Microwave Radiation in Thermal Detection of Buried Objects - Modeling and Experiments

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Abstract:
Many factors limit the efficiency of thermal methods at detecting buried objects. Underground objects create disturbances in distribution of thermal parameters of the soil. Natural conditions of heat exchange can provide suitable thermal image on soil surface – in a form of wanted trace in thermal image. Solar energy is the main source delivering heat to soil. The range and character of changes of heat stream and the rate of accumulation in soil at given day depend on three factors: atmospheric conditions, kind of surface and thermal properties of soil. Microwave sources are used to increase probability of detection of buried objects by IR thermography method. In this paper the results of such computer simulation and experimental tests are presented.

Keywords: IR thermography, buried objects, modeling, microwave

1. Introduction

It has been estimated (in 1999 year) that there are about 110 million anti-personal (AP) and anti-tank (AT) mines scattered on the ground in about 64 countries. The actual number of buried mines is generally underestimated. These mines pose a serious threat to any military operation including US peace-keeping operation and also to unsuspecting civilian populations.

Mines, so far the most feared post-war danger, are composed by the casing, the explosive charge, and the fuse. The casing is made using a variety of materials such as metals, plastics, wood or even cardboard. Sophisticated envelopes have been also constructed to protect mines against detection or environmental agents. Modern bakelite envelopes, as well as synthetic-resin envelopes, keep mines uncorrupted against chemical agents, and seriously reduce the effectiveness of the electronic instruments of detection.

Anti-personal and anti-tank mines were caused 34% losses of American armies during war in Persian Gulf. It was estimated, that annually on the word about several thousand people loses life or suffers injuries in mine incidents. More and more modern technical solutions for detecting mines are applied to reduce number of incidents and enlarge safety of sapper’s work as well as efficiency of mine clearance.

The new treat, which appeared in last years, is an improvised explosive device (IED). According with NATO Combat Engineer Glossary, IED is a device placed or fabricated in any improvised manner incorporating destructive lethal, noxious, pyrotechnic or incendiary chemicals and designed to destroy, incapacitate, harass or distract. It may incorporate military stores, but is normally devised from non-military components [1]. At present the limitation in matter of designing, preparation and use of improvised explosive device is only terrorist’s imagination.

The demining activity is usually divided on „operating activity” and „humanitarian activity”. The operating activity is concerned with military operations aiming on removing a percentage
≥ 70% of contaminative war material. Following international standards, in humanitarian activity the minimum level is 99.6% with a residual risk of 0.4%.

2. Thermal detection of buried objects

On the basis of earlier investigations carried out in MIAT [2-4] it was confirmed that objects which were buried under surface of the ground could be treated as a special case of subsurface material non-homogeneities. One of a method used for nondestructive testing of subsurface structure of materials is IR thermography. IR thermography can be divided into two approaches, a passive approach and an active approach. The passive approach deals with testing materials and structures which are naturally at different (often higher) temperature than an ambient one while in the case of the active approach an external stimulus is necessary to induce relevant thermal contrasts [5]. Transient thermal processes are studied. It is not essential, which process is analysed: heating or cooling. Considering that thermogram (IR image) reflects only instantaneous distribution of radiation temperature on the surface of an object it implies the use of specific procedures of measurement and processing of results for studying the problem. Results of measurements depends on proper selection of time-amplitude dynamics of thermal extortions concerning both the object and kind of awaited anomalies as well as technical limitation of measurement system and testing method. The elaboration process of results received from IR thermography testing for technical diagnostics is not only based on automated algorithms and numerical calculations but also involves heuristic operator’s experience.

The subsurface, thermal “traces” from underground objects can be result of so called surface or volumetric effects. First of them are usually of short duration (hours, days from burying the object) as they result with local change of surface emissivity and loosening soil and introduction of additional air. This air has a slowing down effect on change of temperature but at the same time it can be replaced easily by water and it can give opposite result. The volumetric effects are result of “stability” differences between thermal capacity and thermal conductivity of object and surrounding soil [6]. There are no “stability” differences in reality. Interactions soil-surrounding in nature are result of both cyclic (24 hour) as well as past and current metrological conditions. Water and steam contained in soil are particularly strong source of these changes. This is a large difficulty at modelling radiation phenomenon and many limitations exist in applying well-known IR thermography procedures to detection of anomalies in soil [3, 5, 7]. Possibility of visualizations of instantaneous and very small changes of temperature distribution creates theoretically a chance to detect the heterogeneity of material (object in soil) if testing surface will be suitably heated. Kind of surface and source of extortion of local change of temperature can be theoretically very different, for example source of this energy can be microwave radiation [8].

3. Modeling

3.1. Software

Computer simulations were performed by means of the ThermoCalc™-Mine software which had been developed for WITU purposes by Prof. Vavilov [9]. The ThermoCalc™ Mine software is intended for calculating three-dimensional (3D) temperature distributions in anisotropic six-layer solids which may contain up to nine subsurface defects. The corresponding mathematical heat conduction problem is modeled in Cartesian coordinates and
solved by using an implicit finite-difference numerical scheme. Originally, ThermoCalc™ Mine was developed for simulating thermal nondestructive testing (NDT) problems where transient temperature signals over subsurface defects are of a primary interest. These signals evolve in time and diffuse in space. The earlier two-dimensional version of this software called ThermoCalc-2D™ is successfully used by several thermal NDT research teams worldwide. The unique numerical algorithm implemented in ThermoCalc™ Mine, unlike many commercial software packages currently available, enables modeling very thin defects in rather thick materials without losing computation accuracy. It allows analyzing up to nine defects with a specimen being heated uniformly or non-uniformly with a square or cosine pulse that gives a possibility to study defect cross-influence and lateral 3D heat diffusion. The unique feature of the program allows modeling continuous linear variation of thermal properties across each layer, as well as using an arbitrary function defined by the user. Another unique feature is that the heating of a specimen can be done with a mask-image borrowed from an experiment or produced artificially. A ThermoCalc™ Mine software matches several pulsed thermal NDT techniques used worldwide. It provides a good accuracy of temperature calculations in regard to classical 1D solutions and results obtained with available 2D programs.

3.2. Thermo-physical parameters of sand

The temperature of soil – beside different physical quantities of soil – is one of main factors determining the course of changes for physical, chemical and biological processes in porous material (ground, soil). Distribution of temperature in any point of space and time in porous material shows the dynamic process of heat flow, but it does not give a full image of physical phenomena transferring and accumulating heat in it. Only recognition of basic thermal proprieties of the material makes possible to get better recognition of these processes and also understanding the causes for forming specific thermal relations. The ground, soil and different porous materials create three-phase dispersion bodies consisting of huge quantity of mineral and organic compounds. They are much complicated and do not submit to a simple analysis. The complicated mechanisms of exuding water from solid bodies and character of water flow in soil that is completely different with its small and large content make this analysis not easier. The investigation of influence of individual soil components on transmission of heat in the soil can make possible to understand the phenomenon of transferring and accumulation of heat in soil and to develop and study a model for predicting thermal conditions in soil with a satisfied precision.

Thermo-physical parameters of sand were experimentally calculated to modeling detection of buried objects. Thermal conductivity, thermal capacity and diffusivity were calculated depending on sand moisture content. Thermal conductivity is a phenomenon depending on self-acting leveling temperature without any macroscopic movements within a studied environment. From macroscopic point of view thermal conductivity depends on leveling energy of thermal movements as a result of collisions between particles. The coefficient of thermal conductivity \( \lambda \) is a measure of rate of thermal conductivity. It numerically equals a quantity of energy \( Q \) (J) flowing in unit of time \( t \) (s) through unit of surface \( S \) (m\(^2\)) with gradient of temperature \( \nabla T \) (K·m\(^{-1}\)) equal one:

\[
\lambda = \frac{Q}{t \cdot S \cdot \nabla T} \tag{1}
\]

The unit of measure of coefficient of thermal conductivity is W·m\(^{-1}\)·K\(^{-1}\).

The thermal capacity of soil (C) is a quantity of heat that should be provided (or taken away) to soil causing its temperature grows up (or lowers) about 1 K. The unit of thermal capacity is J·K\(^{-1}\). Thermal capacity of soil for a unit of volume - \( C_v \) (J·m\(^{-3}\)·K\(^{-1}\)) depends on thermal
capacities of respective components of solid phase (particles of different minerals and organic matter), liquid phase (free and connected water) and gas phase (soil air) as well as contribution of these components in soil. The value of thermal capacity of soil $C_v$ is calculated with formula:

$$C_v = \sum_{i=1}^{n} x_i C_{si} + x_w C_{w} + x_a C_{a}$$  \hspace{1cm} (2)

Where:

- $x_i, x_w, x_a \text{ (m}^3 \cdot \text{m}^{-3}\text{)}$ – content of solid, liquid and gas phase components in unit of volume;
- $C_{si}, C_{w}, C_{a} \text{ (J} \cdot \text{m}^3 \cdot \text{K}^{-1}\text{)}$ – thermal capacity on unit of volume of solid, liquid and gas phase components.

Between specific heat $c_i \text{ (J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}\text{)}$ of respective components of soil and their thermal capacity on unit of volume $C_{vi}$ is a following dependence:

$$C_{vi} = c_i \rho_i$$  \hspace{1cm} (3)

Where:

- $\rho_i \text{ (Mg} \cdot \text{m}^{-3}\text{)}$ – density of components of soil.

The coefficient of thermal diffusivity $\alpha$ is a quotient of thermal conductivity and thermal capacity on unit of volume:

$$\alpha = \frac{\lambda}{C_v}$$  \hspace{1cm} (4)

This coefficient defines ability to leveling temperature in all points of studied object. It is a speed of temperature change $\frac{\partial T}{\partial t}$ in analyzed point of soil, caused by a unitary change of temperature gradient $\frac{\partial T}{\partial x} \left(\frac{\partial T}{\partial x}\right)$ and is given with the formula:

$$\alpha = \frac{\partial T}{\partial t} \left(\frac{\partial T}{\partial x} \left(\frac{\partial T}{\partial x}\right)\right)^{-1}$$  \hspace{1cm} (5)

Dimension of coefficient of thermal diffusivity is $\text{m}^2 \cdot \text{s}^{-1}$.

Device KD2 from double needle made by Decagon Devices Inc. was used to measurements of thermal properties of sand. Short heating impulse applied in this probe to measurements of thermal properties permits to minimize thermal movement processes of water and time necessary to measurement. Thermal power is minimized also to minimize movement of water and free convection. The use of relatively short time of heating as well as low level of heating of sensor requires high resolution of measurements of temperature and special algorithms to calculate thermal properties. KD2 Pro measures temperature with resolution 0.001 °C.

Fig.1 shows exemplary results of calculated thermal capacity of sand.
3.3. Model

In order to analyse a possibility for microwave enhancement of thermal detection of buried mine a simulated model of PMD-7 anti-personnel mine was developed and presented on Fig.3. The PDM-7 (Fig.2) is an anti-personnel mine that consist of a wooden box with a hinged lid with a slot cut into it. The slot presses down against a retaining pin, which holds back the striker. When sufficient pressure is applied to the lid of the box the retaining pin moves, allowing the striker to hit the detonator. PDM-7 is in a form of parallelepiped wood box with 51 mm height and 76 mm width and 152 mm length. The weight of mine is 300 g and there is 75 g TNT.

In the table 1 thermal parameters sand and materials which simulates mine are presented.

Table.1. Thermal parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat capacity J/kg-K</th>
<th>Thermal conductivity W/m-K</th>
<th>Specific density kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>885.5</td>
<td>1.134</td>
<td>1607</td>
</tr>
<tr>
<td>Water content 0.035 m³·m⁻³</td>
<td>1595</td>
<td>1.937</td>
<td>1653</td>
</tr>
<tr>
<td>Water content 0.348 m³·m⁻³</td>
<td>2390</td>
<td>0.25</td>
<td>550</td>
</tr>
<tr>
<td>TNT</td>
<td>1703</td>
<td>0.23</td>
<td>1500</td>
</tr>
</tbody>
</table>
Figure 2. PDM-7 mine

Figure 3. Model of buried PDM-7 mine: a) longitudinal section, b) top of view
3.4. Results

Computer simulations were conducted for the model presented on Fig. 3. Some selected results are presented on graphs (Figs. 4-5). Fig. 4 presents changes of temperature at the centre of front surface of this model. Maximum heat pulse density of thermal waves simulating microwave heating is $Q = 2\, kW/\, m^2$ and heating duration $\tau_h = 1200\, s$. The time of calculations was 3000 s. Thermal parameters of sand were accepted for sand with content of water $0.035\, m^3\cdot m^{-3}$ (Table 1) and mine was buried on depth 1 cm. It is visible from Fig.4 that maximum increase of temperature is above $0.35^\circ C$.

![Figure 4. Temperature changes along buried mine on surface of the model](image)

The next simulation shows (Fig. 5) that maximum increase of temperature is above $0.85^\circ C$ for buried mine in the sand having content of water $0.348\, m^3\cdot m^{-3}$ (thermal parameters – Table 1). Maximum heat pulse density of thermal waves simulating microwave heating is $Q = 2\, kW/\, m^2$ and heating duration $\tau_h = 1200\, s$. 

![Diagram of temperature changes along buried mine on surface of the model]
4. Experiment

4.1. Experimental set-up

In order to test the model introduced above at different but controlled in laboratory conditions the laboratory set-up was build (Fig.6). Temperature profiles in soil (sand) were registered in the middle of measurement field. Two mines were buried in the sand: PDT-7 mine (wooden mine) was buried 1 cm under surface of sand and second MS-64 mine (metal mine) was buried 2.5 cm under surface of sand. All investigations were carried out using FLIR SC 7600 thermal camera and set of instruments for measuring: temperature on buried mine, temperature on profile of the soil, temperature on surface of the soil, moisture of the soil, irradiance of the surface and state of external conditions. The measurement field takes the all of the set-up and the plastic specially isolated container with dimension 1000x850x1000 mm. The temperature sensors and mines were placed inside the soil filling container in precisely determined spots. A 900 MHz, 2 kW/m² microwave source was used for illumination and thermal signature of the soil surface was detected in the 3-5 μm band at quasi real-time.
4.2. Results

Fig. 7 presents results of experimental verification of the model by comparing sand profile temperature changes for PDT-7 mine. During experiment temperature and water content of sand were monitored. Probes and micro-thermocouples were located at depth 0.5 cm, 5 cm, 10 cm, 15 cm and 20 cm below the surface along the profile located beyond the influence of the mine.

Figure 7. Temperature signal of the PDT-7 mine buried in sand
The result of test of the MS-64 mine buried in sand is shown in Figure 8. MS-64 and PDT-7 mines were tested in the same conditions.

![Figure 8. Temperature signal of the MS-64 mine buried in sand](image)

Fig. 9 represents these temperature distributions at the end of 20 min heating (microwave 900 MHz, 2 kW/m²) the sandy soil covering the two types of the mines placed at 1 cm depth.

![Fig.9. Thermograms: a) PDT-7 mine buried in sand, b) MS-64 mine buried in sand](image)

5. Conclusion

The elaborated model and procedures of estimating thermal properties of the soil provide very useful data for recognising the phenomena of the thermal profiles on the ground surface depending on the density and moisture features of the soil. Numerical experiments and measurements that were carried out show many physical limitations for applying simple typical procedures for microwave enhancement of thermal detection of buried mines. Author hopes that future works on mentioned program will help to elaborate more effective procedures for considered and many similar applications of the IR thermography.
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References

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