Estimating the Depth of Buried Radioactive Sources using Ground Penetrating Radar and a Gamma Ray Detector

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***Abstract*—This study reports on nonintrusive depth estimation of a buried caesium-137 radioactive source using a ground penetrating radar (GPR) and a gamma ray detector. Specifically, the bulk density estimates from the GPR was used to fit a gamma ray attenuation model to the data from the detector. The depth of the source was successfully estimated when buried up to 18 cm in sand, gravel and soil. This will help in nonintrusive monitoring of nuclear contaminated sites.**

I. INTRODUCTION

Shallow subsurface radioactive contamination is a major health hazard because of the risks of direct exposure to the public and the absorption of these contaminants by plants. Hence, there is a need to know the depth of penetration these contaminants to monitor their evolution in contaminated sites. However, intrusive depth estimation methods are slow while nonintrusive methods such as [1]-[2] are either based on empirical models or are limited to specific radioisotopes. This study reports on the combination of a ground penetrating radar (GPR) and a gamma ray detector for nonintrusive estimation of the depth of a buried radioactive source [3]. Four permittivity mixing formulas were studied to estimate the material bulk density required to fit a gamma ray attenuation model to the data from the gamma ray detector.

II. METHODOLOGY

A. Theoretical framework

The radiation intensities $I_(x, y, z)$ at different positions on the surface (x, y) of a material volume due to a radioactive source buried at depth z is given by [3]:

$$log_e\left(\frac{I_{(x,y,z)}}{I_{(0,0,z)}}\right) \approx -\frac{\mu_m \rho_b}{2z}(x^2+y^2) + log_e\left(\frac{I_{(x,y,0)}}{I_{(0,0,0)}}\right) \quad (1)$$

where μ_m is the mass attenuation coefficient which is relatively constant and ρ_b is the bulk density. However, in order to fit (1) to measured data, the bulk density must be known hence the need for GPR for nonintrusive bulk density estimation. Therefore, the following permittivity mixing formulas were studied namely; Rayleigh, Bottcher and the power law with exponents of 0.5 and 0.65 (referred to as PL0.5 and PL0.65 in this study) [4]. These formulas are given by (2)-(5) respectively where ϵ_b is the bulk permittivity, $\epsilon_s, \epsilon_w, \epsilon_a$ are the permittivities of solid particles, water and air respectively, θ is the water content and ϕ is the porosity of the medium which is given by (6) where ρ_s is the specific density of the solid particles.

$$\frac{\epsilon_b - \epsilon_s}{\epsilon_b + 2\epsilon_s} = (\phi - \theta)\frac{\epsilon_a - \epsilon_s}{\epsilon_a + 2\epsilon_s} + \theta\frac{\epsilon_w - \epsilon_s}{\epsilon_w + 2\epsilon_s} \quad (2)$$

$$\frac{\epsilon_b - \epsilon_s}{3\epsilon_b} = (\phi - \theta)\frac{\epsilon_a - \epsilon_s}{\epsilon_a + 2\epsilon_b} + \theta\frac{\epsilon_w - \epsilon_s}{\epsilon_w + 2\epsilon_b} \quad (3)$$

$$\epsilon_b^{0.5} = (1-\phi)\epsilon_s^{0.5} + (\phi - \theta)\epsilon_a^{0.5} + \theta\epsilon_w^{0.5} \quad (4)$$

$$\epsilon_b^{0.65} = (1-\phi)\epsilon_s^{0.65} + (\phi - \theta)\epsilon_a^{0.65} + \theta\epsilon_w^{0.65} \quad (5)$$

$$\phi = 1 - \frac{\rho_b - \theta}{\rho_s} \quad (6)$$

B. Experimental Methods

The setup for the acquisition of the gamma radiation data is shown in Fig. 1. It consists of a perspex box whose front surface was divided into 4 × 4 cm^2 grids. During the experiment, the box was filled with one of the materials (Table I) under investigation and a 658 kBq caesium-137 (Cs-137) radioactive source was placed at depths varying from 2 cm to 22 cm at 4 cm intervals along the z-axis. At each depth, the intensity of the buried source was measured from seven grids along the diagonal on the front surface of the box using a gamma radiation detector placed inside a tungsten shield.

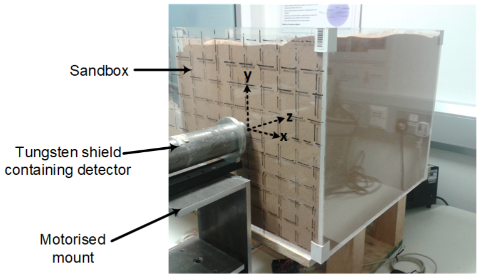

Fig. 1. Setup for gamma data acquisition

TABLE I
PROPERTIES OF THE MATERIALS USED IN THE STUDY

Properties	Sand	10mm Gravel	Soil
Bulk density (ρ_b) (g cm^{-3})	1.52	1.54	1.26
Mass attenuation coefficient. (μ_m)	0.0776	0.0775	0.0773
Solid permittivity (ϵ_s)	4.7	6.5	4.7
Specific density (ρ_s) (g cm^{-3})	2.65	2.65	2.65
Water content (θ) (%)	0.0	0.0	6.0

The bulk permittivity of the materials required to evaluate (2)-(5) was estimated using:

$$\epsilon_b = \left(\frac{1 + [A_m/A_{pec}]}{1 - [A_m/A_{pec}]} \right)^2 \tag{7}$$

where A_m and A_{pec} are the reflected amplitudes from the material and a metallic surface respectively. The GPR system used in the study has a central frequency of 1.2 GHz and the antenna was fixed in a central position 15 cm from the box (Fig. 2). Also, the reflected pulse when the box was empty was subtracted from the measured pulses in order to remove the contributions from the wall of the box and the direct wave.

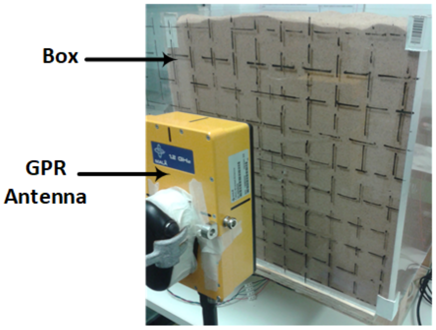

Fig. 2. Setup for GPR data acquisition.

III. RESULTS AND DISCUSSIONS

The error in the estimated bulk densities for the four mixing formulas are shown in Fig. 3. It can be observed that all the formulas yielded reasonably good estimates for both sand and gravel with an average error of 5% and 3.75% respectively. However, the significant difference in the performance of the formulas can be observed in the result for soil where all the formulas except the PL0.65 formula performed very poorly. The poor performance of the three mixing formulas is due to their inability to account for the effects of bound water which is dominant at low water content.

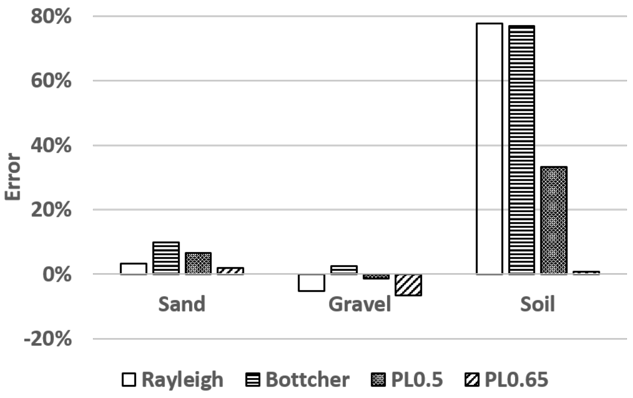

Fig. 3. Error in the estimated bulk densities from the mixing formulas.

Using the bulk density estimates from the PL0.65 formula, (1) was fitted to the gamma radiation data to estimate the depths of the buried Cs-137 source shown in Fig. 4. It can be observed that the depth of the source was relatively well estimated up to 6 cm beyond which the estimated depth linearly deviates from the measured depth. This linear deviation is due to the fact that (1) does not account for the inverse square reduction in the gamma radiation intensity as the depth increases. However, the good linear correlation between the estimated and measured depths as indicated by the high adjusted r-squared values means that a linear correction factor can be applied to the estimated depth to obtained the measured depth. These results shows that this depth estimation technique will be useful in the nonintrusive monitoring of shallow subsurface radioactive contamination in nuclear sites.

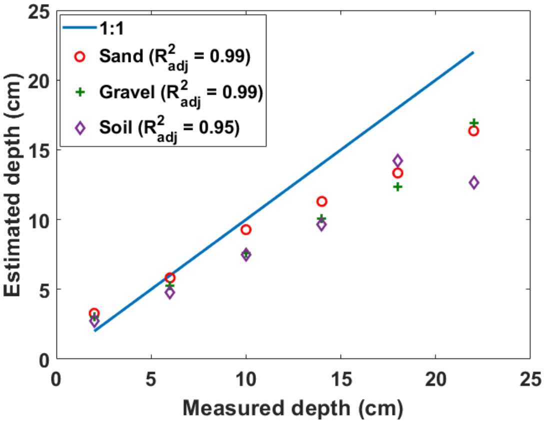

Fig. 4. Estimated depths of the Cs-137 source buried in the three materials.

ACKNOWLEDGEMENT

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