Soil effects on thermal signatures of buried nonmetallic landmines

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ABSTRACT

Thermal sensors hold much promise for the detection of non-metallic landmines. However, the prediction of their thermal signatures depends on a large number of factors. In this paper, an analytical solution for temperature propagation through homogeneous and layered soils is presented to predict surface temperatures as a function of soil heat flux amplitude, soil texture, soil water content, and thermal properties and burial depth of the landmine. Comparison with the numerical model HYDRUS-2D shows that the relatively simple analytical solution proposed here is reasonably accurate. The results show that an increase in soil water content has a significant effect on the thermal signature, as well as on the phase shift of the maximum temperature difference. Different soil textures have relatively little effect on the temperature at the surface. The thermal properties of the mine itself can play a significant role. It is shown that for most soils 10 cm is the maximum burial depth to produce a significant thermal signature at the surface.

Keywords: landmines, detection, thermal infrared, thermal signature, test facility.

1. INTRODUCTION

In recent years thermal infrared (TIR) imaging has come in focus as a promising technique for the detection of landmines and other unexploded ordnance[1]. Since the penetration of optical wavelength electromagnetic radiation in soils is marginal, TIR can only image soil surface temperatures. Potential thermal signatures of landmines at the surface depend on differences in transportation and storage of heat[2]. The thermal signature of a buried mine at the surface is a complex interplay between a number of factors. Soil texture and water content are important factors that control the thermal conductivity (λ) and volumetric heat capacity (C) of the soil overlying and surrounding the landmine[3]. The thermal properties and burial depth of the landmine also play a role in the thermal signature at the surface[4]. The situation becomes more complex as a result of the diurnal and annual heat flux cycles that drive the transport of heat to and from the surface[5].

Several authors[6-8] have used analytical and numerical methods to model the thermal signatures of land mines. However, they have not looked in detail at how soil properties influence the results. Simunek *et al.* have shown in a numerical modeling approach how soil texture and soil water content affect the thermal signatures of landmines[5]. For six different soil types in two different climatic regions of the world they have numerically solved the water flow and heat transport equations, using a finite element and finite difference method as implemented in HYDRUS-2D. One of the major findings of their study is that surface temperature differences between the area above the mine and away from it are generally larger in wet than in dry soils. Therefore, soil watering may be used as a tool to improve thermal signatures. They also observed that both the strongest and the weakest thermal signature of a buried landmine appears in two six-hour time intervals centered around noon and midnight, thus concluding that a continuous 12-hour minimum measurement period is necessary for the highest chances of landmine detection.

The objective of this contribution is to compare the rather elaborate numerical modeling approach with existing analytical solutions of heat propagation through homogeneous and layered media for the prediction of the strength of thermal signatures of buried nonmetallic landmines in field soils. Specifically, focus is on the effects of (i) soil properties, such as texture and water content, and (ii) landmine characteristics, such as burial depth and thermal properties.

2. ANALYTICAL SOLUTIONS FOR THERMAL SIGNATURE OF A SOIL-MINE SYSTEM

Predicting the thermal signature of a buried landmine requires knowledge of the heat flux into the soil, the thermal properties of the landmine, the soil above the landmine and of the soil surrounding the landmine. In this paper, the soil-mine system is approximated by a two-layer soil, where the landmine underlies a soil of thickness *d*. Because thermal conduction through the mine may be an important physical process and the thermal properties of the soil under the mine could be relevant, a three-layer model (soil above mine, mine, and soil below mine) would be preferable[7]. However, for matters of simplification the landmine is considered of infinite depth here. The two-layer soil mine system is surrounded by a homogeneous soil of infinite depth. It is assumed the soil above the mine has the same thermal characteristics as the soil away from the mine.

In this analytical approach it will be assumed that the surface and soil temperatures fluctuate as a pure harmonic function of time around an average value. The surface temperature for the homogeneous soil (T_{hs}) at any specific time (t) can be found by[9]:

$$T_{hs}(t) = T_{avg} + A_{T,hs} \sin \omega t \ . \tag{1}$$

Here, T_{avg} is the average temperature, $A_{T,hs}$ is the daily amplitude of the temperature at the surface, and ω is the radial frequency, given by $2\pi/86400$. The temperature amplitude at the surface is related to the amplitude of the heat flux density (A_H) into the soil by $A_{T,hs} = A_H (\lambda C \omega)^{-0.5}$, where λ is the thermal conductivity and C is the volumetric heat capacity.

The surface temperature for the 2-layer soil (T_{ls}) depends on the thermal characteristics of both soil (layer 1) and landmine (layer 2) and is given by[9]:

$$T_{ls}(t) = T_{avg} + A'_T \sin(\omega t + \varphi'_1) + A''_T \sin(\omega t + \varphi''_1) \ . \tag{2}$$

Here, A'_T and A''_T describe the temperature fluctuation at the surface ($A_{T,ls}$) as a function of the thermal characteristics of both layers, and φ' and φ'' describe the phase shift of the periodic temperature fluctuation. The influence of the thermal properties of the second layer are incorporated in the equations that define A'_T, A''_T, φ', and φ''[9]. In a simplified form, Equation (2) can be written as:

$$T_{ls}(t) = T_{avg} + A_{T,ls} \sin \omega t \ . \tag{3}$$

This equation seems similar to Equation (1), however, the amplitude of the temperature at the surface of this layered soil ($A_{T,ls}$) depends on the amplitude of the heat flux density at the surface (A_H), the thermal properties of both layers and the depth (d) of the landmine:

$$A_{T,ls}(t) = \frac{A_H}{\sqrt{\lambda_1 C_1 \omega}} \sqrt{\frac{\exp(4d/D_1) + 2r_{ls}\exp(2d/D_1)\cos(2d/D_1) + r_{ls}^2}{\exp(4d/D_1) - 2r_{ls}\exp(2d/D_1)\cos(2d/D_1) + r_{ls}^2}} \ . \tag{4}$$

Here, $r_{ls} = (\lambda_1 C_1)^{0.5} - (\lambda_2 C_2)^{0.5} / (\lambda_1 C_1)^{0.5} + (\lambda_2 C_2)^{0.5}$, where the subscripts "1" and "2" denote the first (soil cover) and the second (landmine) layer, respectively, and D_1 is the damping depth for the soil on top of the landmine $(2\lambda/C\omega)^{0.5}$.

When it is assumed that amplitudes of the heat flux densities are equal at the surface, the following relation between the amplitudes of the surface temperature for the homogeneous and the layered soil can be given[9]:

$$\frac{A_{T,ls}}{A_{T,hs}} = \sqrt{\frac{\lambda_{hs} C_{hs}}{\lambda_1 C_1} \frac{\exp(4d/D_1) + 2r_l [\exp(2d/D_1)] \cos(2d/D_1) + r_{ls}^{\ 2}}{\exp(4d/D_1) - 2r_l [\exp(2d/D_1)] \cos(2d/D_1) + r_{ls}^{\ 2}}} \ . \tag{5}$$

The first term $(\lambda_{hs} C_{hs} / \lambda_1 C_1)^{0.5}$ reduces to one in the case that the soil above the mine and the homogeneous soil have equal thermal properties. For high values of d/D_1 (i.e., for a large burial depth of the mine, or a small damping depth of the soil), the second term approaches one. In other words, the temperature variation in the layered soil is restricted to the upper layer, and a buried mine will not result in a detectable thermal signature. The same result (now for any value of d/D_1) is obtained when $r_{ls} = 0$, which is when the thermal diffusivity (λ/C) of the landmine is similar to that of the soil.

3. METHODS AND MATERIALS

For the modeling of the relations given in Section 2 it is necessary to define the heat flux that enters the soil, as well as thermal properties of the landmine and those of the soil. For this study, heat flux properties for conditions in Kuwait and Sarajevo are used[5]. Heat flux amplitudes in Kuwait are 28 and 54 Wm^{-2} for January and July, respectively, while they reach 10 and 31 Wm^{-2} for January and July in Sarajevo. Average soil temperatures were taken 20 °C for July[5] and assumed 15 °C for January, in both Kuwait and Sarajevo. Table 1 presents thermal properties for different soil types and landmines, including calculations for damping depth (D) and thermal diffusivity (λ/C).

Table 1. Thermal properties for different soil types and soil water contents, as well as for different landmine surrogates (RTV3110) and explosives (TNT, Comp B-3, and Tetryl).

	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Volumetric heat capacity ($10^6\ J\ m^{-3}\ K^{-1}$)	Thermal diffusivity ($10^{-7}\ m^2\ s^{-1}$)	Damping depth (m)
Sand dry*	0.29	1.26	2.33	0.08
Sand moist*	1.76	2.09	8.40	0.15
Sand wet*	2.18	2.93	7.43	0.14
Clay dry*	0.25	1.26	2.00	0.07
Clay moist*	1.17	2.09	5.60	0.12
Clay wet*	1.59	2.93	5.43	0.12
TNT#	0.23	2.53	0.93	–
TNT^	0.26	2.14	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	–

* from [9], # from [5], ^ from [4]

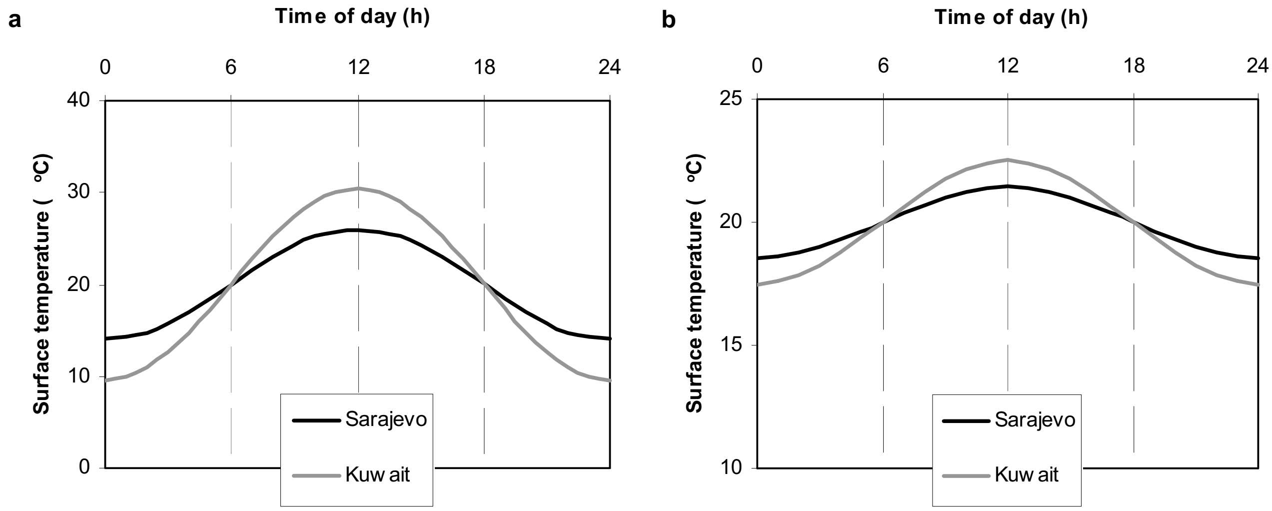
Using this basic information, an analytical model was constructed with similar properties as the numerical model by Simunek *et al.*[5], and the results of both approaches are compared (Section 4.1). Next, it was attempted to demonstrate the effects of soil properties (Section 4.2) and landmine characteristics (Section 4.3) on the thermal signature.

4. RESULTS AND DISCUSSION

4.1 Analytical approach versus numerical solution

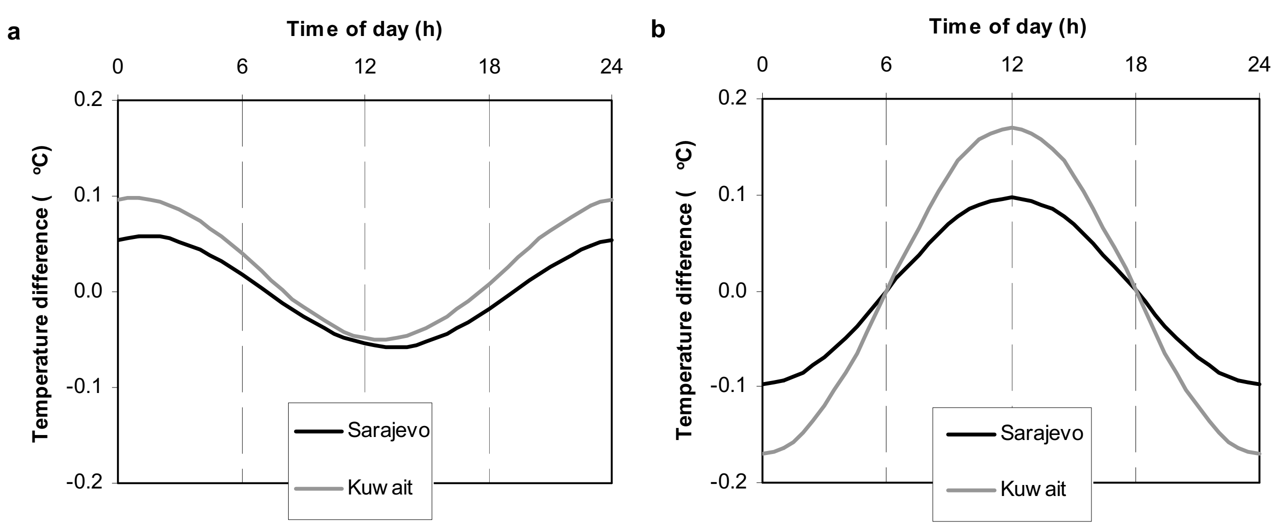
Calculation of July temperature variations at the surface for homogeneous sand with different water contents shows that amplitudes vary between 10 °C for dry Kuwait sand to only 3 °C for wet Sarajevo sand (Fig. 1). These differences can be attributed to the difference in heat flux, which is higher in Kuwait than in Sarajevo, and to the differences in thermal conductivity and volumetric heat capacity for wet and dry sediment (Table 1). The outcomes of the analytical approach is in reasonable agreement with the outcomes of the numerical modeling[5], although amplitudes of the latter are somewhat higher. This small offset can be explained by the use of different thermal properties of the soil. In this study thermal characteristics by Van Wijk[9] were used.

Figure 1. Diagrams showing the predicted July surface temperature of homogeneous dry sand for one day (using Equation (1)) in Kuwait and Sarajevo. Note the different scales on the vertical axes of the diagrams for **(a)** dry and **(b)** wet sand.



Simunek *et al*. modeled temperature differences between the soil surface immediately above the landmine and away from it in HYDRUS-2D[5]. The anti-tank mine, in the model consisting of pure TNT, was buried at a depth of 0.15 m below the surface. In the analytical approach presented here, this configuration and the thermal properties of the landmine were exactly copied. The results show that, whether wet or dry, the maximum temperature difference is only between 0.1 to 0.17 °C (Fig. 2). These values are 2 to 4 times as small as the maximum temperature differences obtained from the numerical model. This discrepancy can be due to different thermal properties (λ, C) used in the numerical and analytical model. Also, the distribution of water around the mine, which is more complex in the numerical model than in the analytical solution can contribute to the difference. Figure 2 shows that the temperature difference for dry sand is smaller than that for wet sand, while at the same time the total temperature amplitude at the surface is larger for dry conditions (Fig. 1). The same effect is predicted in the numerical model.

Figure 2. Plots of the predicted temperature difference in July between the soil surface above a mine, and away from it, for **(a)** dry and **(b)** wet sand in Kuwait and Sarajevo. The landmine was buried at 15 cm depth, and was assigned thermal characteristics of TNT[5].



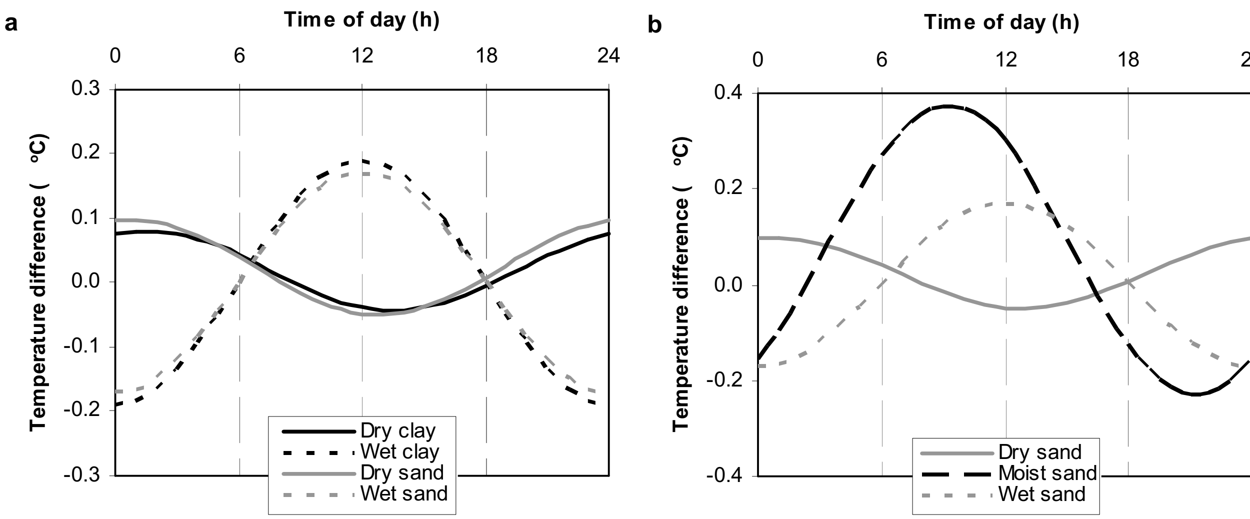
One remarkable difference between the numerical model and the analytical solution presented here, is the phase of the temperature difference. Under dry conditions (Fig. 2a), the surface temperature is higher above the mine at midnight and cooler during mid-day. Under wet conditions (Fig. 2b), the situation has reversed and the surface temperature above the mine is cooler at midnight and warmer during the day. This effect is not predicted by the numerical model, which is another indication that the thermal properties used in the numerical model do not match exactly those of the analytical model. The latter effect can be explained by the thermal properties of the soil, and will be discussed in more detail in the next section.

4.2 Soil texture and soil water content effects

Figure 3a demonstrates that in both dry and wet soils the texture does not make much difference for the thermal signature of a buried landmine. Under wet conditions, the temperature difference is somewhat higher in clay, whereas under dry conditions, sand has a slightly higher temperature difference. Because sand and clay behave so similarly, in the remainder of this paper the landmines are all buried in sand.

The most striking feature in Figure 3a is the change in phase between a dry soil and a wet soil, as was also seen in Figure 2. This implies that the thermal signature of a landmine can be both a positive and a negative temperature difference, depending on the water content of the soil. This effect is more complex than seems apparent from Figure 3a, where the maximum temperature difference occurs close to either midnight or noon. In Figure 3b, where temperature differences at the surface have been modeled for three volumetric water contents (0, 0.2, and 0.4), it can be seen that the combined variation in thermal conductivity and volumetric heat capacity (Table 1) cause significant phase shifts. Unfortunately, there exists no simple linear relation between the soil thermal properties, as controlled by soil water content, on one side and the temperature difference and the temperature phase shift at the surface on the other side. Nevertheless, the analytical model is well capable of predicting thermal signatures based on these effects.

Figure 3. Plot of the predicted temperature difference in July, Kuwait, between the soil surface above a mine, and away from it for **(a)** a sand soil and a clay soil with two different water contents, and **(b)** a sand soil with 3 different water contents. In both plots, the landmine characteristics (depth and thermal properties) are similar to those in Section 4.1.

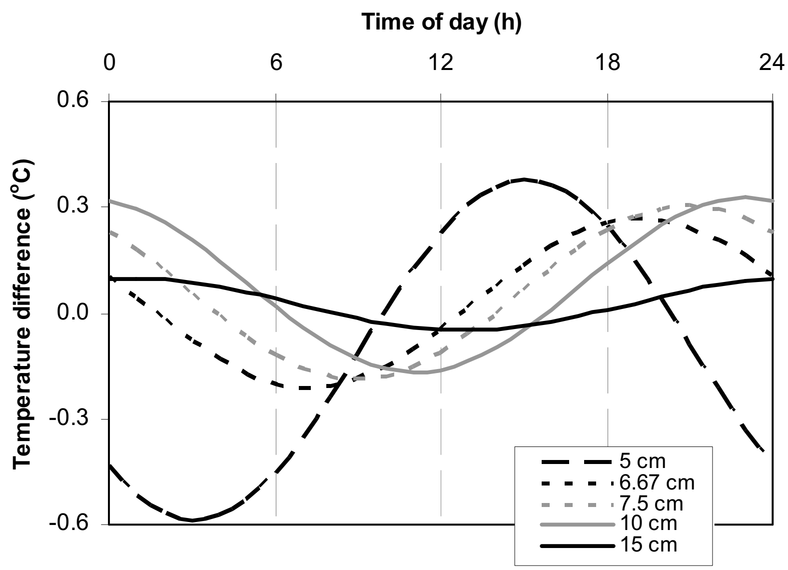


4.3 Landmine properties and burial depth

The burial depth of a landmine has an effect on the amplitude of the temperature at the surface, and thus the thermal signature, as follows from Equation (4). From the same equation it follows that the thermal properties of the landmine, through the parameter r_{ls}, also influence the amplitude of the temperature at the surface.

In Figure 4, the temperature difference between the area above a mine and away from it has been modeled for a TNT landmine buried at different depths in dry sand. The plot shows that the temperature difference decreases with depth, as would be expected. There is a significant phase shift, described by φ' and φ'' in Equation (2), which increases with burial depth. A change of burial depth from 5 to 10 cm, causes the maximum positive peak to shift from 2 PM to 10 PM.

Figure 4. Diagram showing the difference in surface temperature for mines buried at different depths in dry sand. The plot is for July in Kuwait. The mine has the thermal properties of TNT, as used in the examples before.



Thermal properties of the landmine are an important factor to consider. De Jong *et al.*[4] have measured the thermal conductivity and volumetric heat capacity for a number of commonly used explosives and for the material RTV3110, which is used in landmine surrogates. As can be seen in Table 1, the thermal properties cover a quite wide range of values. Although mines are in reality complex structures, they have been modeled here as consisting completely of explosive or surrogate material. The diagrams in Figure 5 show the temperature difference at the surface for different landmines buried at 15 and 6.67 cm depth in sand. Figure 5a clearly demonstrates how different thermal characteristics of the landmines, buried in dry sand, influence the strength of the temperature difference. For wet material, the effect of mine characteristics is less strong. This is due to the fact that all landmines have lower values of λ and C than wet sand (Table 1). A change in burial depth leads to a phase shift of the temperature difference curves (Fig. 5c).

The relation between the amplitudes of the surface temperature for the homogeneous and the layered soil (Equation 5) was calculated for mines at different depths (1 to 20 cm) and different soil conditions. Figure 6a shows that the soil water content plays an important role in amplitude variation at the surface; this in contrast to the soil texture. Sand and clay show a similar behavior of increasing values of $A_{T,ls}/A_{T,hs}$ with decreasing landmine burial depth. The amplitude variation in sand is somewhat larger than in clay. The amplitude variation decreases rapidly for deeper burial depths and any significant amplitude variation is absent for landmine depths over 0.1 m. The thermal signature does not directly follow from this variation in maximum amplitudes, as the phase shift between temperatures above the mine and above homogeneous soil is not included here.

Figure 5. Diagrams showing the difference in surface temperature over time for different surrogate landmines and explosives for July in Kuwait. The mines are buried at 15 cm depth in **(a)** dry sand and **(b)** wet sand. In **(c)**, the landmine is buried at 6.67 cm depth in dry sand.

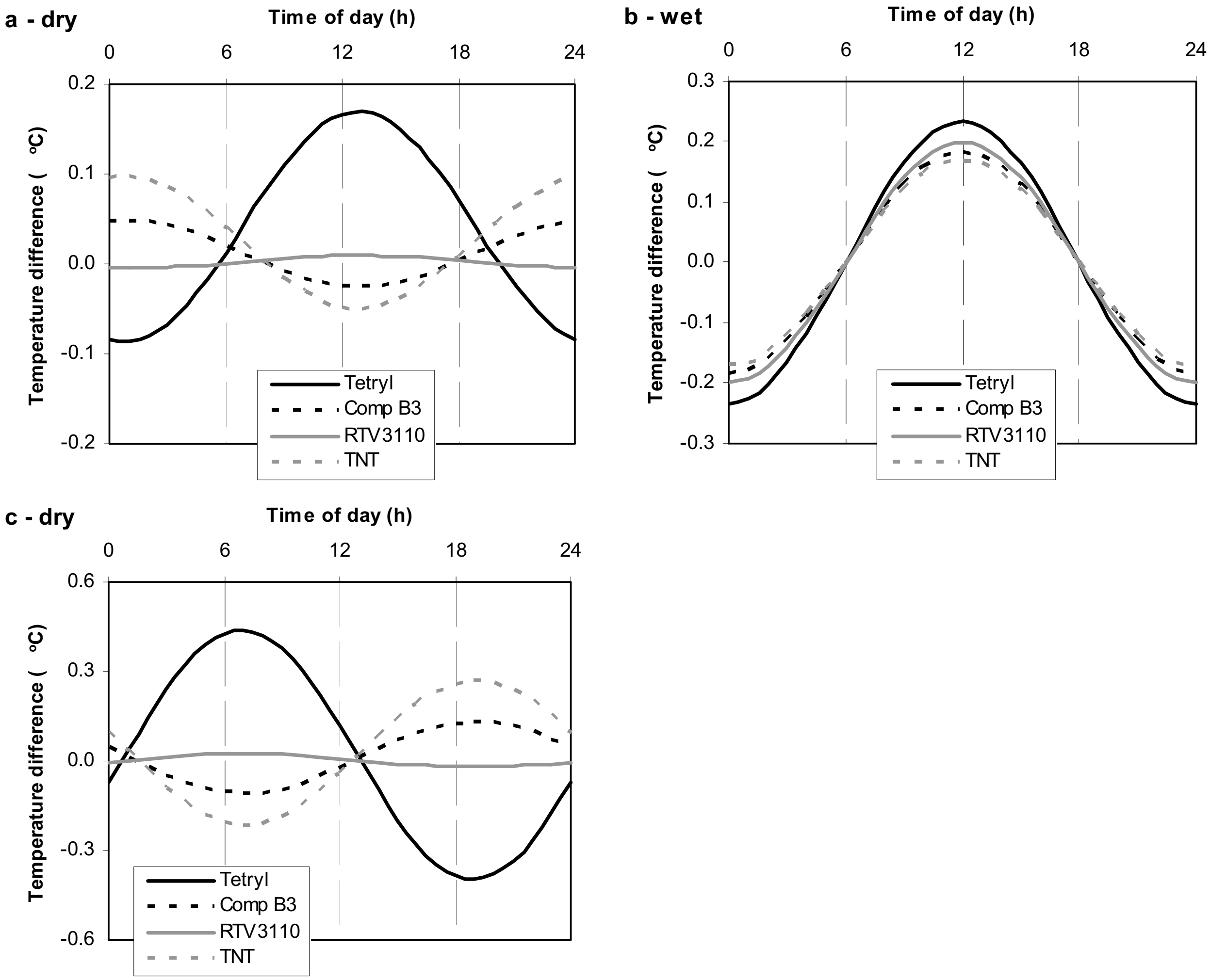
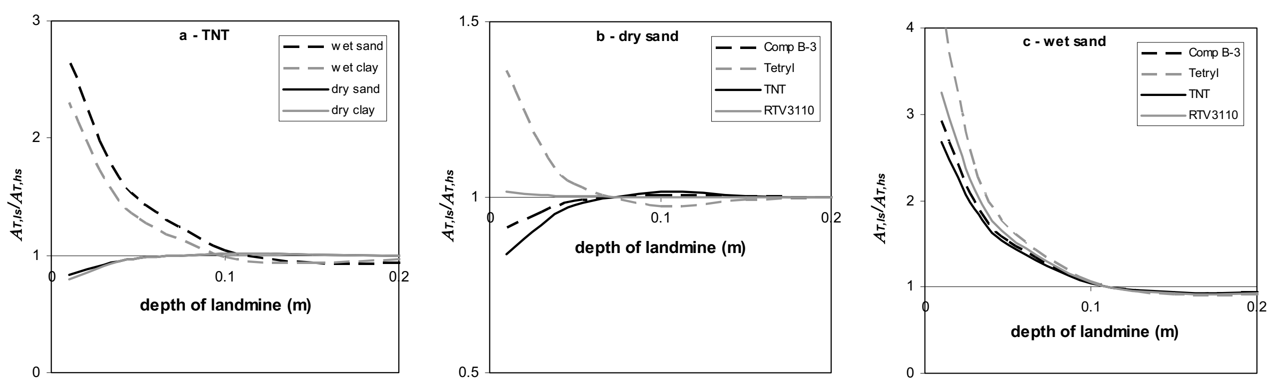


Figure 6. Diagrams showing the difference in the maximum surface temperature amplitude between a layered (i.e., buried landmine) and a homogeneous soil versus depth of the landmine. **(a)** Effect of soil water content and texture for a landmine consisting of TNT. **(b)** Results for 4 types of surrogate mines and explosives, buried in dry sand. **(c)** As (b), but now for landmines buried in wet sand. Note the different vertical scales.



Another aspect that plays a role in the amplitude variation at the surface are the thermal properties of the landmine (Table 1). The temperature amplitude variation at the surface for the surrogate material RTV3110 was compared with three explosives (TNT, Comp B-3, and Tetryl) that are often used in landmines[4]. Under dry soil conditions RTV3110 will not lead to a thermal contrast at the surface (Fig. 6b). This follows from variable r_{ls} being very close to zero. Even though the individual values of λ and C for the landmine are not the same as those for dry sand, the product of the two is. For dry sand, $A_{T,ls}/A_{T,hs}$ is close to one for all modeled substances, with Tetryl leading to a higher amplitude at the surface, whereas the other two explosives cause lower amplitudes than the homogeneous sand (Fig. 6b). In wet sand, $A_{T,ls}/A_{T,hs}$ is significantly larger and positive for all explosives, as well as the surrogate material RTV3110 (Fig. 6c).

5. CONCLUSIONS

The analytical model that was developed is a relatively simple method to predict the thermal signatures of buried nonmetallic landmines. Comparison with the numerical model by Simunek *et al.*[5] shows that the relatively simple analytical solution presented here is reasonably accurate. The results in this paper have shown that the thermal signature at the surface is an interplay of thermal characteristics and soil water content of the soil and of burial depth and thermal properties of the landmine. These different variables control in a complex manner the amplitude of the temperature difference at the surface, as well as the phase shift of the temperature variation above the mine.

The results show that, for equal soil water contents, the soil texture has relatively little effect on the temperature at the surface. Soil water content has a significant effect on the thermal signature, as well as on the phase shift of the maximum temperature difference. However, the strength and phase of the thermal signature also depend on the thermal properties and burial depth of the mine. Therefore, it is impossible to predict the thermal signature accurately without knowing all parameters involved.

In the near future the analytical model will be further refined by a number of additions. Using a multi-layer model instead of the two-layer one, including the soil below the mine, will improve the accuracy of the model. A multi-layer approach will also allow for taking the effects of wetting and drying fronts in the topsoil into account. Including modules for the effect of wind speed, surface roughness, and albedo will allow for a better coupling to regional climatic and terrain characteristics. In the near future, newly designed test lanes with soil different textures and with measurement probes for the continuous monitoring of soil water content and soil temperature will be in operation at New Mexico Tech. Measurements at these test lanes will allow for comparison with, and improvement of the analytical model.

6. ACKNOWLEDGMENTS

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