Strength of landmine signatures under different soil conditions: implications for sensor fusion

Remke L. Van Dam[1#], Brian Borchers[2], and Jan M.H. Hendrickx[1]

[1] *New Mexico Tech, Department of Earth and Environmental Science, 801 Leroy Place, Socorro, NM 87801, USA*

[2] *New Mexico Tech, Department of Mathematics, 801 Leroy Place, Socorro, NM 87801, USA*

[#] *corresponding author e-mail address: rvd@nmt.edu*

Abstract

Most sensors for the detection of buried landmines are influenced by the properties of the soil that surrounds the mine. The temporal and spatial variability in soil properties accounts for a significant part of the detection uncertainty that is associated with most sensors. In particular, most sensor types (e.g., ground-penetrating radar, thermal infrared cameras, and chemical sniffers) are affected by the water content of the soil. However, each sensor type reacts in its own way to variations in soil water content and other soil properties. The resulting variation in sensor performance has serious implications for sensor fusion operations. We show how knowledge of soil physics can contribute to a better understanding of sensor performance and can lead to improved data fusion.

Keywords: landmines, soil variability, detection sensors, sensor fusion

1 Introduction

Landmines pose a serious threat to the society in around 90 countries in the world (ICBL 2001). Although research on how to detect and dispose of landmines started in the early half of the 1900's (BWO 1947, Das et al. 2003), the field of humanitarian demining is only some 20 years old. In recent years, the case for a landmine free world has become stronger, but serious efforts are still needed to develop new and to improve existing technologies that can help in identifying landmine fields, and in detecting and clearing the landmines (MacDonald et al. 2003). Currently, electromagnetic induction sensors (metal detectors) are the only technology that is routinely used in humanitarian demining operations. However, they are mostly of use in detecting metal cased mines. Low-metal landmines are very difficult to detect using metal detectors.

Detection techniques for buried low-metal landmines that are in development can be grouped in 3 main categories: (i) sensors that 'see' an image of the landmine through scattering, (ii) sensors that detect anomalies at the surface or in the soil, and (iii) sensors that detect the landmine explosives or chemicals that are associated with the explosives. Most if not all of these sensors are affected to some degree by soil conditions (Das et al. 2003, Hendrickx et al. 2003b) (table 1). The performance of a sensor under specific soil conditions can be predicted using a thorough understanding of the physics of the soil-mine-sensor system. In this paper we will focus on soil properties that affect the performance of metal detectors, active microwave (category i), passive infrared techniques (category ii), and chemical sniffers (category iii).

Previous work has shown the effect of spatial and temporal variability in the soil-mine system. A significant part of the variability in landmine signatures can in fact be attributed to the temporal and spatial variability that is present in soils. Soil data from a wide range of environmental settings (temperate, tropical, and desert) show that soil water content varies widely and over distances of less than one meter (Bauters et al. 2000, Hendrickx et al. 2001, Wilson et al. 2003). This variability has important implications for sensors that are affected by the soil water content, as their performance may be variable over short distances. A thorough understanding of soil physics may explain the variability in the performance of different sensors for landmine detection.

Sensor fusion operations combine different detection methodologies to reduce false alarm rates and to improve mine detectability (Gunatilaka and Baertlein 2001). However, the performance of most landmine detection sensors is related to sometimes the same (e.g. soil water content) soil properties (Hong et al. 2001). Moreover, each sensor will react in its own particular way to variations in one soil property. The fact that the reliability of each sensing method may vary over time and distance has important implications for sensor fusion.

The goal of this paper is to give an overview of soil effects on different landmine detection sensors with special emphasis on electromagnetic induction, active microwave, passive infrared, and chemical detection techniques. Also we will discuss the implications of time and space variability of detection performance for data fusion operations.

2 Soil properties

The purpose of this section is to provide a succinct introduction to soils and their properties as well as to sources of soil information. Soils are complex natural bodies made up of a heterogeneous mixture of mineral particles, organic matter, liquid and gaseous materials. Soils vary from location to location as a result of soil forming processes that depend on geological parent material, topography, climate, plant and animal life, and time. More than 10,000 different soils have been identified in the United States alone. Every soil consists of one to several layers called horizons, a few to hundreds of centimeters thick that reflect the physical, chemical, and biological processes which have taken place. Horizons are composed of natural aggregates called peds which consist of associations of mineral and organic particles. Peds and particles are often separated from each other by pores that vary widely in size and shape. The spatial arrangement of peds, particles and pores greatly influences soil properties because the organization is frequently systematic (Sumner and Wilding 2000). Information on soil properties can be obtained from soil maps or soil data bases.

Soil survey services worldwide have traditionally produced soil maps at different scales, consisting of delineations called mapping units. Each mapping unit is characterized by a “representative soil profile” that consists of a vertical succession of more-or-less distinct soil horizons (figure 1). The top layer, or A horizon, is the zone of major biological activity and is therefore generally enriched with organic matter and typically darker in color than the underlying soil. Its thickness can vary from 1-2 cm to 15-30 cm. Beneath the A horizon we often find a B horizon, where some of the materials (e.g. clay, organic matter, or carbonates) that are leached from the A horizon by percolating water tend to accumulate. The B horizon is generally thicker than the A horizon. Underlying the B horizon is the C horizon which is the soil parent’s material. In some cases the C horizon consists of weathered and fragmented rock material. In other cases, the C horizon may consist of sedimentary deposits, e.g. fluvial, aeolian, or glacial. Obviously, for landmine detection the composition of the A horizon and – for deeper mines – the B horizon are of most interest.

The boundaries of a mapping unit are not based on a large number of soil profile descriptions but on external above ground features of the soil and the landscape that can be seen in the field or on air photos or other remote sensing images. In other words, a soil surveyor develops a conceptual model about soil changes in the landscape and only then selects the observation points to dig a soil pit for inspection and sampling of “representative soil profiles”. There is a direct relation between the density of representative soil profiles sampled in the field and map scale, which is defined by the number of representative soil profiles per square centimeter of the final map. A detailed soil map at scale 1:10,000 is based on approximately one to four representative soil profiles per hectare (100x100 m) while a soil map with coarser resolution at scale

1:1,000,000 is based on approximately one to four representative soil profiles per 100 km^2 (Buringh et al. 1962, Dent 1986). Therefore, the information on a soil map represents at best the average condition over each mapping unit but contains little or no information about soil variability. For that reason the legends of a soil map often qualitatively cover a range of possible values.

Soil texture is a soil attribute or property that is qualitative but also contains quantitative information. The textural designation of a soil is determined on the basis of the mass ratios of three particle size classes: sand, silt, and clay. Soils with different percentages of sand, silt, and clay are assigned different classes as shown in the textural triangle (figure 2). However, an A horizon assigned textural class “sand” can have a range of clay and silt percentages varying from, respectively, 0-10% and 0-15%.

2.1 Soil databases

Traditionally soil data were stored in archives in paper form. The accessibility of these archives is often quite limited, even by the survey organization themselves. Fortunately, the development of Geographical Information Systems makes it now possible to store soil data in computers so that they can be quickly retrieved. We distinguish between point and area data. Point data are detailed descriptions of representative soil profiles, often including chemical, physical, and mechanical analyses. Soil maps and mapping units are regarded as area data.

Many national and international organizations and agencies have made soils databases accessible on the internet. Additions and changes in electronic accessibility of soils data are occurring continuously. The websites presented in table 2 contain much information about the world soil resources and have linkages with other global, national, and regional databases. At this moment FAO's Soil Map of the World is the best geographic source on global soil resources at a scale of 1:5,000,000. Work is underway to update the world's information on soil resources at a scale of 1:1,000,000 in SOTER, the World Soil and Terrain Database program (Van Engelen 2000).

These soil databases and many other national databases provide much information about the composition of the top soil layer such as texture, organic matter content, bulk density, salt content, etc. However, as has been explained before no soil database will provide site specific information since the number of sampled representative profiles is only an infinitely small fraction of the entire worldwide soil volume. Yet, in many cases the databases will give a clear picture of average soil conditions that are found in a region and the associated soil variability. The need for the use of soil databases in humanitarian demining has been pointed out by Das et al. (2002). We recommend that soil scientists be consulted to extract relevant soil information from these databases for use in mine detection and removal.

2.2 Soil variability

The spatial variability of soil texture, organic matter, and bulk density has a large impact on soil water variability. Their effect is greatly amplified by the unique behavior of the unsaturated soil hydraulic conductivity which depends on soil water content and can decrease 10 million times as the soil dries from water saturation to complete dryness. Although this soil characteristic makes it possible for soils to absorb, retain, and transmit water under a wide variety of initial and local conditions, it also exacerbates the temporal and spatial variability of soil water content. Vertically, the water content gradationally varies due to capillary rise (Johnson et al. 2001) or downward redistribution after infiltration, even in perfectly homogeneous sediments. Horizontally, the water content varies as a result of inhomogeneous soil properties (Rosen et al. 2003). Over time, the water content is affected by precipitation, infiltration, runoff, and evapotranspiration.

Another factor that greatly increases soil water content variability is the occurrence of water repellent soils. These soils are found all over the world and occur under a variety of climatic conditions (Jaramillo et al. 2000). Wetting patterns in these soils are irregular and incomplete (Hendrickx et al. 1992). The heterogeneity of soil texture, organic matter, and bulk density together with the frequent occurrence of water repellency results in a large spatial and temporal variability of soil water content that has been documented in many studies (Saddiq et al. 1985, Hendrickx et al. 1986, Hendrickx and Wierenga 1990, Hendrickx et al. 1990, Hendrickx et al. 1999).

2.3 Pedotransfer functions

Soil water content is the principal soil property that determines soil dielectric constant, soil heat capacity, soil heat conductivity, and vapor diffusivity in soils. Therefore, it follows that, like water content, the soil properties that are important for landmine detection will have a large spatial and temporal variability.

A major problem with soil databases is that soil scientists have traditionally measured the soil properties which are of greatest importance in agriculture. Parameters of direct interest in landmine detection, including the real and imaginary parts of the dielectric constant, magnetic susceptibility, electrical conductivity, thermal conductivity, and heat capacity are often not measured. Fortunately, many of these properties depend in fairly direct ways on more basic properties such as soil texture, density, and water content. Simple models called "pedotransfer functions" have been developed to predict the unmeasured soil parameters that are needed from parameters we know (Bouma 1989). A pedotransfer function is a mathematical relationship between two or more soil parameters that shows a high level of statistical confidence. It is used to estimate a non-measured soil parameter from one or more measured ones.

Numerous pedotransfer functions or "dielectric mixing models" have been proposed that describe the relation between the soil moisture content (and other soil properties) and dielectric constant (Topp et al. 1980, Dobson et al. 1985, Roth et al. 1992, Bohl and Roth 1994, Peplinski et al. 1995, Malicki et al. 1996, Curtis 2001, Robinson and Friedman 2001). For the determination of the real and imaginary parts of the dielectric constant of a soil our research team has used the models of Dobson et al. (1985) and Peplinski et al. (1995), which have been calibrated using a set of experimental observations with a variety of soil textures, water contents, and frequencies. For frequencies between 0.3 and 1.3 GHz the effective soil conductivity is given by:

$$\sigma_e = 0.047 + 0.220\rho_b - 0.411m_s - 0.661m_c .$$

Here, ρ_b is the bulk density of the soil, m_s is the sand mass fraction, and m_c is the clay mass fraction. The real (ε') and imaginary (ε'') parts of the dielectric constant for the bulk soil are estimated by $\varepsilon = \varepsilon' - \varepsilon'' i$, where $i = \sqrt{-1}$, and:

$$\varepsilon' = 1.15\sqrt[\alpha]{1 + \frac{\rho_b}{\rho_s}\left(\varepsilon_s^{\alpha} - 1\right) + \theta_v^{\beta''}\varepsilon'^{\alpha}_{fw} - \theta_v} ,$$

and

$$\varepsilon'' = \sqrt[\alpha]{\theta_v^{\beta''}\varepsilon''^{\alpha}_{fw}} .$$

In these equations, ρ_s is the density of the soil particles, θ_v is the volumetric soil water content, ε_s is the dielectric constant of the soil particles, ε'_{fw} and ε''_{fw} are the real and imaginary parts of the dielectric constant of free water, respectively, and α is an empirically derived constant (0.65). β' and β'' are given by:

$$\beta' = 1.2748 - 0.519m_s - 0.152m_c ,$$

and

$$\beta'' = 1.33797 - 0.603 m_s - 0.166 m_c \,.$$

For frequencies above 1.3 GHz these empirically derived formulas show some small changes (Dobson et al. 1985, Van Dam et al. 2003a).

The soil thermal properties needed to model soil surface temperatures above and away from mines are the volumetric heat capacity and the thermal conductivity (Simunek et al. 2001, Van Dam et al. 2003b). The volumetric heat capacity of soil is often expressed as the weighted sum of the heat capacities of the various soil constituents. The volumetric heat capacity of air is about three orders of magnitude less than that of the other soil constituents and can be neglected so that:

$$C = \rho_b \left(c_s + c_w \theta_g \right)$$

Here, c_s and c_w are the specific heat of soil (0.73 kJ·kg^{-1}K^{-1}) and water (4.18 kJ·kg^{-1}K^{-1}), and θ_g is the gravimetric soil water content (Kluitenberg 2002). Soil thermal conductivity can be determined from an empirical equation with four coefficients that are related to readily available soil properties (Bristow 2002):

$$\lambda = a + b\theta_v - (a - d)\exp[-(c\theta_v)^4]$$

$$a = \frac{0.57 + 1.73\varphi_q + 0.93\varphi_m}{1 - 0.74\varphi_q - 0.49\varphi_m} - 2.8\varphi_s(1 - \varphi_s)$$

$$b = 2.8\varphi_s$$

$$c = 1 + 2.6 \big/ \sqrt{m_c}$$

$$d = 0.03 + 0.7\varphi_s^{\;2}$$

In these equations, φ is the volume fraction of a particular component, and subscripts "*q*", "*m*", and "*s*" indicate quartz, minerals other than quartz, and total solids.

Due to its temporal variability soil water content cannot be obtained from soil data bases. Remote sensing from satellites can be used to determine soil water content in the top layer of the soil (Owe et al. 2001). In addition, the soil science community has developed a number of instruments for the field measurement of soil water content, dielectric constant, and conductivity (Dane and Topp 2002). Soil water content can be determined with time domain reflectrometry (TDR) methods or neutron probes (Topp and Davis 1985, Brisco et al. 1992, Heimovaara et al. 1995, Robinson et al. 1999). Time domain reflectrometry can also be used to determine the dielectric constant of the soil directly. The electrical conductivity can be determined by ground conductivity meters.

Another more direct approach to the problem is to use the landmine sensor itself to measure the most important soil properties. For example, with GPR it would be relatively simple to bury a test target and use the GPR to detect the target. The dielectric properties could then be estimated from the two-way-travel time and the attenuation of the signal.

3 Landmine properties

A typical landmine consists of a plastic or metal case enclosing an explosive charge, along with a fuse mechanism and firing pin to detonate the mine. Anti-personnel landmines are quite small, weighing a few hundred grams at most. These mines are typically laid on the surface or buried within a few centimeters of the surface. Anti-tank landmines are significantly larger, with a weight of several kilograms. These mines are buried at depths of up to 30 centimeters below the surface. Descriptions of some landmines that have been encountered in demining operations have been collected into a database by the Norwegian Peoples Aid non-governmental organization (NPA 2002).

With respect to landmine detection, the most important properties of a landmine are its metal content, which influences the detectability of the mine by GPR and EMI sensors. Although older landmines often had metal cases and were thus relatively easy to detect with EMI and GPR sensors, more modern landmines typically have very low metal content. In some cases, the only metallic part of the landmine is a small firing pin.

A second important property of a landmine is the explosive used. The explosive used is clearly of importance to chemical detection. The design of the landmine case and the explosive used determine the rate at which the explosive leaks from the mine and thus affects the detectability of the mine by chemical detection. (George et al. 2000) measured the TNT flux from actual landmines and found that the flux varies dramatically depending on the design of the mine. The choice of the explosive also affects the thermal conductivity and heat capacity of the mine and is thus of importance to IR sensors. Table 3 shows the thermal properties of some explosives that may be used in landmines.

4 Sensor types

In this section we will discuss the specific soil properties that affect landmine detection sensors. An overview of these properties is given in table 1.

4.1 Electromagnetic induction sensors

Electromagnetic induction (EMI) sensors are more commonly known as metal detectors. EMI sensors are the only technique described in this paper that is routinely used in demining operations. They operate by sending an electric current through a coil, inducing a magnetic field in the subsurface. The magnetic current induces current flow, which in turn generates secondary magnetic fields that are sensed by the detector. The fact that buried metal objects cause different secondary fields than the surrounding soil allow EMI sensors to be used for the detection of buried landmines. Modern EMI sensors are very sensitive and can in principle detect low-metal landmines. However, several soil types pose problems to EMI sensors. Also, clutter that is present in most soils causes numerous false alarms (Bruschini 2002, MacDonald et al. 2003).

Detection performance varies strongly by manufacturer. For such a simple technique this is remarkable and important to realize. Some metal detectors perform well in a variety of soils, but only for shallow depths. Other sensors have problems detecting mines in specific soil types (Das et al. 2001).

4.1.1 Soil moisture content

Soil water content has usually little or no effect on the performance of EMI sensors. The reason for this is the low frequency of EMI sensors. However, EMI sensors are influenced by the soil conductivity, which partly depends on water content. Normally, the water-content induced conductivity variations are not large enough to affect EMI sensor performance. Only in regions with high soil water salinity it can be expected that high-sensitivity EMI sensors will perform poorly.

4.1.2 Soil texture

EMI sensors generally experience the fewest problems detecting low-metal buried mines in sandy soils. In clay and peat soils this performance is somewhat less reliable (Das et al. 2001). However, the influence of soil texture is not very large.

4.1.3 Soil mineralogy

The performance of EMI sensors can be seriously affected by specific minerals present in soils (Bruschini 2002, Butler 2003). As the technique of electromagnetic induction is based on the transmission of a magnetic field in the soil, magnetic properties of soil material can hamper the performance of EMI sensors. Most ferruginous materials in soils around the world are non-magnetic (Cornell and Schwertmann 1996, Van Dam et al. 2002a). However, soils in tropical regions and soils developed on a volcanic substrate are often rich in magnetite and maghemite. These minerals are strongly magnetic and can cause most EMI sensors to malfunction (Das et al. 2001, Das et al. 2003, Van Dam et al. 2004). Also, the presence of ferrimagnetic materials with different shapes and grain sizes causes frequency dependent behavior of the magnetic susceptibility. This effect is referred to as viscous remanent magnetization and has important implications for both time- and frequency-domain EMI sensors (Pasion et al. 2002, Billings et al. 2003).

4.1.4 Summary

Both an elevated primary magnetic susceptibility and a frequency dependence of the magnetic susceptibility due to the presence of iron oxides (and associated minerals) can reduce EMI detector performance. Other than soil mineralogy, soil properties have a relatively small effect on EMI sensors. Successful discrimination of clutter from landmines is the largest problem for the EMI method.

4.2 Active microwave – Ground-penetrating radar

Active microwave is a combination name for a number of different techniques such as ground-penetrating radar (GPR) and synthetic aperture radar (SAR). In this paper we will focus on near-surface GPR applications, in contrast to stand-off systems such as most SAR's, which have to deal with atmospheric effects and surface roughness. GPR has long been recognized as a potentially powerful technique for the detection of underground objects and landmines (Peters et al. 1994), and it is close to being applied in the field.

With most landmines typically buried in the top 30 cm of a soil, in many circumstances GPR offers a good tradeoff between available frequencies (i.e. resolution) and penetration. GPR can detect low-metal landmines but under specific soil conditions reflections may be weak. Since the dielectric properties of the soil control the attenuation of the signal, and because the contrast between the landmine and the background medium controls the scattering and reflection strength, the electromagnetic properties of both mine and soil are crucial variables to understand radar signatures of landmines (Carin et al. 1999, Cross 1999, Hendrickx et al. 2003a). Nevertheless, the temporal and spatial variability in soil properties is seldom incorporated into models for the prediction of landmine signatures. Even when the effects of soil properties are acknowledged, very little modeling and little or no experimental research on the specific problem of soil variability effects has been done.

Pulsed GPR techniques transmit a short electromagnetic pulse typically in the frequency range between 100's of MHz to several GHz. While many GPR applications place the antennas on the ground, landmine detection requires a small elevation above the surface. This induces a significant surface reflection. Due to the bandwidth of the signal and the shallow burial depth of many landmines, the reflection from the landmine is often incorporated in the ground bounce. Some systems use one dominant peak frequency; others use a wide frequency spectrum (WB or UWB).

4.2.1 Soil water content

The dielectric properties of the soil are strongly influenced by the water content, as the dielectric constant of water (80) is a factor 20 times as large as most soil constituents (Topp et al. 1980, Peplinski et al. 1995, Borchers et al. 2000, Van Dam and Schlager 2000, Van Dam et al. 2002b). The relationship between soil water content and bulk electromagnetic properties can be described by simple regression functions, or pedotransfer functions, that sometimes include information about bulk density, particle size distribution and the effect of bound water (Topp et al. 1980, Jackson 1987, Bohl and Roth 1994, Heimovaara et al. 1994). However, these models do not account for the important effect of frequency dependence (Wensink 1993, Curtis et al. 1995, Carin et al. 1999).

Various authors have numerically and experimentally shown the effects of soil water content and frequency dependence on landmine detection (Fritzsche 1995, Carin et al. 1999, DeLuca et al. 1999, Scheers et al. 2000). Most authors agree that at frequencies below 1 GHz the attenuation is relatively low and that attenuation and relaxation losses drastically increase over 1 GHz. Also, it is widely understood that GPR signal attenuation increases with water content. Nevertheless, the modeling results are often very difficult to compare and sometimes contradictory. The reason for this is that each study has its own set of variables. When soil water content, soil type, and frequency range are not standardized, modeling results will be different; this apart from differences in the models used. For a New Mexico clay soil the models by Peplinski et al. (1995) and Dobson et al. (1985) summarize the effects of water content and frequency on the attenuation of GPR signals (figure 3).

For low-metal landmines most studies agree that the presence of soil water enhances the dielectric contrast (Trang 1996, Johnson and Howard 1999, Nguyen et al. 1999). Based on this type of observations and modeling studies, several authors argue that artificial watering of dry soils may improve landmine detection (Powers and Olhoeft 1996, Carin et al. 1999, Borchers et al. 2000). Since larger water contents increase attenuation losses, there exists a trade-off between enhancing dielectric contrasts and increasing signal attenuation. The optimal soil water content for low-metal landmines also depends on burial depth and frequency. With increasing burial depth and higher frequencies the attenuation will become more significant.

Another technique to potentially improve landmine detectability by soil modification is to freeze the soil. Frozen water does not have the disadvantage of a high attenuation. The addition of liquid nitrogen to wet soils could reduce background medium loss and enhance target visibility (Johnson et al. 1999, Koh and Arcone 1999, Jenwatanavet and Johnson 2001). However, this technique is not beyond the concept stage.

Spatial variability – A wetting or drying front at the surface due to precipitation or evapotranspiration will cause different dielectric properties for the top part of the soil. A modeling study for a situation of a snow layer with variable dielectric properties on top of the soil surface can be used to understand this effect (Geng and Carin 1999). A layer with variable dielectric properties at the surface leads to changes in arrival time (apparent depth of the mine) and signature strength. The effect of horizontal variability in soil water content due to water repellent soils or soil inhomogeneities has not yet been studied.

4.2.2 Soil texture

For three types of New Mexico soils, figure 4 shows how the soil texture influences the real and imaginary parts of the dielectric constant. Soil texture has a smaller effect on GPR signals than water content has. The imaginary part of the dielectric constant is slightly larger in clays and silts than in sand. Although it is recognized that GPR signal attenuation is greater in clay soils than in sand soils, thus limiting penetration depth (Fritzsche 1995), part of this difference in field soils can be attributed to the higher water retention capacity of clays.

4.2.3 Summary

Summarizing, it can be said that the detectability of low-metal landmines using GPR mainly depends on the soil water content and frequency used. Higher soil water contents lead to larger dielectric contrasts between the landmine and the soil it is buried in.

However, higher soil water contents also lead to a larger attenuation. With higher frequencies, the resolution is larger, but (notably above 1 GHz) attenuation and relaxation losses become more significant. Therefore, when using GPR for landmine detection, trade-offs are necessary between (i) increased dielectric contrasts between soil and mine by water, or (ii) increased attenuation due to higher soil water contents and higher frequencies.

4.3 Thermal Infrared

Thermal infrared (IR) imaging for geoscience applications has been studied for several decades. Although the potential of thermal IR for the detection of landmines and other unexploded ordnance has been recognized decades ago, only in recent years has it come in focus (DePersia et al. 1995). The advantages of thermal IR sensing over other techniques are its ability to detect mines from longer ranges and to scan large areas at once.

The driving process in thermal infrared imaging is the daily temperature fluctuations as induced by solar radiation (Van Wijk 1963). Inherent to the cyclic nature of the incoming solar radiation, the thermal signatures of underground anomalies follow a cyclic pattern. Several studies have explored the possibilities of heating the soil using microwaves (Deans et al. 2001, DiMarzio et al. 1999, Hermann and Chant 1999, Oktar et al. 2000, Storm and Haugsted 1999). It is shown that this method can enhance the thermal IR signature of landmines.

In recent years, several modeling studies have been done to understand the physics of heat propagation and the generation of thermal signatures ($\Delta_T = T_{mine} - T_{no\_mine}$) at the surface above a buried mine (Simard 1996, Pegrowski et al. 2000, Sendur and Baertlein 2000, Simunek et al. 2001, Khanafer and Vafai 2002). The results of these modeling studies are often contradictory in terms of signal strength and phase shift. The reason for this is that, although all these models incorporate the thermal properties of soil and landmine, they are often considered fixed variables. The important role of soil variability has hardly been systematically studied. Due to difficulties such as surface roughness and wind effects, experimental studies have received little attention.

4.3.1 Soil water content

Most authors agree on the fact that soil water content has a significant effect on the thermal signatures and signal phase shift of buried landmines (Simunek et al. 2001, Van Dam et al. 2003b). However, Baertlein and Sendur (2001) argue that variations in soil water content have a marginal impact. This contradiction may be due to the fact that they focused on a narrower range of water contents (15 to 35 percent). In this range thermal conductivity and thermal diffusivity vary much less than in the soil water content range between 0 and 15 percent, which is much more typical for surface soils (Van Wijk 1963, Hendrickx et al. 2003b).

Due to differences in the soil thermal conductivity and volumetric heat capacity the temperature amplitude at the surface is larger in dry than in wet soils (Simunek et al. 2001). However, the amplitude of the thermal signature is larger in wet than in dry soils.

From figure 5 it follows that the thermal signature is larger in moist soils than wet soils. However, it should be kept in mind that this outcome is only valid for the specific July conditions of a sand soil in Kuwait. In addition to changes in peak amplitude, a change in soil water content causes phase shifts in the peak signal time (figure 5). The peak signal times depend in a complex way on heat flux, water content and landmine properties (Simunek et al. 2001, Van Dam et al. 2003b).

Figure 6 summarizes the effects of soil water content and landmine burial depth on the maximum thermal signatures of a mine consisting of TNT. It is obvious that the maximum thermal signatures at the surface decrease with burial depth of the landmine. A minimum signature is reached between 7 and 12 cm burial depth, but the depth at which this minimum signature is reached increases with soil water content. The subsequent increase in thermal signatures is a result of the temperature wave traveling in two directions, with time delay, in the soil above the landmine. For burial depths over 30 cm no signatures are detected for the soil-landmine conditions here.

For fully dry conditions the signatures are very low for most burial depths. Here, the thermal characteristics of the landmine are similar to those of the soil. For moist to wet conditions the thermal signatures are fairly similar. However, for larger burial depths (5-12.5 cm) the temperature difference becomes more significant. It is important to note that the times during the day that these maximum values are reached vary (Pegrowski et al. 2000, Simunek et al. 2001, Van Dam et al. 2003b).

4.3.2 Soil texture

Most studies agree on the fact that variation in soil texture has only a small effect on the temperature signature at the surface. This is shown by numerical and analytical modeling studies (Baertlein and Sendur 2001, Van Dam et al. 2003b). However, variations in soil texture often influence the water content of the soil (clay has a higher water retention capacity than sand). As a result, soil texture may indirectly influence the thermal signatures. Simunek et al. (2001) have incorporated spatially inhomogeneous soil textures and soil water distributions around the landmine. In his model soil texture has a more significant effect on the thermal signatures.

4.3.3 Summary

The thermal signatures of buried landmines depend in a complex way on incoming heat flux, variation in soil water content, and the burial depth and composition of the landmine. These properties together control the strength of the thermal signature and the phase shift of the signal. Since it is very difficult to predict at what times the passive thermal signature of a buried landmine is strongest or weakest, thermal infrared techniques require continuous measurements during at least one day. When the thermal signature is caused by recent soil disturbance above a landmine, instantaneous measurements may work.

4.4 Chemical detection

Chemical methods for the detection of landmines have received increasing interest in recent years. One reason for this is the success of dogs in detecting and locating buried explosives (Tripp and Walker 2003). The rationale for developing chemical sensors for the detection of landmines is that “when a dog can do it, we should be able to do it”. In recent years, chemical sniffers have become extremely sensitive. However, their performance is highly affected by soil physical properties and inhomogeneities.

The explosives in landmines leak to the surrounding soil. The transport of explosives through the soil occurs by diffusion of vapor in the air phase, by diffusion of dissolved gasses in the soil moisture, and by advection of dissolved gasses in flowing water. Apart from the types of explosives and the landmine casing it is the soil physical properties that play an important role in leaking rates and transport through the soil surface (Albert et al. 2003, Webb and Phelan 2003).

Several authors have studied diffusive transport in soils, both experimentally and numerically (Albert et al. 2000, George et al. 2000, Kjellstrom and Sarholm 2000, Phelan et al. 2000, Webb and Phelan 2000, Fisher and Cumming 2001, Phelan et al. 2001). The results of these studies are not always easy to compare. This is due to the effects that soil properties have on the experiments and models.

4.4.1 Soil water content

Experimental work shows that a higher soil water content decreases the explosive vapors leaking rate. Also, microbiological and abiotic reactions in wet soils decrease the half-life of DNT and TNT, the two most common explosives in landmines (Phelan and Webb 2003). Although the diffusion coefficient of DNT in air is significantly higher than that in water the presence of a small amount of water increases the effective diffusion rate of a soil. This increase is due to vapor-solid sorption processes. The amount of vapor that can be sorbed to solids decreases when the soil water content increases, resulting in a higher gas-phase vapor concentration (Webb and Phelan 2003). In other words, in a dry soil the vapor concentrations are high near the landmine, but the concentrations decrease rapidly with distance from the landmine (Albert et al. 2003). In a moist soil the concentrations near the landmine are lower but higher effective diffusion rates cause the vapor to spread further and more rapidly.

Advective transport due to evaporation and precipitation also affects the explosive concentrations at the surface. Rainfall causes dissolved explosives to wash down the soil profile, while during dry periods solid-phase concentrations at the surface increase (Phelan and Webb 2003, Webb and Phelan 2003). The gas-phase concentrations also depend on precipitation. While small amounts of rainfall can cause an in crease in vapor concentration at the surface (due to solid-vapor sorption effects), large rainfall events usually cause the chemical signature to decrease (Webb and Phelan 2003).

4.4.2 Soil texture

Kjellstrom and Sarholm (2000) considered the vapor distribution in sand, clay, laterite, and magnetite soils, and present experimental results. The differences by soil type were not large.

4.4.3 Soil temperature

Soil temperature strongly affects the behavior of explosives in a soil. In cold climates both leaking and diffusion rates are significantly lower than in warmer climates. A temperature decrease from 22ºC to -4ºC decreases the leakage and diffusion rates by factors between 5 and 20, depending on the soil water content (Albert et al. 2003). However, the half lives of most explosives increase significantly with decreasing temperatures (Webb and Phelan 2003).

4.4.4 Soil inhomogeneities

Soil temperature and soil water content control the diffusion rates of the explosives. It is the soil structure and irregularity that controls the spatial spreading of the explosives through the soil towards the surface. It appears that the explosive vapors are not always to be found directly above buried landmines but often at some distance away (Fisher and Sikes 2003, Grossman and Hutchinson 2003). This is probably due to irregularities in the soil, possibly related to soil forming processes, soil water distributions, water repellent soils, and cracks or roots. Modeling of vapor flow can possibly be improved by using detailed pore space models (Vogel 2000).

4.4.5 Summary

The concentration of explosives at the surface above a landmine depends on a wide range of variables. Soil temperature and soil water content are the most important factors that control the rates of explosive leakage, effective diffusion, and degradation. Surface concentrations are also affected by environmental factors such as the precipitation history. Transport of explosives occurs in both the air and liquid phases and the inhomogeneity of soils can cause an irregular spatial distribution of explosive concentrations at the surface above a landmine.

5 Implications for sensor fusion

There is general agreement that no sensor can by itself be used to find landmines under all conditions. Data fusion techniques are used to combine the information from different sensors to increase the probability of detection and decrease the false alarm rate (Hall and Llinas 1997, Dasarathy 1998, Collins et al. 2001, Gunatilaka and Baertlein 2001, Milisavljevic and Bloch 2003).

Most work on data fusion for landmine detection has involved data fusion at the decision level. That is, data from each sensor is processed to produce a "mine" or "no mine" prediction (Klein 1999). These individual predictions are then combined in a probabilistic manner to obtain an overall prediction of whether or not a mine is present at a suspect location. A variety of algorithms are available for combining the data including voting fusion, neural networks, Bayesian inference and Dempster-Shafer inference (Klein 1999).

In implementing decision level data fusion, it's critical to know the probability of detection and the probability of a false alarm at each detection threshold for each of the sensors. Effectively, a receiver operator characteristic (ROC) curve is needed for each sensor. To date, most research on sensor fusion for landmine detection has assumed that this information can be gained by training the landmine detection system on field data (Aponte et al. 2001, Baertlein et al. 2001, Yee 2001, Collins et al. 2002, Liao and Baertlein 2002). Furthermore, if the performance of the individual sensors is strongly correlated, then the sensor fusion algorithm may also need the correlation coefficients. As a practical matter, models of sensor performance do not seem to be accurate enough to directly provide this information.

Given that soil properties can have a very large influence on the ROC curve associated with a particular sensor, there are several ways to deal with variability of soil properties. We could simply retrain the data fusion algorithm for each new location and new day where we wish to use the system. We could also try to train the algorithm on a very large set of data, representative of all the conditions under which the system would ever be used. However, the resulting data fusion algorithm might be much less effective under particular soil conditions than an algorithm trained on data gathered under those conditions. A third option would be to incorporate information about the soil properties in the area under investigation into the data fusion process.

For example, if a library of ROC curves was available for a GPR sensor under a variety of soil water content and soil texture conditions, then the operator could select the ROC curve from the library corresponding to soil conditions that were closest to the observed conditions. This would be done for each of the available sensors, and the data fusion algorithm would then be optimized for the prevailing conditions.

6 Conclusions

A large body of research has shown that soil physical properties can have important effects on various sensors used in landmine detection systems. Some basic soil properties include temperature, water content, texture, bulk density, and mineralogy. These properties in turn control properties such as electrical conductivity, dielectric constant, thermal conductivity, and heat capacity, which directly effect sensor performance. These properties can be highly variable in space and time.

Multi-sensor landmine detection systems using sensor fusion techniques are being developed to deal with the high false alarm rate and low probability of detection of systems based on a single sensor. Since the performance of individual sensors varies strongly with soil properties, sensor fusion algorithms should be designed to incorporate information about prevailing soil conditions. Incorporating information about soil properties into the sensor fusion process has the potential to greatly improve the performance of multi-sensor landmine detection systems.

Acknowledgements

The work at New Mexico Tech was funded by a grant from the Army Research Office (DAAD19-02-1-027). The authors would like to thank Dr. Russell S. Harmon, Senior Program Manager at the Army Research Office, for his valuable advice and support.

References

Albert, M., Cragin, J. and Leggett, D., 2000, Measurements and modeling of explosive vapor diffusion in snow. *Detection and Remediation Technologies for Mines and Minelike Targets V* (Orlando: SPIE), pp. 489-495.

Albert, M.R., Cragin, J.H. and Perron, F.E., 2003, Diffusion of explosives in frozen and unfrozen soil. *Detection and Remediation Technologies for Mines and Minelike Targets VIII* (Orlando: SPIE), pp. 740-745.

Aponte, H.I., Campana, S. and McGovern, M.A., 2001, Multi-sensor fusion for vehicle mounted mine detection. *Detection and Remediation Technologies for Mines and Minelike Targets VI* (Orlando: SPIE), pp. 934-942.

Baertlein, B.A., Liao, W.J. and Chen, D.H., 2001, Fusion of acoustic LDV and GPR data. *Detection and Remediation Technologies for Mines and Minelike Targets VI* (Orlando: SPIE), pp. 970-978.

Baertlein, B.A. and Sendur, I.K., 2001, The role of environmental factors and mine geometry in thermal IR mine signatures. *Detection and Remediation Technologies for Mines and Minelike Targets VI* (Orlando: SPIE), pp. 449-460.

Baumgardner, M.F., 2000, Soil databases. In M.E. Sumner (ed.) *Handbook of soil science* (CRC Press: Boca Raton), pp. 1-40.

Bauters, T.W.J., Steenhuis, T.S., DiCarlo, D.A., Nieber, J.L., Dekker, L.W., Ritsema, C.J., Parlange, J.Y. and Haverkamp, R., 2000, Physics of water repellent soils. *Journal of Hydrology*, **231**, 233-243.

Billings, S.D., Pasion, L.R., Oldenburg, D.W. and Foley, J., 2003, The influence of magnetic viscosity on electromagnetic sensors. *EUDEM-SCOT2, International Conference on Requirements and Technologies for the Detection, Removal and Neutralization of Landmines and UXO* (Brussels: Eudem).

Bohl, H. and Roth, K., 1994, Evaluation of dielectric mixing models to describe the θ(ε)-relation. *Time Domain Reflectometry in environmental, infrastructure and mining applications* (Evanston, Illinois: United States Department of Interior Bureau of Mines), pp. 309-317.

Borchers, B., Hendrickx, J.M.H., Das, B.S. and Hong, S., 2000, Enhancing dielectric contrast between land mines and the soil environment by watering: modeling, design, and experimental results. *Detection and Remediation Technologies for Mines and Minelike Targets V* (Orlando: SPIE), pp. 993-1000.

Bouma, J., 1989, Using soil survey data for quantitative land evaluation. In B.A. Stewart (ed.) *Advances in soil science*, **9** (New York: Springer-Verlag), pp. 177-213.

Brisco, B., Pultz, T.J., Brown, R.J., Topp, G.C., Hares, M.A. and Zebchuck, W.D., 1992, Soil moisture measurement using portable dielectric probes and time domain reflectometry. *Water Resources Research*, **28**, 1339-1346.

Bristow, K.L., 2002, Thermal conductivity. In J.H. Dane and G.C. Topp (eds.) *Methods of soil analysis: Part 4, physical methods*, **SSSA Book Series no. 5** (Madison: Soil Science Society of America), pp. 1209-1226.

Bruschini, C., 2002, *A multidisciplinary analysis of frequency domain metal detectors for humanitarian demining*, Ph.D. thesis, Vrije Universiteit Brussel, Brussels.

Buringh, P., Steur, G.L. and Vink, A.P.A., 1962, Some techniques and methods of soil survey in The Netherlands. *Netherlands Journal of Agricultural Science*, **10**, 157-178.

Butler, D.K., 2003, Implications of magnetic backgrounds for unexploded ordnance detection. *Journal of Applied Geophysics*, **54**, 111-125.

BWO, 1947, Detection and clearance of mines, pamphlet no. 6 (Field engineering and mine warfare).

Carin, L., Geng, N., McClure, M., Sichina, J. and Nguyen, L., 1999, Ultra-wide-band synthetic-aperture radar for mine-field detection. *IEEE Antennas and Propagation Magazine*, **41**, 18-33.

Collins, L.M., Huettel, L.G., Simpson, W.A. and Tantum, S.L., 2002, Sensor fusion of EMI and GPR data for improved landmine detection. *Detection and Remediation Technologies for Mines and Minelike Targets VII* (Orlando: SPIE), pp. 872-879.

Collins, L.M., Zhang, Y., Li, J., Wang, H., Carin, L., Hart, S.J., Rose-Pehrsson, S.L., Nelson, H.H. and McDonald, J.R., 2001, A comparison of the performance of statistical and fuzzy algorithms for unexploded ordnance detection. *IEEE Transactions on Fuzzy Systems*, **9**, 17-30.

Cornell, R.M. and Schwertmann, U., 1996, *The iron oxides - structure, properties, reactions, occurrence and uses*, **XXXI**, (Weinheim: VCH publishers).

Cross, G., 1999, Soil properties and GPR detection of landmines - a basis for forecasting and evaluation of GPR performance (Burnaby: Golder Associates).

Curtis, J.O., 2001, Moisture effects on the dielectric properties of soils. *IEEE transactions on geoscience and remote sensing*, **39**, 125-128.

Curtis, J.O., Weiss Jr., C.A. and Everett, J.B., 1995, Effect of soil composition on complex dielectric properties (Vicksburg: US Army Corps of Engineers, Waterways Experiment Station).

Dane, J.H. and Topp, G.C., (eds.) 2002, *Methods of soil analysis: Part 4, physical methods*. **SSSA Book Series No. 5**. (Madison: Soil Science Society of America).

Das, Y., Dean, J.T., Lewis, D., Rosenboom, J.H.J. and Zahaczewsky, G., 2001, A multi-national technical evaluation of performance of commercial off the shelf metal detectors in the context of humanitarian demining (Ispra: European Commission Joint Research Center).

Das, Y., McFee, J.E. and Cross, G., 2002, Soil properties database for humanitarian demining: a proposed initiative. *17th World Congress of Soil Science* (Bankok: The International Union of Soil Science).

Das, Y., McFee, J.E., Russell, K., Cross, G. and Katsube, T.J., 2003, Soil information requirements for humanitarian demining: the case for a soil properties database. *Detection and Remediation Technologies for Mines and Minelike Targets VIII* (Orlando: SPIE), pp. 1146-1157.

Dasarathy, B.V., 1998, Decision fusion benefits assessment in a three-sensor suite framework. *Optical Engineering*, **37**, 354-369.

De Jong, W., Lensen, H.A. and Janssen, Y.H.L., 1999, Sophisticated test facility to detect land mines. *Detection and Remediation Technologies for Mines and Minelike Targets IV* (Orlando: SPIE), pp. 1409-1418.

Deans, J., Schmithals, G. and Carter, L.J., 2001, An analysis of a thermal imaging method for landmine detection using microwave heating. *Journal of Applied Geophysics*, **47**, 123-133.

DeLuca, C., Marinelli, V., Ressler, M. and Ton, T., 1999, Unexploded ordnance detection experiments at extensive, fully ground-truthed test sites at Yuma Proving Ground and Eglin AFB. *Detection and Remediation Technologies for Mines and Minelike Targets IV* (Orlando: SPIE), pp. 1025-1034.

Dent, D.L., 1986, Acid sulphate soils: a baseline for research and development (Wageningen: International Land Reclamation Institute).

DePersia, A.T., Bowman, A., Lucey, P. and Winter, E.M., 1995, Phenomenology considerations for hyperspectral mine detection. *Detection Technologies for Mines and Minelike Targets* (Orlando: SPIE), pp. 159-167.

DiMarzio, C.A., Rappaport, C.M., Wen, L., Sauermann, G.O. and Scott, H.E., 1999, Microwave-enhanced infrared thermography. *Detection and Remediation Technologies for Mines and Minelike Targets IV* (Orlando: SPIE), pp. 173-179.

Dobson, M.C., Ulaby, F.T., Hallikainen, M.T. and El-Rayes, M.A., 1985, Microwave dielectric behavior of wet soil - Part II: dielectric mixing models. *IEEE Transactions on Geoscience and Remote Sensing*, **GE-23**, 35-46.

Fisher, M. and Cumming, C., 2001, Detection of trace concentrations of vapor phase nitroaromatic explosives by fluorescence quenching of novel polymer materials. *7th International Symposium on the Analysis and Detection of Explosives* (Edinburgh, Scotland, UK).

Fisher, M.E. and Sikes, J., 2003, Minefield edge detection using a novel chemical vapor sensing technique. *Detection and Remediation Technologies for Mines and Minelike Targets VIII* (Orlando: SPIE), pp. 1078-1087.

Fritzsche, M., 1995, Detection of buried landmines using ground penetrating radar. *Detection Technologies for Mines and Minelike Targets* (Orlando: SPIE), pp. 100-109.

Geng, N. and Carin, L., 1999, Wide-band electromagnetic scattering from a dielectric BOR buried in a layered lossy dispersive medium. *IEEE transactions on antennas and propagation*, **47**, 610-619.

George, V., Jenkins, T.F., Phelan, J.M., Leggett, D.C., Oxley, J., Webb, S.W., Miyares, P.H., Cragin, J.H., Smith, J. and Berry, T.E., 2000, Progress in determining the vapor signature of a buried landmine. *Detection and Remediation Technologies for Mines and Minelike Targets V* (Orlando: SPIE), pp. 590-601.

Grossman, S. and Hutchinson, K., 2003, Study of explosive residues found above buried landmines. *Detection and Remediation Technologies for Mines and Minelike Targets VIII* (Orlando: SPIE), pp. 718-727.

Gunatilaka, A.H. and Baertlein, B.A., 2001, Feature-level and decision-level fusion of noncoincidently sampled sensors for land mine detection. *IEEE transactions on pattern analysis and machine intelligence*, **23**, 577-589.

Hall, D.L. and Llinas, J., 1997, An introduction to multisensor data fusion. *Proceedings of the IEEE*, **85**, 6-23.

Heimovaara, T.J., Bouten, W. and Verstraten, J.M., 1994, Frequency domain analysis of time domain reflectometry waveforms 2. A four-component complex dielectric mixing model for soils. *Water Resources Research*, **30**, 201-209.

Heimovaara, T.J., Focke, A.G., Bouten, W. and Verstraten, J.M., 1995, Assessing temporal variations in soil water composition with time domain reflectometry. *Soil Science Society of America Journal*, **59**, 689-698.

Hendrickx, J.M.H., Baerends, B., Raza, Z.I., Sadiq, M. and Akram Chaudhry, M., 1992, Soil salinity assessment by electromagnetic induction on irrigated land. *Soil Science Society of America Journal*, **56**, 1933-1941.

Hendrickx, J.M.H., Borchers, B., Woolslayer, J., Dekker, L.W., Ritsema, C. and Paton, S., 2001, Spatial variability of dielectric properties in field soils. *Detection and Remediation Technologies for Mines and Minelike Targets VI* (Orlando: SPIE), pp. 398-408.

Hendrickx, J.M.H., Das, B.S. and Borchers, B., 1999, Modeling distributions of water and dielectric constants around landmines in homogeneous soils. *Detection and Remediation Technologies for Mines and Minelike Targets IV* (Orlando: SPIE), pp. 728-738.

Hendrickx, J.M.H., Hong, S., Miller, T.W., Borchers, B. and Tobin, H., 2003a, Soil effects on ground penetrating radar detection of buried nonmetallic mines. In C.S. Bristow and H.M. Jol (eds.) *Ground Penetrating Radar in Sediments*, **SP211** (London: Geological Society), pp. 187-194.

Hendrickx, J.M.H., Van Dam, R.L., Borchers, B., Curtis, J.O., Lensen, H.A. and Harmon, R.S., 2003b, Worldwide distribution of soil dielectric and thermal properties.

Detection and Remediation Technologies for Mines and Minelike Targets VIII (Orlando: SPIE), pp. 1158-1168.

Hendrickx, J.M.H. and Wierenga, P.J., 1990, Variability of soil water tension in a trickle-irrigated chile pepper field. *Irrigation Science*, **11**, 23-30.

Hendrickx, J.M.H., Wierenga, P.J. and Nash, M.S., 1990, Variability of soil water tension and soil water content. *Agricultural Water Management*, **18**, 135-148.

Hendrickx, J.M.H., Wierenga, P.J., Nash, M.S. and Nielsen, D.R., 1986, Boundary location from texture, soil moisture, and infiltration data. *Soil Science Society of America Journal*, **50**, 1515-1520.

Hermann, J. and Chant, J., 1999, Microwave enhancement of thermal landmine signatures. *Detection and Remediation Technologies for Mines and Minelike Targets IV* (Orlando: SPIE), pp. 154-166.

Hong, S., Miller, T.W., Tobin, H., Borchers, B., Hendrickx, J.M.H., Lensen, H.A., Schwering, P.B.W. and Baertlein, B.A., 2001, Impact of soil water content on landmine detection using radar and thermal infrared sensors. *Detection and Remediation Technologies for Mines and Minelike Targets VI* (Orlando: SPIE), pp. 409-416.

ICBL, 2001, Landmine monitor report 2001: toward a mine-free world (New York: Human Rights Watch).

Jackson, T.J., 1987, Effects of soil properties on microwave dielectric constants (Transportation Research Board).

Jaramillo, D.F., Dekker, L.W., Ritsema, C.J. and Hendrickx, J.M.H., 2000, Occurrence of soil water repellency in arid and humid climates. *Journal of Hydrology*, **231/232**, 105-114.

Jenwatanavet, J. and Johnson, J.T., 2001, An analytical model for studies of soil modification effects on ground penetrating radar. *IEEE transactions on antennas and propagation*, **49**, 923-933.

Johnson, J.T., Jenwatanavet, J. and Wang, N., 1999, Soil modification studies for enhanced mine detection with ground penetrating radar. *Detection and Remediation Technologies for Mines and Minelike Targets IV* (Orlando: SPIE), pp. 739-748.

Johnson, J.T., Ungan, B.U. and Wiggins, D.R., 2001, Environmental and target influences on microwave radiometers for landmine detection. *Detection and Remediation Technologies for Mines and Minelike Targets VI* (Orlando: SPIE), pp. 440-448.

Johnson, P.G. and Howard, P., 1999, Performance results of the EG&G vehicle mounted mine detector. *Detection and Remediation Technologies for Mines and Minelike Targets IV* (Orlando: SPIE), pp. 1149-1159.

Khanafer, K. and Vafai, K., 2002, Thermal analysis of buried land mines over a diurnal cycle. *IEEE Transactions on Geoscience and Remote Sensing*, **40**, 461-473.

Kjellstrom, A.H. and Sarholm, L.M., 2000, Analysis of TNT and related compounds in vapor and solid phase in different types of soil. *Detection and Remediation Technologies for Mines and Minelike Targets V* (Orlando: SPIE), pp. 489-495.

Klein, L.A., 1999, *Sensor and data fusion concepts and applications*, (Bellingham: SPIE).

Kluitenberg, G.J., 2002, Heat capacity and specific heat. In J.H. Dane and G.C. Topp (eds.) *Methods of soil analysis: Part 4, physical methods*, **SSSA Book Series no. 5** (Madison: Soil Science Society of America), pp. 1201-1208.

Koh, G. and Arcone, S.A., 1999, Radar detection of simulant mines buried in frozen ground. *Detection and Remediation Technologies for Mines and Minelike Targets IV* (Orlando: SPIE), pp. 749-755.

Liao, W.J. and Baertlein, B.A., 2002, Fused performance of passive thermal and active polarimetric EO demining sensors. *Detection and Remediation Technologies for Mines and Minelike Targets VII* (Orlando: SPIE), pp. 880-891.

MacDonald, J., Lockwood, J.R., McFee, J.E., Altshuler, T., Broach, J.T., Carin, L., Harmon, R.S., Rappaport, C., Scott, W.R. and Weaver, R., 2003, *Alternatives for Landmine Detection* (RAND).

Malicki, M.A., Plagge, R. and Roth, C.H., 1996, Improving the calibration of dielectric TDR soil moisture determination taking into account the solid soil. *European Journal of Soil Science*, **47**, 357-366.

Milisavljevic, N. and Bloch, I., 2003, Detection of low-metal content objects by evidential fusion of mine detection sensors. *Integrated Computer-Aided Engineering*, **10**, 51-61.

Nguyen, L., Kappora, K., Wong, D., Ressler, M. and Sichina, J., 1999, Mine detection performance in different soil conditions using data from an ultra-wideband wide-area surveillance radar. *Detection and Remediation Technologies for Mines and Minelike Targets IV* (Orlando: SPIE), pp. 930-941.

NPA, 2002, *Landmine Database* (Norwegian People's Aid).

Oktar, T.R., Rappaport, C.M. and Dimarzio, C.A., 2000, Effects of surface roughness on microwave heating of soil for detection of buried landmines. *Detection and Remediation Technologies for Mines and Minelike Targets* (Orlando: SPIE), pp. 200-208.

Owe, M., De Jeu, R.A.M. and Walker, J.P., 2001, A methodology for surface soil moisture and vegetation optical depth retrieval using the microwave polarization difference index. *IEEE Transactions on Geoscience and Remote Sensing*, **39**, 1643-1654.

Pasion, L.R., Billings, S.D. and Oldenburg, D.W., 2002, Evaluating the effects of magnetic susceptibility in UXO discrimination problems. *SAGEEP* (Las Vegas: EEGS).

Pegrowski, P., Swiderski, W., Walczak, R.T. and Lamorski, K., 2000, Buried mine and soil temperature prediction by numerical models. *Detection and Remediation Technologies for Mines and Minelike Targets* (Orlando: SPIE), pp. 1392-1403.

Peplinski, N.R., Ulaby, F.T. and Dobson, M.C., 1995, Dielectric properties of soils in the 0.3-1.3 GHz range. *IEEE Transactions on Geoscience and Remote Sensing*, **33**, 803-807.

Peters, L., Daniels, J.J. and Young, J.D., 1994, Ground-penetrating radar as a subsurface environmental sensing tool. *Proceedings of the IEEE*, **82**, 1802-1822.

Phelan, J.M., Gozdor, M., Webb, S.W. and Cal, M.P., 2000, Laboratory data and model comparisons of the transport of chemical signatures from buried landmines/UXOs. *Detection and Remediation Technologies for Mines and Minelike Targets V* (Orlando: SPIE), pp. 462-473.

Phelan, J.M. and Webb, S.W., 2003, Data-model comparison of field landmine soil chemical signatures at Ft. Leonard Wood. *Detection and Remediation Technologies for Mines and Minelike Targets VIII* (Orlando: SPIE), pp. 728-739.

Phelan, J.M., Webb, S.W., Gozdor, M., Cal, M.P. and Barnett, J.L., 2001, Effect of soil wetting and drying on DNT vapor flux - laboratory data and T2TNT model comparisons. *Detection and Remediation Technologies for Mines and Minelike Targets VI* (Orlando: SPIE), pp. 868-878.

Powers, M.H. and Olhoeft, G.R., 1996, Computer modeling to transfer GPR UXO detectability knowledge between sites. *UXO Forum* (Williamsburg: Department of Defense Explosives Safety Board), pp. 347-356.

Robinson, D.A. and Friedman, S.P., 2001, Effect of particle size distribution on the effective dielectric permittivity of saturated granular media. *Water Resources Research*, **37**, 33-40.

Robinson, D.A., Gardner, C.M.K. and Cooper, J.D., 1999, Measurement of relative permittivity in sandy soils using TDR, capacitance and theta probes: comparison, including the effects of bulk soil electrical conductivity. *Journal of Hydrology*, **223**, 198-211.

Rosen, E.M., Blackburn, A.C., Ayers, E.L. and Bishop, S.S., 2003, Investigation into the sources of persistent ground-penetrating radar false alarms: data collection, excavation, and analysis. *Detection and Remediation Technologies for Mines and Minelike Targets VIII* (Orlando: SPIE), pp. 185-190.

Roth, C.H., Malicki, M.A. and Plagge, R., 1992, Empirical evaluation of the relationship between soil dielectric constant and volumetric water content as the basis for calibrating soil moisture measurements by TDR. *Journal of Soil Science*, **43**, 1-13.

Saddiq, M.H., Wierenga, P.J., Hendrickx, J.M.H. and Hussain, M.Y., 1985, Spatial variability of soil water tension in an irrigated soil. *Soil Science*, **140**, 126-132.

Scheers, B., Acheroy, M. and Vander Vorst, A., 2000, Time domain modeling of UWB GPR and its application on landmine detection. *Detection and Remediation Technologies for Mines and Minelike Targets V* (Orlando: SPIE), pp. 1452-1460.

Sendur, I.K. and Baertlein, B.A., 2000, Numerical simulation of thermal signatures of buried mines over a diurnal cycle. *Detection and Remediation Technologies for Mines and Minelike Targets V* (Orlando: SPIE), pp. 156-167.

Simard, J., 1996, Improved Landmine Detection Capability (ILDC): systematic approach to the detection of buried mines using passive IR imaging. *Detection and Remediation Technologies for Mines and Minelike Targets* (Orlando: SPIE), pp. 489-500.

Simunek, J., Hendrickx, J.M.H. and Borchers, B., 2001, Modeling transient temperature distributions around landmines in homogenous bare soils. *Detection and Remediation Technologies for Mines and Minelike Targets VI* (Orlando: SPIE), pp. 387-397.

Storm, J. and Haugsted, B., 1999, Detection of buried land mines facilitated by actively provoked IR signature. *Detection and Remediation Technologies for Mines and Minelike Targets IV* (Orlando: SPIE), pp. 167-172.

Topp, G.C. and Davis, J.L., 1985, Measurement of soil water content using time-domain reflectometry (TDR): a field evaluation. *Soil Science Society of America Journal*, **49**, 19-24.

Topp, G.C., Davis, J.L. and Annan, A.P., 1980, Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resources Research*, **16**, 574-582.

Trang, A.H., 1996, Simulation of mine detection over dry soil, snow, ice, and water. *Detection and Remediation Technologies for Mines and Minelike Targets* (Orlando: SPIE), pp. 430-440.

Tripp, A.C. and Walker, J., 2003, The great chemical residue detection debate: dog versus machine. *Detection and Remediation Technologies for Mines and Minelike Targets VIII* (Orlando: SPIE), pp. 983-990.

Van Dam, R.L., Borchers, B., Hendrickx, J.M.H. and Harmon, R.S., 2003a, Effects of soil water content and texture on radar and infrared landmine sensors: implications for sensor fusion. *EUDEM-SCOT2, International Conference on Requirements and Technologies for the Detection, Removal and Neutralization of Landmines and UXO* (Brussels: Eudem).

Van Dam, R.L., Borchers, B., Hendrickx, J.M.H. and Hong, S., 2003b, Soil effects on thermal signatures of buried nonmetallic landmines. *Detection and Remediation*

Technologies for Mines and Minelike Targets VIII (Orlando: SPIE), pp. 1210-1218.

Van Dam, R.L., Hendrickx, J.M.H., Harrison, B., Borchers, B., Norman, D.I., Ndur, S.A., Jasper, C., Niemeyer, P., Nartey, R., Vega, D., Calvo, L. and Simms, J.E., 2004, Spatial variability of magnetic soil properties. *Detection and Remediation Technologies for Mines and Minelike Targets IX* (Orlando: SPIE).

Van Dam, R.L. and Schlager, W., 2000, Identifying causes of ground-penetrating radar reflections using time-domain reflectometry and sedimentological analyses. *Sedimentology*, **47**, 435-449.

Van Dam, R.L., Schlager, W., Dekkers, M.J. and Huisman, J.A., 2002a, Iron oxides as a cause of GPR reflections. *Geophysics*, **67**, 536-545.

Van Dam, R.L., Van Den Berg, E.H., Van Heteren, S., Kasse, C., Kenter, J.A.M. and Groen, K., 2002b, Influence of organic matter on radar-wave reflection: sedimentological implications. *Journal of Sedimentary Research*, **72**, 341-352.

Van Engelen, V.W.P., 2000, SOTER: the World Soils and Terrain Database. In M.E. Sumner (ed.) *Handbook of soil science* (Boca Raton: CRC Press).

Van Wijk, W.R., (ed), 1963, *Physics of plant environment*. (New York: John Wiley & Sons).

Vogel, H.J., 2000, A numerical experiment on pore size, pore connectivity, water retention, permeability and solute transport using network models. *European Journal of Soil Science*, **51**, 99-105.

Webb, S.W. and Phelan, J.M., 2000, Effect of diurnal and seasonal weather variations on the chemical signatures from buried landmines/UXO. *Detection and Remediation Technologies for Mines and Minelike Targets V* (Orlando: SPIE), pp. 474-488.

Webb, S.W. and Phelan, J.M., 2003, Effect of weather on landmine chemical signatures for different climates. *Detection and Remediation Technologies for Mines and Minelike Targets VIII* (Orlando: SPIE), pp. 970-982.

Wensink, W.A., 1993, Dielectric properties of wet soils in the frequency range 1-3000 MHz. *Geophysical Prospecting*, **41**, 671-696.

Wilson, D.J., Western, A.W., Grayson, R.B., Berg, A.A., Lear, M.S., Rodell, M., Famiglietti, J.S., Woods, R.A. and McMahon, T.A., 2003, Spatial distribution of soil moisture over 6 and 30 cm depth, Mahurangi river catchment, New Zealand. *Journal of Hydrology*, **276**, 254-274.

Yee, M.L., 2001, Multi-sensor probabilistic fusion for mine detection. *Detection and Remediation Technologies for Mines and Minelike Targets VI* (Orlando: SPIE), pp. 959-969.

Table 1. Overview of soil effects on different technologies for non-mechanical detection of buried low-metal landmines. For many of the technologies various names are used; here we list the most common names for each method. The technologies are subdivided in (i) metal detectors, (ii) sensors that 'see' an image of the landmine through scattering, (iii) sensors that detect anomalies at the surface or in the soil, and (iv) sensors that detect the landmine explosives or associated chemicals. The list of soil properties is not complete; for example, dielectric properties is not mentioned in the list but is strongly related to soil water content.

	Soil water content	Soil texture	Soil mineralogy	Soil temperature
Electromagnetic induction sensors	×	×	×	
Active microwave (GPR, SAR, UWB)	×	×		
Thermal infrared	×	×		×
Vapor detectors (many types, MS, IMS, GC)	×	×	×	×

Table 2. Four major soil databases, based on Baumgardner (2000) and Hendrickx et al. (2003b), and the compendium of on-line soil survey information by D.G. Rossiter (http://www.itc.nl/~rossiter/research/rsrchss.html).

Soils Data	Agency	Website
SOTER, WISE other soil databases	International Soil Reference and Information Center Wageningen, The Netherlands	www.isric.nl
Digital Soil Map of the World	Food and Agriculture Organization (FAO) Rome, Italy	www.fao.org
World Soil Resources	Natural Resources Conservation Service U.S. Department of Agriculture Washington, D.C. U.S.A.	www.nhq.nrcs.usda.gov
Canadian Soil Information System	Agriculture and Agri-Food Canada Ottawa, Canada	www.res.agr.ca

Table 3. Thermal properties for different explosives (TNT, Comp B-3, and Tetryl) commonly used in landmines. For reference the properties of the landmine surrogate RTV3110 is included. Data were derived from De Jong et al. (1999) and Simunek et al. (2001).

	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Volumetric heat capacity ($10^6\ J\ m^{-3}\ K^{-1}$)	Thermal diffusivity ($10^{-7}\ m^2\ s^{-1}$)
TNT	0.23 – 0.26	2.14 – 2.53	0.93 – 1.21
RTV3110	0.20	1.76	1.14
Comp B-3	0.22	2.13	1.03
Tetryl	0.09	1.79	0.50

List of figures

Figure 6. Plot of maximum thermal signature ($\Delta_T = T_{mine} - T_{no\_mine}$) versus landmine burial depth. The relation is given for different water contents. The mine is composed of TNT, and buried in a sand soil. The model (Van Dam et al. 2003b) was run for July in Kuwait. In this model effects of wind speed and surface roughness were left out of consideration.

Figure 1

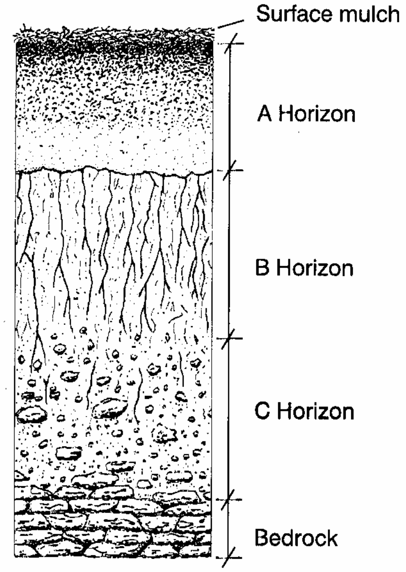


Figure 2

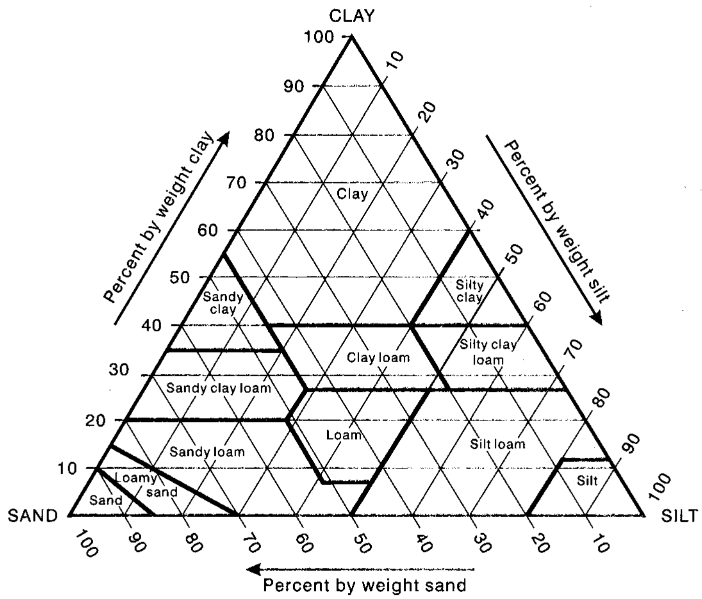
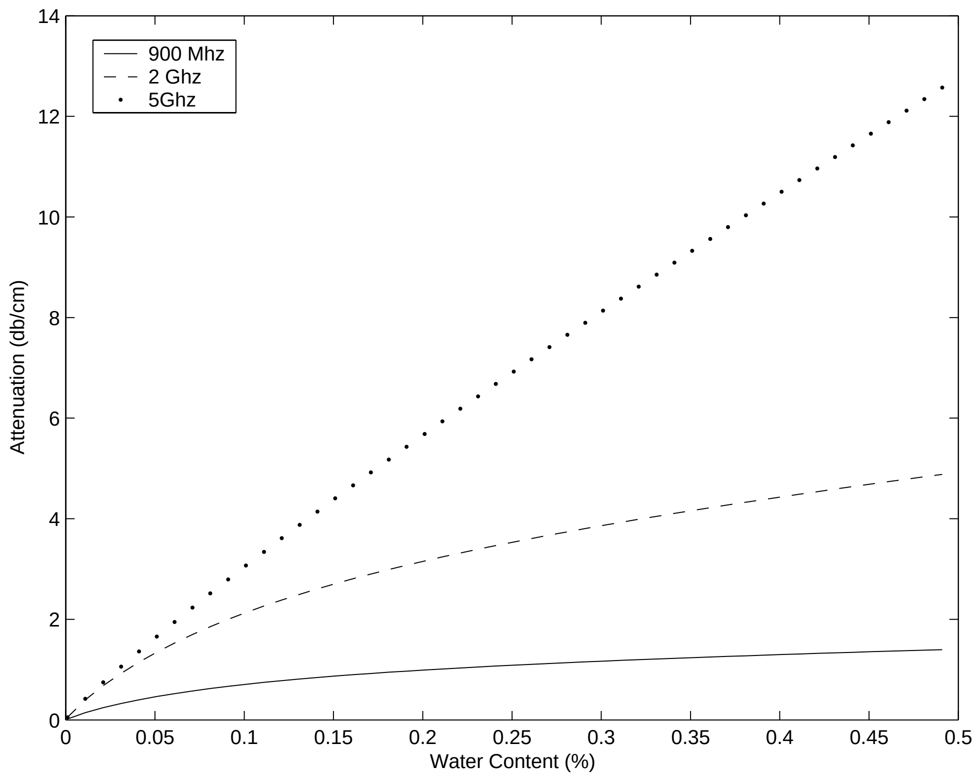
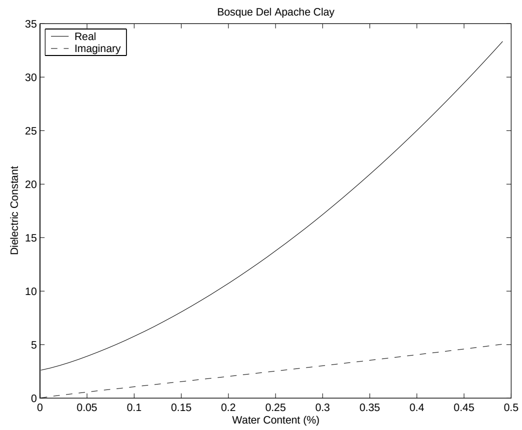

CLAY
100
90
80
70
60
50
40
30
20
10
SAND
SILT
Percent by weight clay
Percent by weight silt
Percent by weight sand
Clay
Sandy clay
Silty clay
Clay loam
Silty clay loam
Sandy clay loam
Loam
Silt loam
Sandy loam
Loamy sand
Sand
Silt

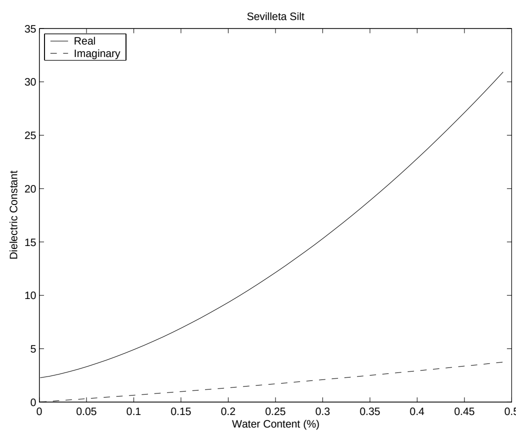
Figure 3



14
12
10
8
6
4
2
0
Attenuation (db/cm)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Water Content (%)
900 Mhz
2 Ghz
5Ghz

Figure 4


Bosque Del Apache Clay
Real
Imaginary
Dielectric Constant
Water Content (%)
0
5
10
15
20
25
30
35
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5


Sevilleta Silt
Real
Imaginary
Dielectric Constant
Water Content (%)
0
5
10
15
20
25
30
35
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5

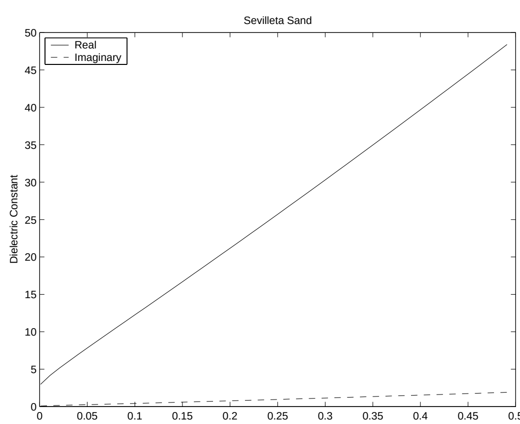

Sevilleta Sand
Real
Imaginary
Dielectric Constant
Water Content (%)
0
5
10
15
20
25
30
35
40
45
50
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5

Figure 5

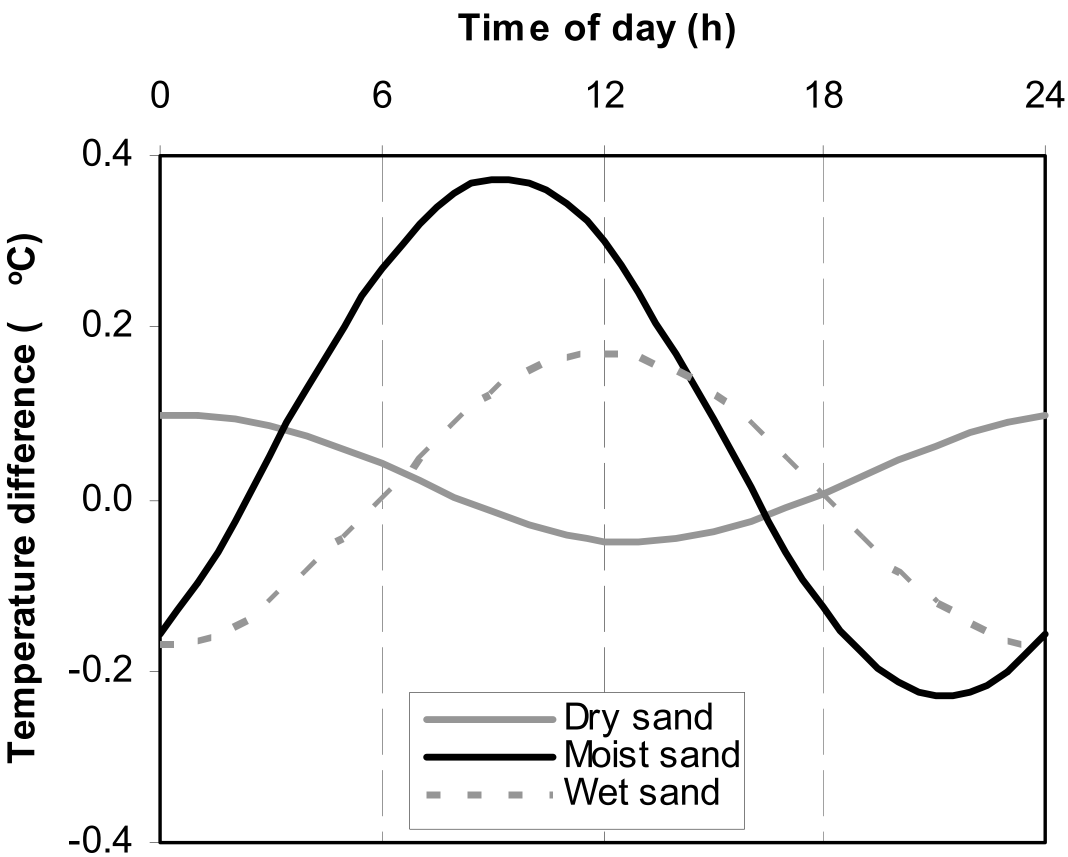
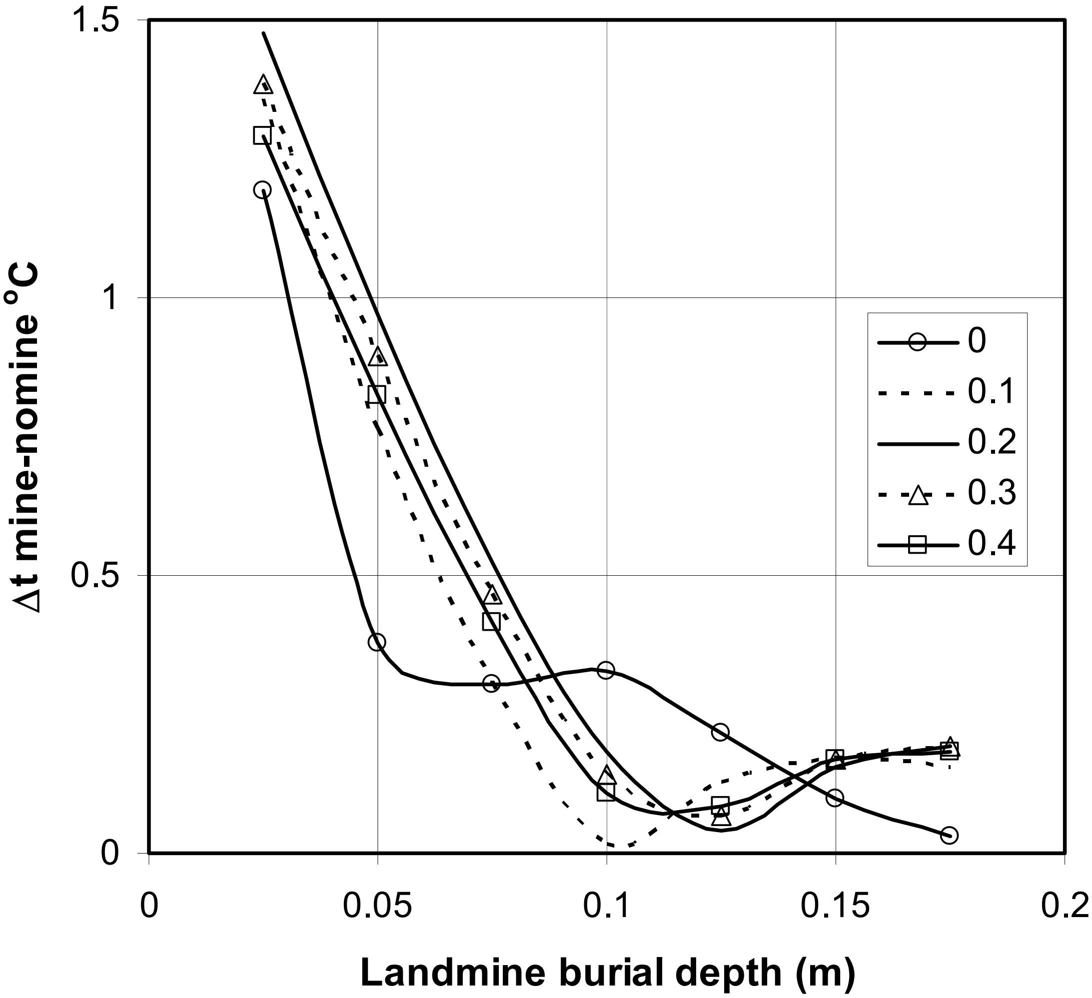

Time of day (h)
0
6
12
18
24
0.4
0.2
0.0
-0.2
-0.4
Temperature difference (°C)
Dry sand
Moist sand
Wet sand

Figure 6



1.5
1
0.5
0
0
0.05
0.1
0.15
0.2
Δt mine-nomine °C
Landmine burial depth (m)
0
0.1
0.2
0.3
0.4