Around 200 g of each soil was sieved in a 2 mm (10 Mesh) sieve to separate the small aggregates and particles with sizes smaller than 2 mm from the rest of the soil. This procedure was also made to standardize the samples. Before sieving, the soil samples were oven-dried, to 105 °C for 24 hours, to reduce the influence of the soil water content in the measurements.

A cylindrical plastic container with an internal diameter of c. 3.25 cm was selected for accommodating the soils samples (Figs. 2d and 2e). Using this container, the relation between the sample thicknesses and the recipient volume were: 1.24 (10 mL), 1.78 (15 mL), 2.31 (20 mL), 2.86 (25 mL) and 3.40 cm (30 mL). A pestle with approximately the same container internal diameter was utilized for levelling the soil inside it (Fig. 2d).

The container with the sample was mounted in the experimental setup with its bottom put in contact with the ^{137}Cs gamma ray source. The distance between the source and the GM detector was c. 6.5 cm. To minimize the counting related to secondary photons, a 0.050 mm thickness Aluminum sheet was placed between the soil sample and the GM detector window.

Two methods for measuring the mass attenuation coefficient were utilized: the first one was based on the elemental composition of the soils and the second one was based on the slope of the graph ln (I) versus the path length (ρx). The elemental composition and the calculation of μ for the soils were analyzed, respectively, by energy dispersive x-ray fluorescence (EDXRF) technique and the XCOM computer code (National Institute of Standards and Technology). Details about the procedures followed by EDXRF measurements can be found in Ferreira et al. [11].

The second method was also used to obtain the density of compacted soil samples. The samples were manually pressed with the pestle up to a thickness of around 2.31 cm (half volume of the container). After compaction, the GM counts were recorded for a time interval of 10 minutes. It has to be mentioned that counts related to the background radiation (c. 386 counts) was subtracted of all the I measurements. The linear adjustment equation of the plot ln (I) versus the path length was afterward utilized for the determination of ρ. The schematic diagram of the experimental steps is presented in Fig. 3. This experimental setup here presented is usually employed in a typical experiment for the students in laboratory classes.

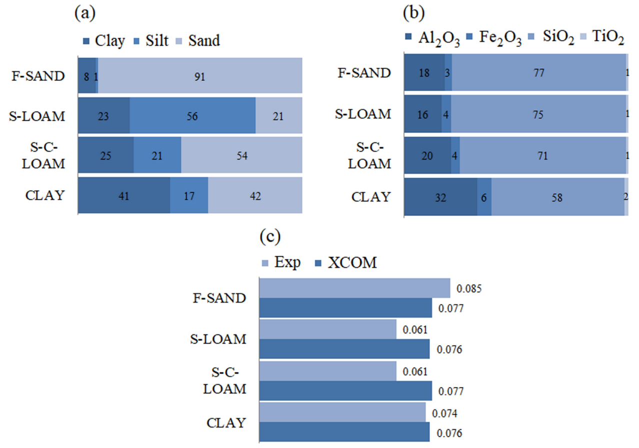

Figure 4: (a) Soil textural classes expressed in percentage. (b) Soil chemical composition based on oxides expressed in percentage. (c) Mass attenuation coefficient (Exp: experimental; XCOM: theoretical). F-SAND: Fine Sand; S-LOAM: Silt Loam; S-C-LOAM: Sandy Clay Loam; CLAY: Clay.

4. Experimental results

The different soil textural classes are shown graphically in Fig. 4a.

The chemical composition of the most abundant elements (Al, Si, Fe, and Ti) in the soils studied is presented in Fig. 4b. As can be seen, as a characteristic of Brazilian soils, SiO_2 and Al_2O_3 were responsible for more than 90% of the elemental composition of the investigated samples [11].

The experimental mass attenuation coefficients, based on the slope of the linear adjustment curves of ln (I) versus ρx, are presented in Fig. 4c and Table 1. The calculated μ determined via XCOM is also shown in Fig. 4c. The theoretical μ (XCOM) was utilized for comparison reasons to that one obtained by the experimental setup here proposed (Exp).

The calculated μ presented similar values among soils, which indicates that their elemental composition had minor influence in the mass attenuation coefficient for the photon energy studied (c. 0,660 MeV). This result is in accordance with others presented in the scientific literature [7].

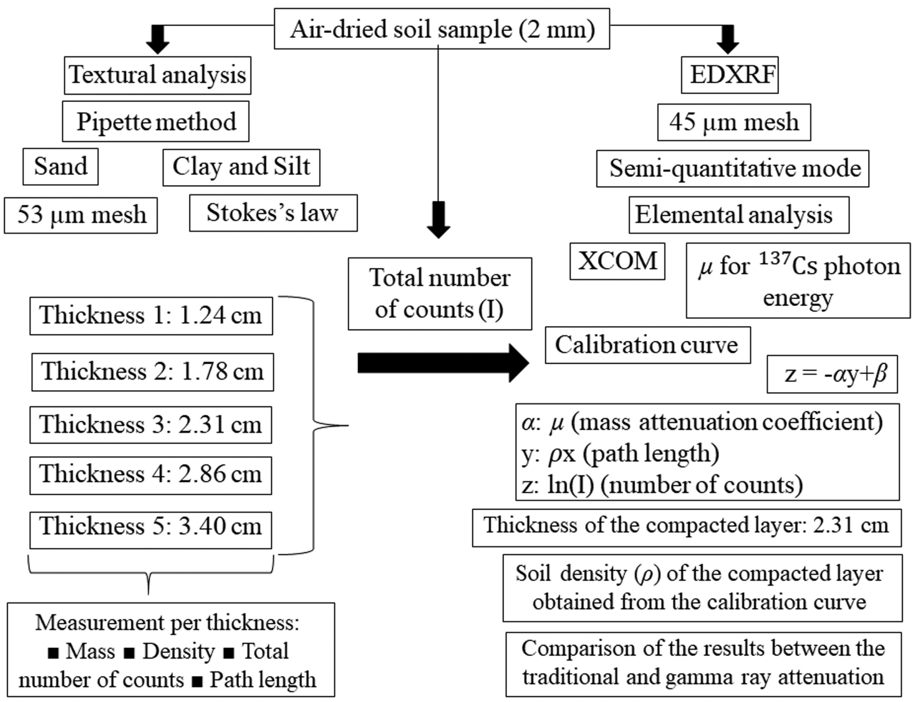

Figure 3: Schematic diagram of the procedures carried out in this study.

Table 1: Linear adjustment parameters of the graphs of ln (I) versus path length (ρx) for the soils studied

Soil/Parameter	α	β	R^2	p
F-SAND	-0.085	9.528	0.982	<0.01
S-LOAM	-0.061	9.350	0.978	<0.01
S-C-LOAM	-0.061	9.403	0.989	<0.01
CLAY	-0.074	9.443	0.981	<0.01

F-SAND: Fine Sand; S-LOAM: Silt Loam; S-C-LOAM: Sandy Clay Loam; CLAY: Clay; I: Transmitted photon intensity (cps); x: Soil thickness (cm); ρ: Soil density (g cm^{-3}); R^2: Coefficient of determination.

Table 2: Soil density determined by the traditional (TRAD) and by the gamma ray attenuation (GRA) methods.

Soil/Methods	TRAD	GRA	RD (%)
F-SAND	1.58	1.61	-1.9
S-LOAM	1.14	1.16	-1.8
S-C-LOAM	1.35	1.37	-1.5
CLAY	1.16	1.19	-2.6

RD: Relative difference obtained by: RD = $[(\rho_{\mathrm{TRAD}} - \rho_{\mathrm{GRA}})/\rho_{\mathrm{TRAD}}] \times 100$

Differences between the experimental and calculated μ varied from c. 3% (CLAY), c. 9% (F-SAND), and c. 20% (S-C-LOAM and S-LOAM) among soils (Fig. 4c). It was observed that in the worst cases (S-C-LOAM and S-LOAM) the emerging radiation intensity was less affected by the variation of the sample thickness (1.24 to 3.40 cm) [12]. Even being μ determined by the Beer-Lambert attenuation law close to that one determined by the XCOM, it is important to emphasize that the laboratory set up is prone to not produce accurate measurements of μ due to the lack of source and detector collimation as well as the type of detector and electronics used [13]. Then, errors as here reported are perfectly possible to be noticed. Nonetheless, this kind of experiment serves mainly for introducing to the students important aspects of the radiation attenuation by the matter.

Graphs of the gamma ray intensity transmitted across the soil samples for the different thicknesses indicate that all points lie on straight lines (Table 1 and Fig. 5). The experimental points more distant from the straight lines can be related to the detection of scattered photons by the GM detector, influenced by the nonexistence of collimation in the utilized experimental set up [14]. In this case, to collimate source and detector would worsen the signal/noise rate as low activity radioactive sources are usually employed for educational purposes [15,16].

The graphs of ln (I) versus ρx also served to measure the density of the soil. The values of ρ determined by the experimental apparatus proposed are given in Table 2.

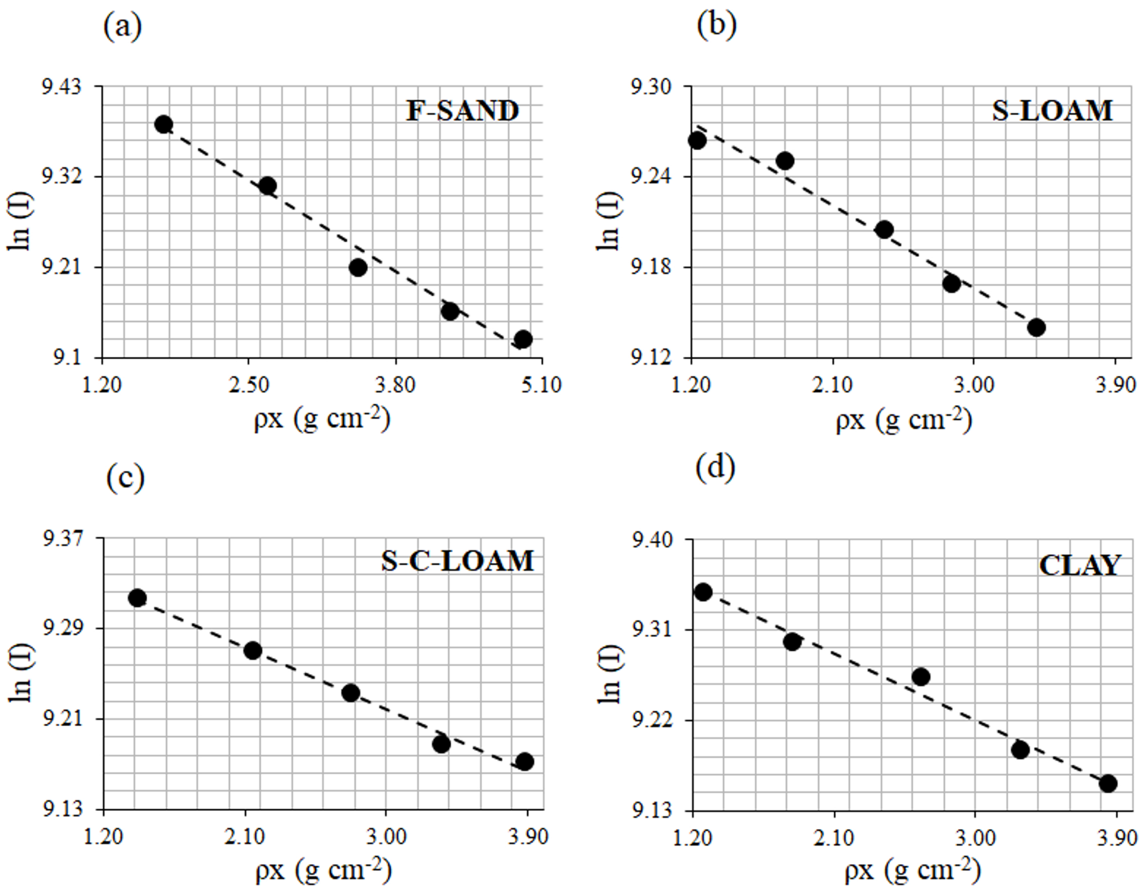

Figure 5: Gamma ray photons transmitted ln (I) as function of the path length (ρx). (a) F-SAND: Fine Sand. (b) S-LOAM: Silt Loam. (c) S-C-LOAM: Sandy Clay Loam. (d) CLAY: Clay.

The largest difference between the traditional and GRA method was observed for the CLAY soil sample. However, all the soils investigated presented very good agreement between methods (RD<3%). The largest difference found for the clayey soil can related to the size of the clay particles (<0.002 mm) and their capacity for filling the spaces between pores inside the plastic container [9]. However, the results obtained in this paper are an indicative that the method proposed can be used with success for the determination of the soil density. For instance, educational studies related to soil compaction due to natural or anthropogenic causes could also be easily carried out utilizing the experimental set-up presented.

5. Concluding remarks

The experimental apparatus here proposed, that uses an educational gamma ray attenuation system, permitted measuring, with very good agreement in relation to the traditional method, the density of soil samples. The curves (graphs of ln (I) versus path length) obtained in the experiments allowed presenting very important aspects of the radiation attenuation by the matter that is frequently modeled by the Beer-Lambert attenuation law. The experiment can be somehow extended by proposing the investigation of soil bulk variations due, for instance, to soil compaction, a subject of interest for engineering and environmental physics students.

Acknowledgements

The authors would like to thanks the CNPq for the productivity grant in research (303726/2015-6), and the Capes by Doctorate grants.

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