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AIR-DRIED SOIL COMPACTION MEASUREMENT BY COMPTON SCATTERED GAMMA RAYS

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ABSTRACT

In the broadest sense, all modes of interaction of ionizing radiation with matter could be employed in measuring techniques for material identification and process control. This work presents a densitometer designed to measure air-dried soil compaction. Supralinearity on set is observed to be a function of target density and its atomic number. For soils, a useful range of up to 50 mm has been identified for photon energy of 662 keV of 137 Cs radioisotopes. A minimum detectable density of $0.13 g/cm^3$ at a 97% confidence level is also demonstrated.

KEYWORDS. Compton instruments, compaction measurements, soil densitometer.

INTRODUCTION

In recent times, there has been resurgence in the applications of gamma and X - radiation to the study of physical characteristics of soil including density, mass attenuation coefficients, water content, and soil particle sizes (Crestana et al, 1986; Mudahar & Sahora, 1988; Cruvinel et al, 1990; Cesareo et al, 1993).

Several studies in the last few years have shown its potential in soil density measurement, soil compaction discrimination, and data related to water flow patterns in the soil. In all these applications, the transmission mode of photon measurement has been applied. One basic requirement in transmission measurements is access from both sides to the object being studied. This tends to limit the applicability of such technique, especially in the case of extended objects and also in relatively inhospitable agricultural environments, where access is limited to one side of the object. It has been particularly the case for direct field measurements, which perhaps explain why most measurements reported to date, have been laboratory-based.

Unfortunately, the best possible sample preparation cannot replicate the situation obtaining in undisturbed soil. It is, therefore, desirable to find a technique allowing *in-situ* measurement of the various parameters important in soil science. One such method employs backscatter photons for density measurement and mapping.

Compton backscatter densitometry has continued to gain momentum (Ball et al, 1998; Shukla et al, 1985; Hanson & Gigante, 1989; Balogun & Spyrou, 1993), and both coherently and

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incoherently scattered photon techniques have been singly or severally investigated for medical applications (Webster & Lillicrap, 1985; Mooney, 1996).

Industrially, Compton scattering measurements have found applications in areas such as quality control of machine tools, vehicular parts, and explosive charges in missiles as well as buried land mine detection (Lawson, 1995; Stokes et al, 1982; Sharaf, 2001). In all these, the positioning flexibility of the detector and source system has been capitalized on, and represents an opportunity for soil studies. Past efforts at *in-vivo* measurements using the transmission mode have been largely destructive and likely to have born little or no relation to *in situ* conditions. Here, we present a study of the variation of scattered photon numbers with density and introduce an application of this technique to air-dried soil densitometry.

INSTRUMENTATION AND MEASUREMENTS

In general, soil could be said to consist of four major components. These include organic matter, which is the product of dead animals and plants in varying stages of decomposition as well as a large spectrum of living organisms, and mineral matter derived from weathering of source rocks, water, and air.

The soil samples employed in this study were obtained from a research station, a few kilometers from São Carlos, São Paulo State, Brazil. Samples were obtained at a depth range of 5.0 – 50.0 cm. This enabled us to reduce organic matter occurrence in our sample and increase the chance of sample homogeneity. The soil was then dried in free air at room temperature for a period of more than four weeks, after which it was hand-crushed. Soil aggregate segregation was achieved by manually sieving the sample with the aid of Bertel Industry Ltd. of Brazil set of sieves. Five different soil aggregate ranges were thus obtained: 1.00 – 2.00 mm, 0.50 – 1.00 mm, 0.21 – 0.50 mm, 0.10 – 0.21 mm, and particle sizes less than 0.10 mm in diameter. The air-dried and sieved soil samples were then placed in a number of thin-walled 50x50x80-mm Perspex boxes. By using a graded pressure on the soil surface, we varied the soil mass packed into boxes of fixed volume, thus achieving adequate density variation. This method eliminated dependence of measured quantity on soil type since the same soil is used at different packing ratios. Bulk densities of these were then estimated using the gravimetric method (Schwab & Frevert, 1985).

The experimental setup employed in this study is schematically shown in figure 1. A 137 Cs radioactive source is housed in a lead castle, which serves as shielding, making it possible to change source collimator. Gamma ray energy emitted by the source was 662 keV and source strength at the time of the experiment was 200 MBq. The source was provided with a 2.00 mm diameter boreholed collimator. The detector is also housed in a 5mm-thick lead jacket with a 2 x 4-mm rectangular holed collimator. The counting system took into account a NaI(Tl) scintillation detector, a spectroscopic amplifier, a single-channel analyzer (SCA), and a dual timer/counter. The NaI(Tl) detector was choosing for its photo peak efficiency at 250 keV scattered photon energy, at a 120^{o} scattering angle, the choice of which was informed by a numerical estimate of the angular dependence of the scattering volume. A best volume resolution at a $90^{o} \pm 30^{o}$ scattering angle range was achieved. Anode output of the detector's photomultiplier tube (PMT) was fed into an ORTEC 572 amplifier for charge amplification, integration, and pulse shaping. The resulting voltage pulse then passes into an SCA for digitalization.

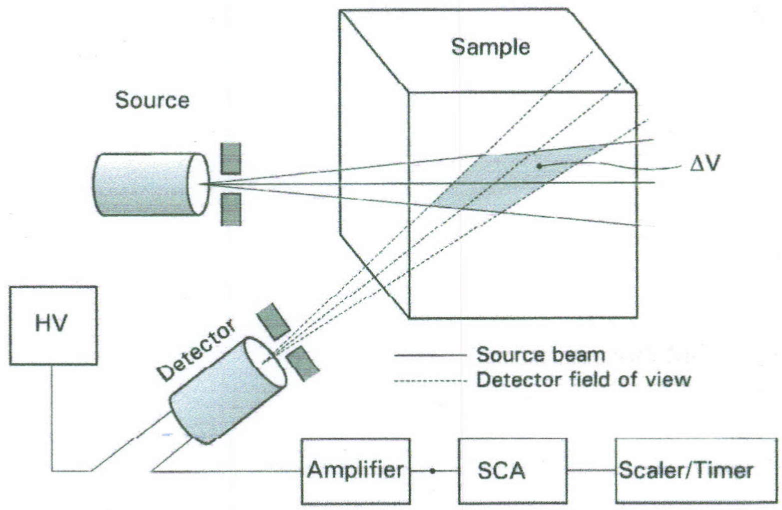

Figure 1. The experimental setup employed for soil compaction measurements (HV is the high voltage power supply, SCA is the single channel analyzer, ΔV is the soil volume covered by the gamma-ray photons in each measurement).

The SCA enabled to choose a lower-level pulse height E, below which no pulse was recognized, and a window-width ΔE within which all pulses were recorded. Besides, by setting a given lower level and a window it was possible to establish a selectively record of photon energy incident on the detector. By serially moving the lower level discriminator from a minimum value to a 10.0V maximum at a fixed 0.1V window width, it was possible to record counts for the entire spectrum. This was done for the case when an empty Perspex box was placed in the beam as the scatterer, to serve as a blank or background spectrum for the carried out measurements. The spectrum for the box when filled with soil was also taken. With such arrangement, it was also possible to set the counting window between 2.5V and 4.3V, corresponding to full width at tenth maximum (FWTM) of the scattered photo peak.

Using each soil sample as a target, the scattered photon number was recorded over a 100 second counting time. Ten replicate measurements were carried out for each sample. The precision obtained in all cases was better than 3%. Background counts were estimated by using an empty Perspex box, similar to the ones holding the samples as targets. These counts number were then subtracted from the scattered photon number recorded for each sample, and the result was obtained as a net count. Background measurements were made at the beginning and end of each day. No statistically significant difference in background counts was recorded during the period under study.

RESULTS AND DISCUSSIONS

For a given collimator size, length, and, its distance from the scattering center, scattering volume increases with increasing angle in the back-scattering geometry. The best volume resolution was found within the 90°±20° scattering angle range. Though volume resolution also decreases towards the forward scattering angles, resolution rate loss is much more pronounced in the backscatter angles.

The spectra of scattered photons with and without soil sample are presented in figure 2, in which two peaks are readily distinguishable. The first one, occurring at the lower energy end of the spectrum with its centroid at 3.5V, is attributable to those photons that were Compton-scattered from the sample into the detector. Interestingly, this peak appears only when there is soil in the Perspex box and never for the blank. On the other hand, the second photo peak, with a centroid at 7.1V, is present virtually the same degree in both background and sample spectra, a fact attributable to direct leakage of photons from the source, through the shielding material, to the detector. In fact, an additional 50mm-thick steel slab was placed between source and detector to reduce the leakage to its present level. Taking a window at FWTM for both background and sample spectra, a signal-to-noise ratio of 11.11 was obtained for a 50 seconds counting time.

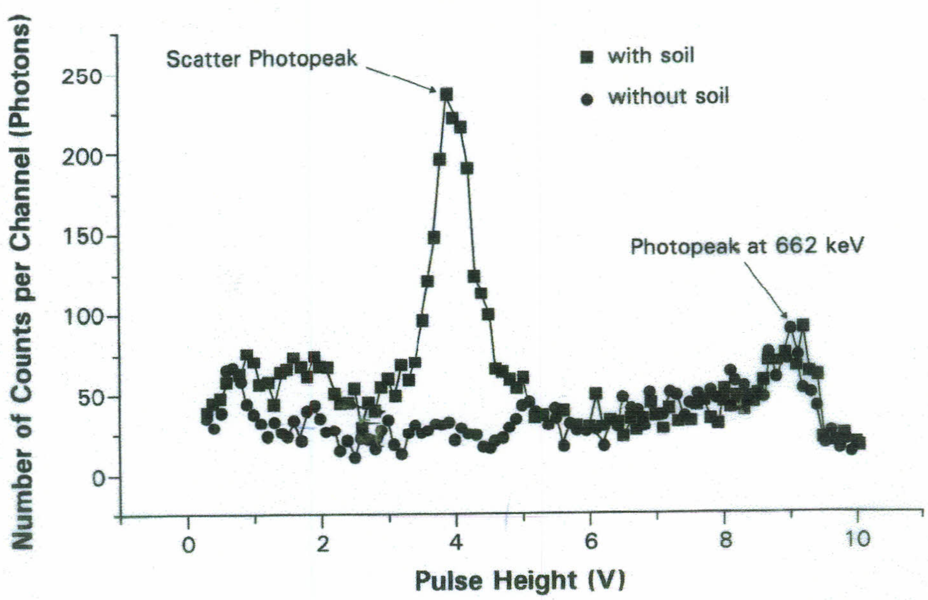

Figure 2. The spectra of scattered photons with and without soil sample.

Figure 3 shows the plot of the number of scattered photons against soil density obtained at various soils aggregate sizes ranges, combined from several measurements. For such result it was possible to examine the influence of changing soil aggregate on the density dependence of the number of scattered photons. Linear relationships were observed within all aggregate size ranges. In all cases, the coefficients of linear regressions, r^2, were greater than 0.97.

The linear relationships found, however, was independent of soil aggregate size, possibly as a result of the insensitivity of the technique to the elemental constituents of the sample. The major difference between soils of different aggregate sizes is air content. Therefore, since the volume sampled is constant, air content reduces density causing the data point to recede down the curve. It was also observed a direct proportionality between number of scattered photons and soil bulk density, the linear relationship experimentally obtained did have a positive intercept on the vertical axis. This could be explained as a result of a number of measurement artifacts which include attenuation of incident and scattered gamma ray beams as they transverse the object and acceptance of multiply scattered photons within the solid angle subtended by scattering volume at the detector. However, the good linear relationship obtained between the number of scattered photons and soil density demonstrates the potential of this technique in soil densitometry.

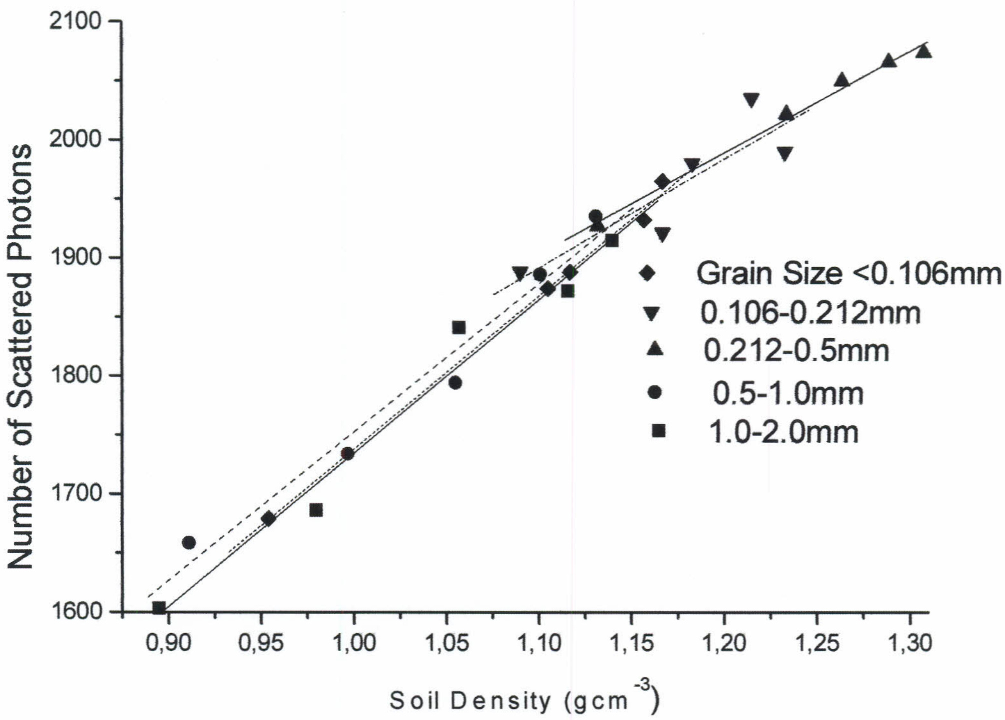

Figure 3. Plot of scattered photons against soil density obtained at various soils aggregate sizes ranges.

Therefore, in order to estimate the precision of this technique, it has been considered fifty replicate measurements of a given sample. The range of density values obtained for the sample was from 1.17 to 1.28. Within a 97% confidence level, a 0.13g/cm^3 limit of detection has been estimated for the system. Obviously, these quantities are expected to vary according to incident and scattered photon energy, the scattering angle, and background noise.

CONCLUSION

This study has demonstrated the viability of a Compton backscatter photon measurement to accurately determine density of a given air-dried soil sample with less than 3% error. A signal to-noise ratio of better than 11 has been demonstrated for a soil sample counted for 50 seconds. This was improved by 27% when the counting time was increased four times. After a replicate measurement of 50, the relative uncertainty in our measurements was estimated at less than 4% and a minimum detectable density of 0.13g/cm^3 was obtained at a 97% confidence level. The measurement is shown to be linear over the range of soil densities important in agricultural soil compaction studies. It is therefore envisaged that the technique could find applications in agricultural fields, where soil compaction, occasioned by repeated usage of agricultural implements and vehicles could be a limiting factor in production and quality control.

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