Validation Of A Model For Nonintrusive Depth Estimation Of Buried Radioactive Wastes

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***Abstract*—This paper presents improved results using a Cadmium Zinc Telluride (CZT) detector for a recently developed image-based nonintrusive depth estimation method for buried radioactive wastes. It showed that the use of the CZT detector resulted in an improved maximum detectable depth of 18 cm with a significantly lower average count rate of 14 cps compared to the maximum detectable depth of 12 cm with an average count rate of 100 cps previously obtained using an organic liquid scintillator.**

***Index Terms*—Radioactive land contamination, Noninstrusive depth estimation, Gamma imaging, Nuclear decommissioning, Cadmium Zinc Telluride detector**

I. Introduction

WIDE spread shallow subsurface radioactive contamination such as the case reported in the beaches of Dounreay in Northern Scotland [1] are a major environmental and decommissioning challenge. This is because of the difficulty in estimating the depth of penetration of the contamination without having recourse to intrusive techniques such as logging which are time consuming and have limited extent for sampling. Furthermore, some of the reported nonintrusive techniques are either based on empirical models [2], [3] or are limited to radionuclides with more than one photo peaks in their gamma spectrum [4], [5]. In addition, the nonintrusive technique reported in [6] require specialized shielding and collimator arrangements. Therefore, a novel image-based nonintrusive depth estimation technique using an approximate three-dimensional (3D) linear attenuation model was recently developed [7]. This paper presents improved results from the technique using a Cadmium Zinc Telluride (CZT) semiconductor detector.

II. Methodology

A. The approximate 3D linear attenuation model

Given a source buried inside a material at depth z (see Figure 1), the ratio of the intensity $I_{(x,y,z)}$ measured at any position (x, y) on the surface of the material to that measured from a reference position (i.e. $(x, y) = (0, 0)$) on the same surface is given by:

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

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where $J_{(x,y,z)} = \frac{I_{(x,y,z)}}{I_{(0,0,z)}}$, μ_m = mass attenuation coefficient, ρ_b = bulk density, and $K_{(x,y,0)} = \frac{I_{(x,y,0)}}{I_{(0,0,0)}}$. The depth z of the buried source can be estimated by fitting Equation (1) to the data of the intensities obtained by measuring the spectra of the buried source from discrete positions on the surface of the material volume. Detailed derivation and analysis of Equation (1) can be found in [7].

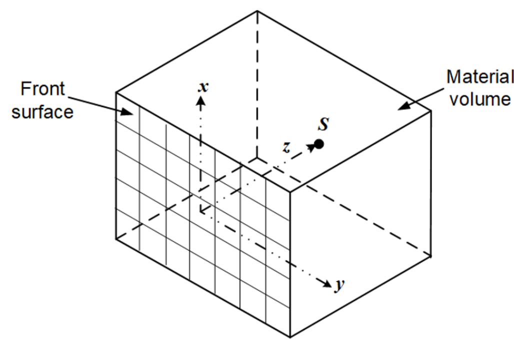

Fig. 1. Radioactive source S buried inside a material volume.

B. Experiment

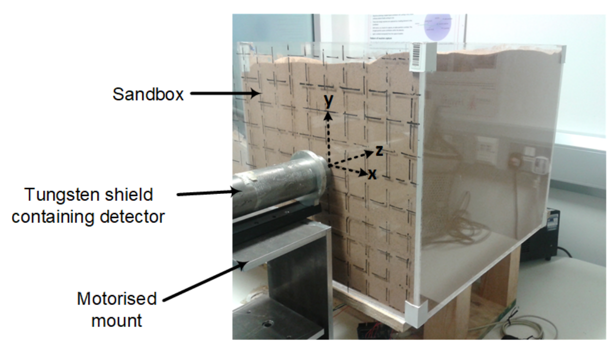

Fig. 2. Experiment setup.

The setup for the experiment is shown in Fig. 1. It consists of an acrylic plastic box filled with sand. The measured bulk density of the sand is 1.55 g cm^{-3} and the calculated mass attenuation coefficient is 0.0776. The mass attenuation coefficient of the sand was calculated using its elemental weight fractions obtained from Scanning Electron Microscopy and the mass attenuation coefficients of each element obtained from [8]. The radiation source used in the experiment is a sealed 329 kBq Cs-137 point source. The source was attached to one end of a calibrated pipe whose other end protrudes behind the box. This was used to adjust the position of the source along the z-axis. The CZT detector (CZT/500S from Ritec (Riga, Latvia)) was placed inside a hollow cylindrical tungsten shield with an inner radius of approximately 4 cm. The shield was then attached to a motorised mount for automated positioning at any desired position on the front of the box. The output from the detector was connected to an oscilloscope (sampling rate = 500 kSa/s) controlled by a personal computer which processed the pulses to generate the pulse height spectrum. During the experiment, the position (i.e. depth) of the source was varied from 2 to 20 cm at 2 cm intervals along the z-axis. At each depth, the spectrum was acquired from an area of 28 $\times$ 28 cm^2 divided into 4 $\times$ 4 cm^2 grids resulting in 49 spectra per depth. Finally, a scanning time of 25 minutes per position was used in the experiment.

III. Results and Discussions

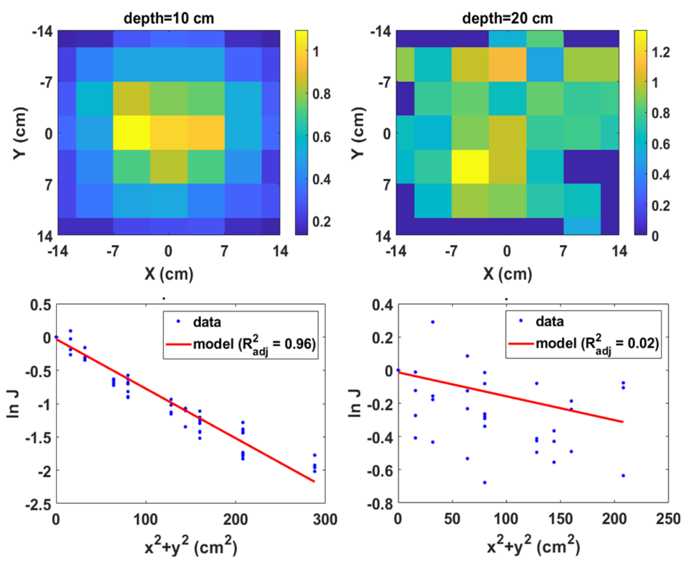

Fig. 3. Radiation images obtained at 10 cm and 20 cm depths (top row) and graphs of the model for both images respectively (bottom row)

The radiation images obtained when the Cs-137 source was buried at depths of 10 cm and 20 cm respectively are shown in the top row of Figure 3. The pixel values of the images are the photon count at 662 keV from the spectrum measured at the corresponding x-y position on the front surface of the sandbox. The complete defocussing of the image at depth of 20 cm is due to significant attenuation of the gamma rays. The fitting of the attenuation model (i.e. Equation (1)) to the data from both radiation images are shown in their corresponding graphs in the bottom row of Figure 3. A negative linear trend in the data points can be observed for the graph of depth = 10 cm with a good model fit as indicated by the high adjusted r-squared value. Conversely, the data points for the graph at depth = 20 cm are randomly distributed which corroborate the attenuation effect identified in its image. Consequently, a poor model fit can be observed with a very low adjusted r-squared value of 0.02.

The estimated depths of the buried source from the fitted model are shown in Figure 4. It can be observed that the

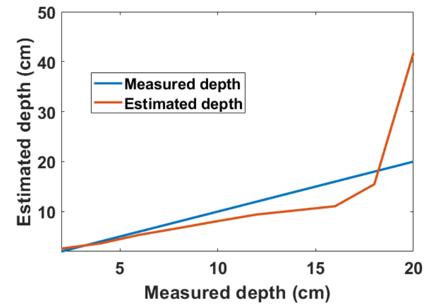

Fig. 4. Measured and estimated depths for the buried caesium-137 source.

estimated depth tracks the real depth up to 18 cm after which there is a sudden jump due to large error caused by significant attenuation of the gamma rays as already identified in the radiation image. However, an increasing deviation of the estimated depths from the measured depth can be observed as the depth increases. This deviation is due to the fact that Equation (1) does not account for the inverse square decrease of the radiation intensity as the depth increases. However, Figure 5 shows that there is a good linear correlation between the measured and estimated depths up to 18 cm. This means that the measured depth can be predicted from the estimated depth after calibration. The average count rate for the experiment was 14 cps where the average count rate is defined as the average of the count rates for each depth when the detector is located axially with the source. This achievement of a maximum detectable depth of 18 cm with an average count rate of 14 cps is a significant improvement compared to the 12 cm maximum depth with an average count rate of 100 cps obtained using an organic liquid scintillator [7].

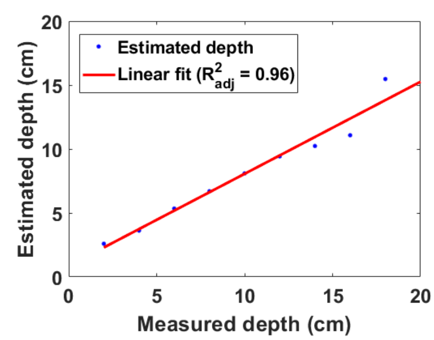

Fig. 5. Good linear correlation between the measured and estimated depths.

IV. Conclusion

Improved results using a CZT detector have been obtained for a nonintrusive method of estimating the depth for buried radioactive wastes. The use of the CZT increased the maximum detectable depth by 50% using only 14% of the average count rate compared to previous work. This will enable rapid nonintrusive localization of buried wastes at greater depths thereby eliminating one of the major challenges associated with decommissioning such wastes.

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