Enhancing dielectric contrast between land mines and the soil environment by watering: modeling, design, and experimental results.

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ABSTRACT

The complex dielectric constant of the soil surrounding a landmine and its contrast with the dielectric constant of the landmine are critical to the effectiveness of ground penetrating radar (GPR) for landmine detection. These parameters affect the velocity and attenuation of the radar signal as well as the strength of the reflection from the mine. The dielectric properties of the soil depend on the soil texture and bulk density as well as the soil water content. In previous work, we have simulated the unsaturated water flow around a landmine. In this paper we summarize a collection of models that can be used to predict the dielectric constant, velocity of the GPR signal, attenuation, and reflection coefficient from soil type and soil water content. These models have been integrated into a MATLAB software package. Using these models, we can determine whether or not field conditions are appropriate for use of GPR. Under dry conditions, the soil water content may be too low for good GPR performance. If the soil is too dry, we can select an appropriate level of soil water content and design a watering scheme to bring the soil water content up to the desired level. We present a case study in which a soil watering scheme was designed, simulated, and then performed at a field site.

Keywords: Landmine Detection, Ground Penetrating Radar, Dielectric Properties, Modeling

1. INTRODUCTION

The dielectric properties of the soil surrounding landmines have an important effect on the performance of ground penetrating radar (GPR) systems for landmine detection. The dielectric properties of the soil depend on the soil texture, bulk density, and water content. Although soil texture and bulk density cannot be changed, it is possible to manipulate soil water content by watering the soil. In section 2 of this paper we discuss a suite of models that can be used to predict the dielectric properties of soil and the resulting response of a ground penetrating radar system. The model outputs can be used to determine whether or not GPR is likely to be an effective sensor under particular field conditions. In situations where the soil is too dry for GPR to work well, we can use the models to determine a water content level that will permit the effective use of GPR. Given a desired soil water content, we can design a watering plan that will bring the soil water content up to the desired level. We can also use simulation models of unsaturated water flow around the landmine to verify that such a plan is likely to have the desired effect. In section 3, we present an example in which this approach was used to design a watering plan for a dry sand soil at the Sevilleta National Wildlife Refuge. The watering scheme was simulated to verify that it would bring soil water content up to the desired level. We then performed a field experiment in which the watering plan was followed and direct measurements of soil water content were obtained. The experimental results confirmed the model predictions.

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2. MODELS OF SOIL DIELECTRIC PROPERTIES AND RADAR RESPONSE

The dielectric properties of a soil depend on a number of factors, including its bulk density, the texture of the soil particles (sand, silt, or clay), the density of the soil particles (typically about $2.6\ \mathrm{g/cm^3}$), the volumetric water content of the soil, the temperature, and the frequencies of interest.[1-3] Recent research has also shown that the dielectric properties of soil depend on the amount of "bound water" which is in close contact with minerals in the soil.[4-5] Theoretical and empirical models of the dielectric properties of the different components of the soil have been combined into semiempirical mixing models which can be used to predict the dielectric properties of field soils.[1,4,5,6,7]

In this section we summarize the 1995 model of Peplinski, Ulaby, and Dobson.[7] This model is a variant of the earlier model of Dobson, Ulaby, Hallikainen and El-Rayes.[5] The earlier model was calibrated for frequencies in the range of 1.4 to 18 Ghz.[8] The model discussed here was calibrated by fitting the model to a set of experimental observations with a variety of soil textures, soil water contents, and frequencies from 0.3 to 1.3 Ghz.[7]

The inputs to this model consist of the volumetric water content θ, the frequency f, the fraction of sand particles S, the fraction of clay particles C, the density of the soil particles ρ_S (a typical value is $2.66\ \mathrm{g/cm^3}$), and the bulk density of the soil ρ_B. An empirically derived formula for effective conductivity is

$$\sigma_{\mathrm{eff}} = 0.0467 + 0.2204\rho_B - 0.4111S + 0.6614C. \tag{1}$$

The sand and clay fractions also enter the model through two constants which depend on the soil type but are independent of the frequency and soil water content.

$$\beta^{\prime} = 127.48 - 0.519S - 0.152C \tag{2}$$

$$\beta^{\prime\prime} = 1.33797 - 0.603S - 0.166C \tag{3}$$

The real and imaginary parts of the dielectric constant for the free water are given by

$$\varepsilon_{\mathrm{fw}} = \varepsilon_{\mathrm{fw}}^{\prime} - \varepsilon_{\mathrm{fw}}^{\prime\prime} i \tag{4}$$

where

$$\varepsilon_{\mathrm{fw}}^{\prime} = \varepsilon_{\mathrm{w}\infty} + \frac{\varepsilon_{\mathrm{w0}} - \varepsilon_{\mathrm{w}\infty}}{1 + (2\pi f \tau_{\mathrm{w}})^2} \tag{5}$$

and

$$\varepsilon_{\mathrm{fw}}^{\prime\prime} = \frac{2\pi f \tau_{\mathrm{w}}(\varepsilon_{\mathrm{w0}} - \varepsilon_{\mathrm{w}\infty})}{1 + (2\pi f \tau_{\mathrm{w}})^2} + \frac{\sigma_{\mathrm{eff}}}{2\pi\varepsilon_0 f}\frac{(\rho_S - \rho_B)}{\rho_S \theta} \tag{6}$$

In these formulas, ε_0 is the dielectric permittivity of free space, $\varepsilon_{\mathrm{w0}}$ is the static dielectric constant of water (80.1 at $20^\circ\mathrm{C}$), $\varepsilon_{\mathrm{w}\infty}$ is the high frequency limit of $\varepsilon_{\mathrm{fw}}^{\prime}$ (4.9), and τ_{w} is the relaxation time of water ($9.23\times10^{-12}\,\mathrm{s}$ at $20^\circ\mathrm{C}$.) The dielectric constant of the soil particles is given by the empirical model

$$\varepsilon_s = (1.01 + 0.44\rho_s)^2 - 0.062. \tag{7}$$

Finally, the real and imaginary parts of the dielectric constant for the bulk soil are estimated by

$$\varepsilon = \varepsilon' - \varepsilon'' i \tag{8}$$

where

$$\varepsilon' = 1.15\left[1 + \frac{\rho_B}{\rho_S}\left(\varepsilon_s^{\alpha} - 1\right) + \theta^{\beta'}\varepsilon'^{\alpha}_{fw} - \theta\right]^{1/\alpha} - 0.68 \tag{9}$$

and

$$\varepsilon'' = \left[\theta^{\beta''}\varepsilon''^{\alpha}_{fw}\right]^{1/\alpha}. \tag{10}$$

In these formulas, $\alpha = 0.65$ is a constant that has been empirically fitted to the data.

Given the complex dielectric permittivity of the soil and the dielectric constant of a landmine buried in the soil, we can attempt to model the response of a GPR system. The response of the radar depends in complicated ways on transmitted power, the frequency at which the radar operates, the geometry of the radar transmitter and receiver antennas, the depth to the mine, scattering from the mine, the surface roughness of the soil, and the sensitivity of the receiver. In the following, we present a simplified model that incorporates only attenuation effects and a simple model of reflection of plane waves from a flat surface.[9] More sophisticated models incorporating the specific features of particular GPR systems should be used when they are available.

As GPR signals travel through the soil, they are attenuated at a rate determined by the complex dielectric constant of the soil. The round trip attenuation loss in db is given by

$$\text{Attenuation Loss} = 17.3718\, d\, \alpha \tag{11}$$

where d is the depth to the object from which the GPR signal is reflecting, and α is given by

$$\alpha = \frac{2\pi f}{c}\sqrt{\frac{\varepsilon_s'}{2}\left(\sqrt{1 + \left(\frac{\varepsilon_s'}{\varepsilon_s''}\right)^2} - 1\right)} \tag{12}$$

Notice that the attenuation increases with frequency. The attenuation also increases with the dielectric constant as soil water content increases.

A second important factor in the performance of GPR systems for landmine detection is the strength of the reflection from the landmine. For the simplest case of a plane wave, vertically incident on the top of the mine, the reflection coefficient is given by

$$r = \frac{\sqrt{\varepsilon_s} - \sqrt{\varepsilon_m}}{\sqrt{\varepsilon_s} + \sqrt{\varepsilon_m}} \tag{13}$$

where ε_s is the complex dielectric constant for the soil, and ε_m is the dielectric constant of the mine. The reflection loss in db is given by

$$\text{Reflection Loss} = -10 \log |r|^2 \tag{14}$$

Notice that the reflection coefficient depends on the difference between dielectric constants of the mine and the soil. As these constants approach each other, the strength of the reflected wave goes to zero, and the mine becomes invisible.

The mathematical models described here have been integrated into a MATLAB package that can be used to predict the performance of ground penetrating radar systems under field conditions. The necessary input data consists of the soil texture (in the form of sand and clay fractions), the bulk soil density, and the volumetric soil water content.

3.AN EXAMPLE

As an example of our approach, we describe an experiment performed at the Sevilleta National Wildlife Refuge near Socorro, New Mexico. The soil at this site is a dry sand, with a typical soil water content of 5%, and a soil texture of 95% sand, 2% silt and 3% clay. The bulk density of the soil is approximately 1.6 grams per cubic centimeter. The soil texture and bulk density were determined using standard methods.[10,11] We considered the case of a landmine with a dielectric constant of 6 buried at a depth of 15 cm.

Figure 1 shows the attenuation and reflection losses for a radar operating at 1.2 Ghz. The smallest losses occur in a very dry soils with less than 1% volumetric water content and in moist soils with water contents exceeding 15%. So the best conditions for land mine detection using GPR are extremely dry conditions or moist conditions.

Unfortunately, most soils have field water contents near the soil surface that are neither extremely dry nor moist. Field water contents of less than 1% will only occur under very arid climatic conditions. Another aspect of soil water regimes is the large spatial variability of field soil water contents[12]. Even if the average soil water content was near 1%, some areas in the soil would have higher water contents. Thus surveys under dry soil conditions are not recommended. Since

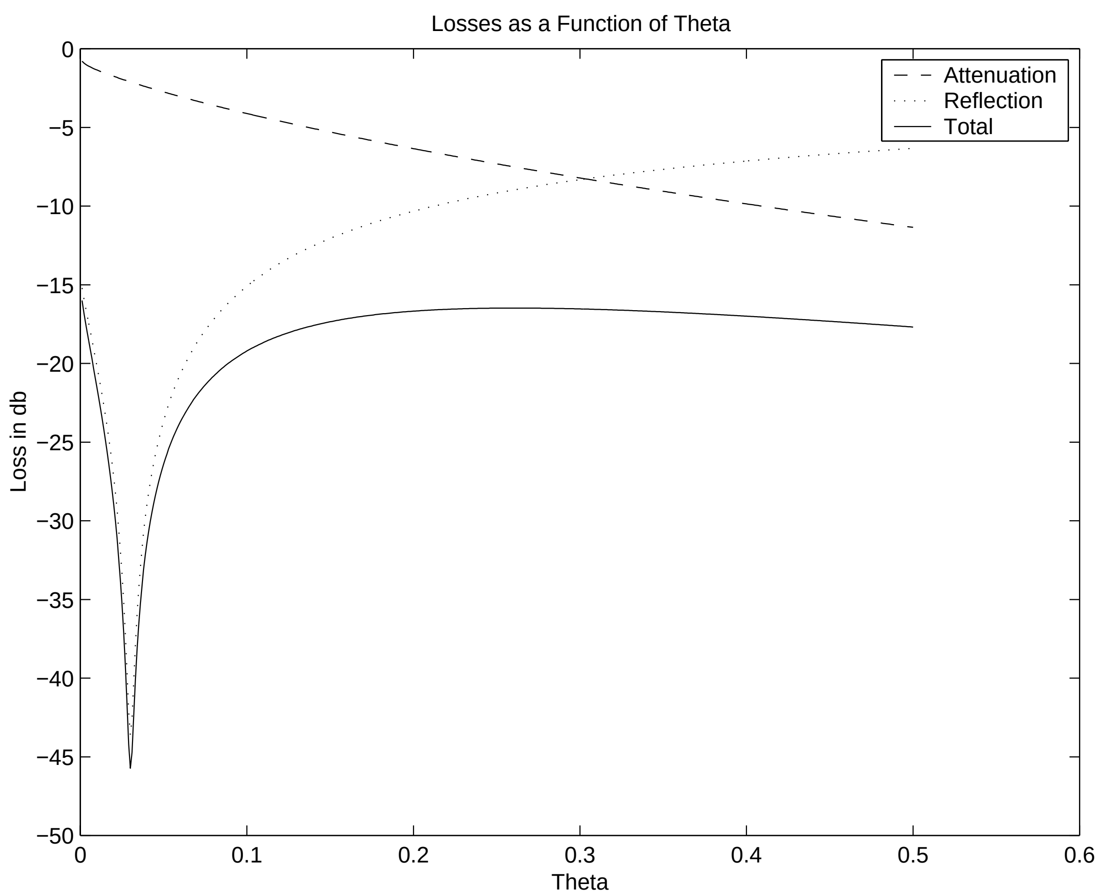

Figure 1: Attenuation and reflection losses for the Sevilleta sand.

typical water contents of surface soils hover between 2% to 15%, we conclude on the basis of the losses in Figure 1 that natural soil conditions form a poor environment for landmine detection using GPR. However, if the sand soil is wetted to water contents exceeding 20% conditions improve considerably and become insensitive to local variations in soil water content due to spatial variability. Since the practice of irrigation on agricultural lands is common in most parts of the world, a wide range of technological solutions has been developed to wet field soils in a cost-effective manner which makes soil watering a feasible approach to enhancing GPR response in mine fields.

With prevailing water content levels of around 5% at our test site, there is very little contrast between the dielectric constant of the soil and the dielectric constant of the mine. We would like to raise the soil water content to about 20%. A rough calculation shows that since 15% of 40 cm is 6 cm, the application of 6 cm of water should be sufficient to raise the average soil water content from 5% to 20% throughout the top 40 cm of soil. However, since some water will penetrate below 40 cm, and since the distribution of water within the soil will not be completely uniform, we plan to apply a total of 10 cm of water. In designing a watering plan, it is important to take into account how fast the soil can absorb water. For this sand soil, a watering rate of about 5 cm per hour is reasonable.

Figure 2 shows a schematic view of the experimental profile, including the landmine simulant and four depths at which we will measure soil water content (2 cm, 12 cm, 30 cm, and 37 cm.) The landmine simulant is buried at a depth of 15 cm, and has a radius of 15 cm and a height of 8 cm.

Figure 3 shows the results of a HYDRUS-2D simulation of our watering scheme.[13] We have previously described the use of HYDRUS-2D to simulate the unsaturated flow of groundwater around landmines.[14] HYDRUS-2D does not compute a full three dimensional simulation of water flow for general models. Instead, we used a feature of HYDRUS-2D to compute the three dimensional water flow for a model with radial symmetry around the axis of the landmine. The soil hydraulic parameters that affect the movement of water in the soil were estimated from the soil texture using a feature of HYDRUS-2D. An initial condition of 2% water content at the surface, ramping up to 7% water content at 40 cm was used to initialize the simulation. The figure shows that at the end of the watering period, the soil water content should be raised to around

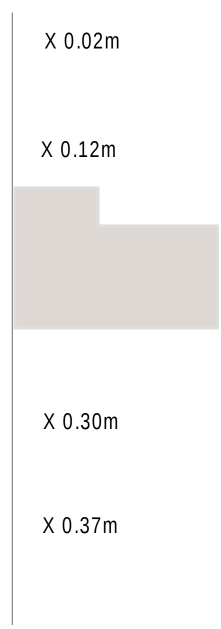

Figure 2: Layout of the landmine simulant and locations of water content measurements.

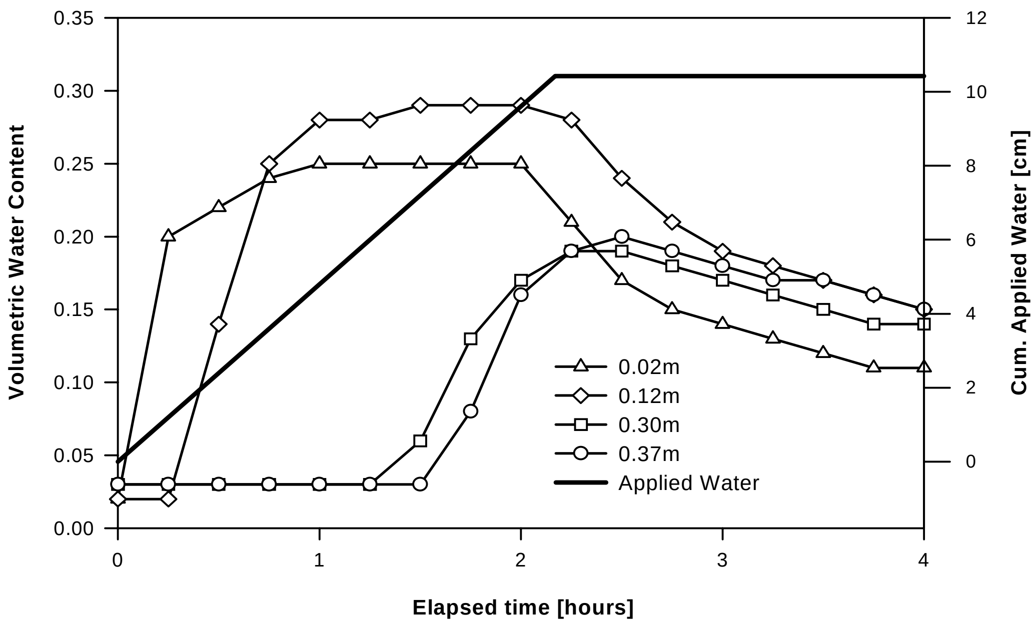

Figure 3: Hydrus-2D Simulation of water contents above and below the mine.

20% throughout the first 40 cm of the soil. The soil water content is somewhat lower beneath the mine, because it takes a fairly long period of time for water to move through the soil and around the obstruction. The simulation also shows that within about five hours, the soil water content will drop back down to around 10%.

Next, we performed a field experiment in which the same watering scheme was used at the Sevilleta site. Water was applied using a sprinkler system. Two 250 gallon tanks of water were required. There was a pause in the watering after the first hour to refill the tank. The soil water content was measured using time domain reflectometry (TDR) .[10, 15] Figure 4 shows how the soil water content above and below the mine evolved during the watering process. As expected, the actual soil water content was near 20% at all monitoring points by the end of the watering process. Despite the fact that watering the field did not proceed precisely as planned, the watering scheme did generally work as predicted by the simulation.

4. SUMMARY AND CONCLUSIONS

In this paper we have described a collection of models which can be used to predict the dielectric properties of field soils given information about soil texture, bulk density, and water content. Given the dielectric properties of a soil, it is possible to predict how ground penetrating radar (GPR) signals will be attenuated by the soil. It is also possible to predict how the contrast between the dielectric constant of the soil and the dielectric constant of a landmine will affect the strength of the reflected GPR signal.

In situations where the dielectric properties of the soil make it unlikely that GPR will be an effective sensor for landmine detection, we can use a watering scheme to add water to the soil and change the dielectric constant. It is possible to design a watering scheme that will bring about the desired change in the soil water content and dielectric constant. We can use a simulation of the unsaturated flow of water through the soil to verify that the watering scheme will produce the desired change in the soil water content.

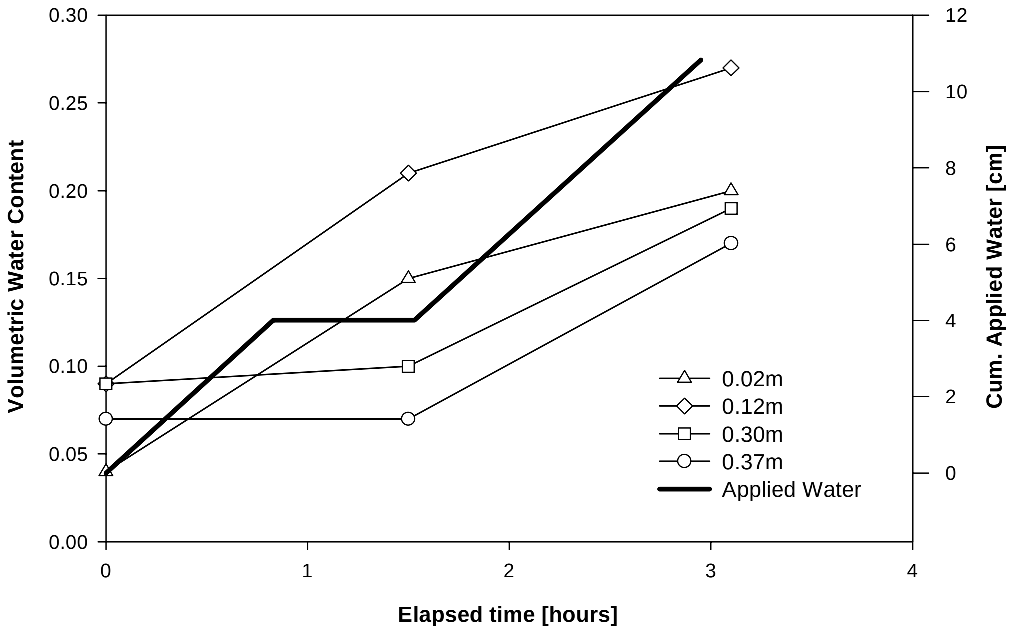

Figure 4: Measured soil water contents above and below the mine.

As an example of this approach, we considered a situation in which an anti-tank landmine simulant was buried at a depth of 15 cm in a dry sand soil. The model of the dielectric properties of the soil showed that GPR was likely to perform poorly under these circumstances because of the lack of strong contrast between the dielectric constant of the soil and the mine. The model of the dielectric properties also showed that if we could increase the water content of the soil to approximately 20%, then the dielectric constant of the soil would be favorable to GPR detection of the landmine. We designed a watering plan to bring the soil water content up to 20%. A simulation of the watering scheme verified that the watering plan should have the desired effect. In a field experiment, we followed the watering plan and found that as expected, the soil water content was increased to about 20% both above and below the mine.

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