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AN IMPROVED METHOD TO MEASURE IN SITU WATER CONTENT IN A LANDFILL USING GPR

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Abstract:
The ability to estimate and evaluate in situ water content is fundamental to the effective operation of a landfill, as water content has a direct impact on decomposition of waste and ultimately on landfill gas generation. Currently, it is a challenge to measure water content in situ without serious disruptions to the landfill operation. Ground penetrating radar (GPR) is a non-destructive technology that can estimate the water content of landfills in situ. The challenge to using GPR in landfill applications is the selection of an appropriate mathematical relationship that represents the electromagnetic wave as it propagates through the landfill mass. Specifically, a mathematical relationship is needed to describe the relationship between the dielectric permittivity of the landfill soil and the volumetric water content of the soil. Having this relationship will improve the analysis of the GPR data. For this study, the complex refractive index model (CRIM), a volumetric mixing model, was selected to determine volumetric water content of the soil from real GPR images. The results show that using CRIM can provide more accurate results than the typical Topp equation. The study also determined optimum conditions for water content measurements via GPR for an antenna frequency of 1GHz with an offset distance between the transmitter and receiver of 3 m.

1. INTRODUCTION

The water content of the soil in a landfill is an essential parameter in landfill control applications for processes such as decomposition of waste and landfill gas generation (LFG) as a source of renewable energy (Yochim, 2010). Furthermore, the water content of the landfill is an important parameter in the design and control of bioreactor landfills (Guérin et al., 2004).

Ground penetrating radar (GPR) is a non-destructive method that has been used to effectively estimate the soil water content of landfills in situ (Yochim et al., 2013). GPR does not measure the soil water content directly; however, it detects changes in the electrical properties of the soil due to changes in soil water content. These electrical properties of the soil include dielectric permittivity, electrical conductivity and magnetic permeability. The dielectric permittivity (dielectric constant) of the soil is considered the most important parameter when using GPR for soil water content, because water has a much higher dielectric permittivity than other earth materials due to the polar nature of water molecules (Everett, 2013).

Since GPR does not measure the soil water content directly, GPR data must be validated by comparing the estimated soil water content with reference data measured by other means. The most common of these is the Standard Method (also known as the gravimetric method), which is based on measuring the mass of soil samples which have been oven-dried for a specific period of time. Then, the mass of the dried samples are converted to volume by considering the bulk density of the soil. The disadvantages of this method are the sample sizes, high cost and destructive nature of the test on the actual site (Endress and Bertrand, 2006; Huiseman et al., 2003; Parkin et al., 2000; Yochim, 2010). In this study, GPR measurements have been validated by comparing the estimated GPR water content with estimated water content using the Standard Method (reference data) as reported by Yochim (2010).

Several approaches have been developed to estimate the soil water content by using GPR data. These approaches include: empirical equations, volumetric mixing models, differential effective medium approximation (DEMA) and frequency-specific functions (Vandam, 2014) for which petrophysical relationships connecting the dielectric properties of soil with the soil water content have been derived. The accuracy of estimating the soil water content depends on choosing the appropriate petrophysical relationship. Choosing an appropriate relationship depends on several factors, such as availability of soil variables to the user, frequency of the GPR equipment, and desired level of detail of the output (Vandam, 2014; Steelman and Endress, 2011). This means that there is no general approach that is optimal for use in all situations.

Selecting an appropriate petrophysical (mathematical) relationship that connects the dielectric permittivity and volumetric water content of the soil for use with GPR in an active landfill, is challenging. The empirical equation developed by Topp et. al. (1980) is the simplest empirical equation and is suitable for many different types of soil, but not for clay. Although simple, the Topp equation (Eq.1) has limited effectiveness for estimating the soil water content as it does not consider porosity and other soil properties that can impact the electromagnetic properties of the soil.

[1] $\Theta = -5.3 \cdot 10^{-2} + 2.92 \cdot 10^{-2} K - 5.5 \cdot 10^{-4} K^2 + 4.3 \cdot 10^{-6} K^3$

Where:
K = dielectric constant of the soil mixture (unitless)
Θ = water content (m^3/m^3)

In contrast to the empirical equations, volumetric mixing models can consider many parameters, including the dielectric constant of soil mixture, the dielectric constant of each constituent of the soil mixture, the volumetric water content and the porosity of the soil (Franco et al., 2003). The volumetric mixing models can also include a component to represent the presence of organic matter or another liquid besides the water, such as oil (Vandam, 2014). The general formula of the volumetric mixing model is shown in Eq. 2:

[2] $\varepsilon_{\mathrm{mix}}^{\alpha} = \sum_{i=1}^{n} v_i \varepsilon_i^{\alpha}$

Where:

$\varepsilon_{mix}^{\alpha}$ = complex bulk effective permittivity (i.e., real part of the dielectric permittivity which is called dielectric constant, K) of the soil mixture (F/m)
v_i = volume fraction of the i th component.
ε_i^{α} = dielectric permittivity of i th component (Kiα)
α = geometrical fitting parameter varying from (-1) to (1) depending upon the orientation of the electric field with respect to the surface of the medium

When the fitting parameter α equals 0.5, the volumetric mixing model in Eq. 2 becomes the complex refractive index model (CRIM) as shown in Eq. 3. CRIM is the most commonly used volumetric model as it gives reasonable accuracy (Vandam, 2014; Franco et al., 2003).

[3] $\sqrt{k_{mix}} = (1-n)\sqrt{k_p} + \theta\sqrt{k_w} + (n-\theta)\sqrt{k_a}$

Where:

k_{mix} = dielectric constant of the soil mixture (unitless)
n = porosity (unitless)
θ = water content (m^3/m^3)
k_a = dielectric constant of air (1; unitless)
k_p = dielectric constant of solid material (unitless)
k_w = dielectric constant of water (80-81; unitless)

Applying CRIM to estimate the water content requires identifying the dielectric constant of the soil mixture, water, air and the dielectric constant of the solid minerals. Rust and Russell (2000) determined an empirical relationship connecting the soil porosity with the dielectric constant of the solid minerals. This relationship provides an acceptable value of the dielectric constant of the solid minerals of the soil (Huisman et al., 2003). The dielectric constant (K) is considered unitless because it is the ratio between the complex dielectric permittivity of a material divided by the complex dielectric permittivity of the vacuum (Saarenketo, 1998).

The objective of this study was to compare CRIM determined water content values to previous water content values determined by the Topp equation (Yochim et al., 2013). The field GPR measurements taken by Yochim were reanalyzed using CRIM and the resulting water content values were compared to the previously taken field sample measurements of an active landfill operated by the Region of Waterloo's Waste Management Division. Statistical analysis was completed to validate the differences in water content. In addition, sensitivity tests were carried out to identify the optimum antenna frequency and the optimum offset distance between the transmitter and receiver to enhance the accuracy of GPR data interpretation when using CRIM.

2. METHODOLOGY

The study used the field data set obtained for the landfill of the Region of Waterloo's Waste Management Centre (Yochim, 2010). Yochim et al. (2013) applied the Topp equation (Eq.1) to estimate the water content of the landfill and found that the Topp equation overestimated the water content at some depths and underestimated the water content at other depths of the landfill when compared to the field measured water content data.

The estimated volumetric water content using the CRIM equation was based on the extracted velocity of EM wave propagation from GPR traces. The GPR traces, using the borehole GPR survey method, were reported in Yochim (2010). The variation in estimated soil volumetric water content by the CRIM was related to the variation of depth of GPR traces. The variation of GPR borehole depth was between -0.92 m to -5.72 m.

The first step in estimating water content using CRIM was to calculate the dielectric constant of the soil mixture (k_{mix}). The dielectric constant of the soil mixture (k_{mix}) was estimated using the relationship between the velocity of a reflected electromagnetic (RFEM) wave in a medium (v), and the velocity of an EM wave in a vacuum (c = 0.3 m/ns), as shown in Eq.4 (Yochim et al., 2013; Takahashi et al., 2012). In this study, the dielectric constant of the soil mixture (k_{mix}) was calculated using the extracted velocity (Eq.4) of EM propagation from GPR measurements (Yochim, 2010).

[4] $v = \frac{c_o}{\sqrt{k_{mix}}}$

Where:

v = velocity of EM propagation (m/s)

c_o = velocity of light in the space (3×10^8 m/s)

k_{mix} = dielectric constant of the host material (soil mixture) (unitless)

Applying CRIM to estimate the soil water content requires identifying the following parameters: soil porosity, dielectric constant of soil mixture, dielectric constant of air, dielectric constant of water and dielectric constant of solid minerals. The dielectric constant of the solid minerals was determined using Eq.5 (Rust and Russell, 2000).

[5] $(K)^{0.96} = \varphi+6.97^{0.96}(1-\varphi)$

Where:

K = dielectric constant of solid minerals (equal to k_p in Eq.3)
Φ = porosity of solid materials (referred to as n in Eq. 3)

To analyze the results statistically, the two samples-equal variance T-test was used to compare the accuracy of the Topp results to the accuracy of the CRIM results. The results that were closer to the reference data can be considered as the more accurate and acceptable results.

The T-test technique was applied first to validate the calculated results from the Topp equation (i.e., estimated soil volumetric water content) with reference data (estimated volumetric water content by lab experiments using the standard method). The second application of the T-test method was to validate the calculated results from the CRIM equation (i.e., estimated soil volumetric water content) with the reference data. The calculated P-values of the two stages were then compared. The P-value is the probability of obtaining a result equal to or extremely more than the reference data (standard method). The P-value has a usual cut off (0.05). This means that if the calculated P-value > 0.05, there is no evidence of a difference between the mean of the two analysed groups. In contrast, if the calculated P-value <0.05, there is strong evidence of the difference between the mean of the two analysed groups. The R-program, which is statistical software, has been used to calculate the P-value for the T-test calculations.

Furthermore, sensitivity tests were conducted for both the antenna frequency and the offset distance between the transmitter and receiver to identify both the optimum antenna frequency and optimum offset distance. The sensitivity test was based on generating (2D) synthetic surface-based reflection GPR data sets. A series of the synthetic GPR datasets has been generated using the range (100MHz, 200MHz, 450MHz, 1GHz and 1.5GHz) values of the frequency and the range (1m-1.5m, 2m, 2.5m and 3m) values of the offset distance. Generation of the (2D) synthetic surface-based reflection GPR datasets was based on the Finite Difference Time Domain (FDTD) numerical modeling method via Matlab (Irving and Knight, 2006).

3. RESULTS AND DISCUSSION

3.1 Estimation of water content by using CRIM

Table 1 reports the estimated water content (WC %) by CRIM and Topp. Yochim et al. (2013) used the Topp equation to estimate the soil water content since it is simple to use and does not require other input parameters like CRIM. The challenge with using CRIM was obtaining the dielectric constant of the solid minerals as one of the input parameters.

Visual review of the results in Table 1 shows that both methods reported the variation in water content with depth, ranging from -0.92m to -5.72m. Both methods showed the same trend, with Sample 6 having the lowest water content. Overall, the Topp results were generally lower than the CRIM results. Better comparison is possible with the T-test as described in Section 3.2.

3.2. Statistical Analysis (Two samples - equal variance, T-test)

T-test is the statistical technique used to assess the relative accuracy of CRIM results by analysing the difference between the CRIM results for calculated water content with the measured reference data (i.e., estimated water content by the standard method). The assessment process uses the calculated P-value through the T-test. The assessment process of CRIM includes analyzing two groups, which are the

Table 1: Estimated water content by CRIM and Topp

# Sample	Lab WC % Vol	CRIM W.C % Vol	Topp WC % Vol
1	7.4	20.3	19.9
2	21.2	15.0	14.9
3	25.9	13.9	14.1
4	15.4	11.8	11.7
5	24.7	15.4	15.5
6	30.6	9.3	9.9
7	20.8	10.5	10.6
8	27.5	25.6	24.9

estimated volumetric water content by CRIM, and the water content of the landfill measured in the lab (reference data). The estimated P-value, obtained by using the R-program for the mean of the two analysed groups, was equal to P-value=0.0657, which was greater than 0.05. This means there is no significant difference between the mean values of the calculated water content by CRIM and the mean of the reference data.

The assessment process for the Topp results includes analyzing two groups which are: estimated water content by Topp and the water content measured in the lab (reference data). The calculated P-value was equal to 0.02283 based on the R-program. This means that there is evidence that the difference between the calculated water content by using the Topp equation and estimated water content by lab measurements is insignificant.

However, the P-value related to the comparison between CRIM results and the reference data (P=0.0657) was larger than the P-value related to the comparison between Topp results and the reference data (P=0.02283). This means that the results of CRIM are closer to lab measurements (reference data) than the results of Topp. Thus, for estimating the volumetric water content of the landfill, CRIM can provide more accurate results than Topp.

The results of the sensitivity test for optimizing the optimum frequency was conducted by generating a series of (2D) synthetic surface-based reflection GPR data sets with a range of dominant frequencies. The range of the dominant frequencies used was 100MHz, 200MHz, 450MHz, 1GHz and 1.5GHz. The values of offset distances tested were 0.5, 0.75, 1.0, 1.25, 1.5 and 2 m.

Table 2 shows the estimated water content for different values of x. The ideal frequency for the numerical modelling was determined at 1GHz. Using the optimum frequency, the reflected electromagnetic wave velocity (RFEM), dielectric constant (K_{mix}), and the volumetric water content were calculated for each offset distance (x). Table 2 shows that the optimum offset distance is 3 m, as it had the lowest percentage of error in the water content measurement. The percentage of difference of water content was calculated by taking the percentage of the difference between the initial water content (θ=0.074) and the calculated water content. The initial water content was determined from the laboratory estimated water content for the soil sample at the depth (d=0.4 m).

Table 2: Results of simulations of the soil model, with frequency=1GHz, Initial water content=0.074

Offset x (m)	(m/ns) velocity	Dielectric Constant (K_{mix})	Calculated water content	% error of water content
1	0.160	3.512	0.028	60
2	0.143	4.364	0.058	19
3	0.134	4.938	0.069	5

4. CONCLUSION

The ability of using GPR to estimate the volumetric water content of landfills has various advantages as testing could be in situ and less destructive than the traditional standard method using the gravimetric approach. The challenge in estimating the moisture content of the landfills via GPR was the selection of an appropriate petrophysical relationship that could provide the most accurate results possible, when compared with the reference data.

This study shows that when the volumetric model is modified to give the CRIM relationship, CRIM provides better water content results when compared to the Topp equation using the same GPR data set. This was confirmed using the statistical analysis (T-test) on the CRIM and Topp results, when compared to the reference data.

The completed sensitivity tests showed that the optimum GPR parameters for landfill soil water content measurements were an antenna frequency of 1 GHz with the offset distance of 3 m between the transmitter and receiver.

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