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A thermographic step-heating technique for metallic pollutant detection in soils

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ABSTRACT

A feasibility study of the detection of metallic pollutants in soil with thermographic measurement techniques is presented in this paper. This study proposes an alternative method to current techniques for detection and identification of contaminated soils by non-destructive testing to reduce costs and the required execution time. For this purpose, step-heating thermography is used as measurement technique. Taking into account the soil thermal models, different pre-processing methods are applied to the captured thermogram sequences to characterize the soil thermal response data; and Artificial Neural Networks (ANN) are used as a processing tool to discern the presence or absence of contaminants in soil. The selected ANN configuration will determine the contaminated soil identification rates, making the false negative rate worse with the false positive improvement.

1. Introduction

Soil thermal analysis techniques are based on the study of the thermal behavior of the materials, of which they are made, from the changes produced in its structure and chemical composition. These modifications can be analyzed by measuring the variation of different properties of the material depending on the temperature. Among thermal analysis techniques, these ones are more important: Thermogravimetry (TG) [1–4], Differential Thermal Analysis (DTA) [1,5,6], Differential Scanning Calorimetry [1,7,8], Atomic Absorption Spectrophotometry (AAS) [9,10], Gas Chromatography (GC) [1,11] and infrared spectroscopy [12,13]. The complexity of the above techniques for the detection and identification of contaminated soil makes necessary to explore alternative techniques to simplify these processes. These techniques require highly costly processes, which involve drilling for soil sampling, collection, identification and preservation of samples. Therefore, the detection of contaminants by fast, reliable and non-contact infrared thermography measurements could reduce economic and time costs. A feasibility study is presented based on infrared thermography techniques. The contaminant detection is based on the thermal analysis of the soil. This analysis consists of studying the soil thermal response to an external excitation. In the literature, several passive and active methods have been used in soil characterization and analysis by infrared thermography. For example, passive ones have been used for detecting buried objects [14,15], microbial activity [16], waste-disposal sites [17], biogas controlling [18] and evaporative fluxes evolution [19], and the active ones, like Escherichia coli detection [20] and the energy-dissipating ability evaluation [21] in soil samples testing. In this work active thermographic techniques, such as step-heating thermography [22–25], are used for the feasibility study of the contaminants detection in soils applying artificial neural networks [26,27].

This work begins (Section 2) explaining the mathematical model that characterizes the soil heat transfer. This model depends on the boundary conditions and soil physical and thermal characteristics. A detailed knowledge of this model enables a right interpretation of the involved processes and the obtained results. Next, in Section 3, infrared thermography techniques are described, which are based on the capture of infrared radiation emitted by all bodies due to their thermal condition (above 0 K temperature). From the applications of this technique, infrared images (thermograms) are captured from the heat emitted by objects, allowing to determine their temperature. In this section, different thermographic methods are detailed and explained, obtaining a features and capabilities overview of each method. It involves an approach to thermal imaging techniques according to their type, defining various applications that make infrared thermography one of the most promising techniques in the scientific and professional fields [24]. Subsequently, in the Section 4, step-heating thermography is

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described in detail; it is the technique used in this work, explaining the pre-processing methods applied to the obtained thermal images.

The Section 5 details the use of Artificial Neural Networks (ANN), tools that, due to its learning capacity, robustness and flexibility in computer programming, enable that results (obtained by active thermography infrared) adapt themselves to the processing requirements, identifying the presence of contaminant in the samples. It shows an overview of the behavior of the ANN, specifying the configurations that are used in this work. Finally, the results are shown.

2. Soil thermal model formulation

The soil is an open and dynamic system composed of three phases. The solid phase, which is made up of inorganic and organic components, leaving chambers which are occupied by liquid and gas phases. The liquid phase is mainly composed by water which can contain ions and pollutant in solution or suspension, air and roots and organisms that live in soil. The gas phase primarily contains oxygen and carbon dioxide. All these elements give to the soil its physical and chemical properties [28].

Due to the complexity of the soil thermal model, this can be simplified applying the assumption that the soil is isotropic and homogeneous, thus its thermal properties are constant. Furthermore, it is also assumed that the air–soil interface (soil surface) is flat, and the soil moisture content variation in the samples volume is negligible during the analysis period (the samples were stored in a climatic chamber to guarantee the same conditions in all the samples and the moisture content was measured before each test). Neither the presence of vegetation or grass on the ground has been taken into account. The proposed thermal model is presented for bare soils subject to known boundary conditions. Both soil and contaminants will be modeled as isotropic solids [15]. The soil volume is modeled as a cubic volume (Ω) with a ground-surface interface (Γ), composed of various physical processes. This model is given by the equation of single phase heat in time [29] shown below,

$$\frac{dT}{dt}(x,y,z,t) - \alpha\Delta T(x,y,z,t) = 0 \quad \text{with} \quad \alpha = \frac{k}{\rho c_p} = \frac{k}{C_a} \tag{1}$$

where ρ (kg/m^3) is the density, c_p (J/kg K) specific heat, k (W/mK) thermal conductivity, C_a (J/m^{3}K) the volumetric heat capacity, α (m^2/s) the thermal diffusivity and T (K) the temperature distribution in the solid.

In order to solve the system, the following boundary conditions must been considered,

$$\begin{matrix} \frac{dT}{dt}(x,y,z,t) = q_{net} & \text{for} \quad \tau \times \Gamma \\ \frac{dT}{dt}(x,y,z,t) = 0 & \text{for} \quad \tau \times \delta\Omega \setminus \Gamma \end{matrix} \tag{2}$$

$$T(x,y,z,t=t_0) = T_0 \quad \text{in } \Omega$$

$$T(x,y,z\rightarrow\infty,t) = T_\infty$$

where $\tau = \{t_0, \ldots, t_f\}$ is the test time range, Γ is the surface accessible part for the measurements, and T_∞ (K) the soil temperature at certain depth.

The first condition in (2) sets the heat flux through the accessible portion to the measures (Γ) of the soil contour, while the exchange through its other contours is assumed to be zero (second condition). The third and fourth conditions in (2) represent the initial temperature distribution in the soil and its depth condition, respectively. It is assumed that the temperature at a certain depth remains constant [15]. The heat flow is established by the heat transfer (convection and radiation), which is introduced through the boundary condition in the soil–air interface.

$$q_{net} = q_{sun}(t) + q_{rad}(t) + q_{cov}(t) \tag{3}$$

where q_{net} is the net heat flow in the normal direction to the soil accessible surface for measurements, q_{sun} is the incident solar radiation, q_{rad} is the heat transfer term due to radiation, including long-wave radiation from the atmosphere (q_{sky}) and the emission of the soil surface (q_{soil}) [30] and q_{conv} is the sensible heat transfer from the earth to the atmosphere due to convection.

As shown, the heat transfer process between soil and atmosphere is a complex problem that involves a significant amount of physical variables. However, a record of the temperatures involved can be measured in practical situations.

3. Infrared thermography

Infrared thermography techniques are classified into active or passive, based on the existence or lack of external excitation sources, respectively. Active thermography offers the advantage of evaluating objects at room temperature due to the heat flow in the material that it is resulted of an external excitation. As a result, thermograms, with thermal patterns that enable a quantitative characterization of the specimen interior, are obtained. The external excitation, which a specimen can be submitted to, can have different origins, as many as energy sources are known: kinetic, potential, mechanical, chemical, electrical, radiation or nuclear [22], producing a thermal wavefront (thermal energy).

For simplicity and security, radiant energy sources (which is spread by means of electromagnetic waves) are often used and limited to wavelengths range, where the radiation does not have enough energy to break an atomic bond (non-ionizing radiation). Therefore, there is a radiation spectrum range from ultraviolet to radio frequencies. Another factor to consider is the excitement duration. Pulsed energy (more or less temporary) and modulated energy have to be distinguished. This gives way to different techniques types in active infrared thermography, among which pulsed thermography, long-pulsed or step-heating thermography and lock-in thermography are the best known. These techniques can be used both in transmission and in reflection depending on the configuration of the test [24,25].

The following sections describe the main techniques by active infrared thermography as listed above.

3.1. Pulsed thermography

Pulsed thermography is based on the application of a short thermal pulse (few ms) as a source of excitation. These pulses are generated by powerful flashes, causing temperature increases during the excitation. After the pulse, the temperature decays because the energy (the thermal front) is propagated by diffusion under the surface and also because of radiation and convection losses, showing the presence of defects by a thermal contrast on the surface [22,24,25].

Considering the study of heat transfer in the simplest case, the equation of a pulsed thermal wave propagating through a homogeneous and semi-infinite material is given by the Fourier diffusion equation [29]:

$$T(z,t) = T_0 + \frac{Q}{\sqrt{k\cdot\rho\cdot c_p\cdot\pi\cdot t}}\exp\left(-\frac{z^2}{4\cdot\alpha\cdot t}\right) \tag{4}$$

where T_0 (K) is the initial temperature gradient induced by the heat source, Q (J/m^2) is the energy absorbed by the surface, ρ (kg/m^3) the material density, k (W/mK) the material thermal conductivity, c_p (J/kg K) the specific heat, α (m^2/s) the thermal diffusivity, z (m) depth and t (s) time.

Therefore, the temperature at material surface ($z = 0$) can be expressed as: