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Soil properties and performance of landmine detection by metal detector and ground-penetrating radar — Soil characterisation and its verification by a field test

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ABSTRACT

Metal detectors have commonly been used for landmine detection, and ground-penetrating radar (GPR) is about to be deployed for this purpose. These devices are influenced by the magnetic and electric properties of soil, since both employ electromagnetic techniques. Various soil properties and their spatial distributions were measured and determined with geophysical methods in four soil types where a test of metal detectors and GPR systems took place. By analysing the soil properties, these four soils were classified based on the expected influence of each detection technique and predicted soil difficulty. This classification was compared to the detection performance of the detectors and a clear correlation between the predicted soil difficulty and performance was observed. The detection performance of the metal detector and target identification performance of the GPR systems degraded in soils that were expected to be problematic. Therefore, this study demonstrated that the metal detector and GPR performance for landmine detection can be assessed qualitatively by geophysical analyses.

1. Introduction

There are still more than 70 countries worldwide affected by landmines and unexploded ordnance (UXO). The International Campaign to Ban Landmines (ICBL) identified at least 73,576 casualties in these countries during the past 10 years (ICBL, 2009). Although the dissemination of landmines is considerably reduced today, a large number buried during past conflicts still threaten the population of affected countries.

The most common tool for detecting buried landmines is the metal detector, which has been used for more than 50 years because of the simple operation, relatively low costs, and high reliability of this technique. Metal detectors operate via the principle of electromagnetic induction (EMI) in the frequency range from 100 Hz to 100 kHz. Commercial demining detectors typically produce an audible beep when an object containing metal is present in a sensitive area, although the object may not be a landmine. Consequently, an extremely large number of false alarms may occur during clearance operations. The sources of these false alarms include screws, nails, and shrapnel from former bomb explosions. In addition, soil with considerable magnetic properties can create false alarms, especially if the frequency dependence of magnetic susceptibility is high (Das, 2006). Clearance operations are hindered tremendously because all metal detector alarm sources must be investigated in most humanitarian demining operations. For example, approximately 200 million items were excavated during the clearance operation in Cambodia between 1992 and 1998, and only approximately 500,000 items (i.e., less than 0.3%) were landmines or other explosive devices. With such a slow clearance speed, an estimated 450–500 years are required to clear all mines in the world, which assumes that no new mines are laid (MacDonald et al., 2003). This estimate indicates the necessity of accelerating clearance operations.

One proposed method for this acceleration is the use of subsurface sensing techniques in non-destructive manner that enables the identification of false alarm sources. For example, this identification allows for application of a rapid excavation process for non-explosive devices as tested in Bushoff and Cresci (2008) which is expected to speed up the total clearance operation. A significant number of studies have been performed on the discrimination of targets. One approach is to analyse metal detector responses (e.g., Pasion et al., 2007; Shubitidze et al., 2007; Throckmorton et al., 2007). Another approach is to exploit other subsurface sensing techniques in addition to a metal detector or as a standalone detector. Such techniques include nuclear quadrupole resonance (NQR) (e.g., Garroway et al., 2001; Jakobsson et al., 2005; Somasundaram et al., 2007), chemical vapour analysis/spectrometry (e.g., Cumming et al., 2001), seismic (e.g., Sabatier and Xiang, 2001; Scott et al., 2001; Zeng and Liu, 2001), and infrared detection (e.g., Khanafer et al., 2003; Muscio and Corticelli, 2004). None of the above listed technologies has been available for humanitarian demining until now because of the complexity, high costs, and large size of these systems.

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Ground-penetrating radar (GPR) has been considered the most promising subsurface sensing technique for demining in combination with a metal detector. GPR will be deployed relatively soon due to the ability of this method to detect both metallic and non-metallic landmines, imaging capability, simplicity, and relatively low production cost (e.g., Bruschini et al., 1998; Brunzell, 1999; Chen et al., 2001; Lopera and Milisavljevic, 2007). Furthermore, the capability for imaging and post-processing data enables the identification of detected objects (e.g., Savelyev et al., 2007; Ho et al., 2008; Takahashi and Sato, 2008). A system combining GPR and a metal detector is commonly called a dual sensor. In the operation of such a system, the metal detector is used as the primary sensor for detection and localisation of metal-containing object, and the system then switches to GPR as the secondary sensor for target identification. Basically, both sensors transmit electromagnetic fields into the ground and measure the returned fields, which contain information on the target buried in the soil. The returned field is disturbed if the soil has distinct magnetic and/or dielectric properties (Das, 2006; CEN, 2008; Cross, 2008; Igel, 2008), and information on the target is not retrievable in worst cases, which may result in missed landmine detections. Therefore, studies of soil influence on both metal detector and GPR are very important for assessing the productivity and safety of clearance operations.

In this paper, the relationships between soil properties and performance of landmine detection sensors will be discussed. Soil properties that principally affect the detection techniques and their influence on these methods will be briefly reviewed in the following section. These soil properties were measured in the field during a test campaign of metal detectors and dual sensors to observe and demonstrate the associated correlations. According to these measurements, the comprehensive evaluation of test soils for the detection performance was accomplished. The estimation was compared to the performance of detectors from the test campaign, and the influence of soil was clearly observed.

2. Influence of soil on demining sensors

Antipersonnel (AP) landmines (i.e., blast mines) are usually buried shallowly or just beneath the ground surface and always surrounded by soil. Therefore, detection techniques are usually influenced by soil. There are some soil properties that have a relatively large influence on metal detectors and GPR, of which the practical roles are briefly reviewed in this section.

2.1. Magnetic susceptibility

The magnetic susceptibility of soils is caused by the presence of ferrimagnetic minerals, mainly magnetite, titanomagnetite, and maghemite. Magnetite and titanomagnetite are prevalent in basic magnetic rocks, and concentrations of these minerals may be higher in soils than in the associated parent rock material due to residual enrichment during soil formation processes (Singer and Fine, 1989). This enrichment occurs because these minerals have a higher resistance to weathering compared to a variety of other soil minerals (Friedrich et al., 1992). Maghemite is formed during weathering and soil genesis and is the product of magnetite oxidation (Schwertmann, 1988) or can be formed as a new mineral by dissolved iron crystallisation (Mullins, 1977). Magnetite and maghemite can also be formed as a result of bacterial activity (e.g., Fassbinder et al., 1990), thermal transformation of Fe-oxides during fires (Kletetschka and Banerjee, 1995), or may arise from anthropogenic atmospheric inputs (Dearing et al., 1996).

Magnetic susceptibility κ is considered the most influential soil property on the electromagnetic induction (EMI) technique employed by metal detectors (Das, 2006). In general, the absolute level affects the frequency-domain (continuous wave; CW) metal detectors, and the frequency dependence of susceptibility has more influence on time-domain (pulse induction; PI) detectors (Cross, 2008). The normalised voltage v^{soil} induced in the receiving coil with a radius b due to a non-conductive soil in half-space configuration can be written as (Das, 2006):

$$v^{soil} = j\mu_0\omega\pi ab\left[\frac{\kappa}{2+\kappa}\right]m(h) \tag{1}$$

where μ_0, ω, and a are the magnetic permeability of the air, angular frequency, and radius of the transmitting coil, respectively, and $m(h) = \int_0^\infty J_1(\lambda a)J_1(\lambda b)\exp(-2\lambda h)\,d\lambda$ with J_1, h, and λ as the Bessel function of the first kind and order 1, distance to the soil, and an integration variable, respectively. As the equation exhibits, soil with a high magnetic susceptibility creates additional responses to metal detectors and can be misinterpreted as a metal detection and/or disturb response from landmines. This can result in false alarms and missing mine detections. The majority of modern metal detectors have a ground compensation function that aims to reduce the soil influence; however, overcompensation or the wrong settings reduce the sensitivity of metal detection, which also results in missed mine detection.

Although magnetic susceptibility theoretically influences GPR, the effect must be extremely high to influence the signal. For example, Jol (2009) suggests that it must be greater than 30,000 SI × 10^{-5} to have an influence comparable to dielectric permittivity. Soils exhibiting such high magnetic susceptibility are extremely rare. Even tropical soils, which often display high susceptibility, with values in this range are exceptional (Preetz et al., 2008; Igel et al., 2009). Therefore, magnetic susceptibility has practically no influence on GPR in most soil.

Investigation of soil magnetic susceptibility can easily be performed by electromagnetic induction based measuring devices either in the field or laboratory. However, the frequency dependence may only be measured in the laboratory.

2.2. Electric conductivity

Soil can be described as a three-phase composite: the solid matrix, pore fluid, and gaseous pore filling. These three phases cause three mechanisms of conduction that determine the electric conductivity of geologic materials. The first is electronic conductivity caused by the free electrons in the crystal lattice of the minerals, and the second is electrolytic conductivity caused by the aqueous liquid in the pore space featuring dissolved ions. These two types of conductivity are independent of frequency over a wide range. However, the third conduction called surface conductivity often exhibits frequency dependence. Surface conductivity is determined from the inner surface of the soil and is associated with the cation exchange capacity of the material, which is typically high for clay minerals and soil organic matters (Igel, 2007; Knödel et al., 2007).

Electric conductivity σ is considered an influential soil property on metal detectors, but less than magnetic susceptibility and only if extremely high (Das, 2006). However, electric conductivity influences GPR in the normal range. The property is related primarily to the attenuation of electromagnetic waves, such that a radar signal cannot propagate a long distance in a highly conductive medium. The depth of electromagnetic field decay $1/e$ (~−8.7 dB) is called skin depth and is often used to assess the penetration depth. For a slightly conducting material, such as soil, this approximate depth is (Shen and Kong, 1995):

$$\delta \approx \frac{2}{\sigma}\sqrt{\frac{\varepsilon}{\mu}} \tag{2}$$

where ε and μ are the absolute dielectric permittivity and magnetic permeability of the material, respectively. The equation indicates that electric conductivity is more influential on penetration depth than