Soil Properties Database for Humanitarian Demining: A Proposed Initiative

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1. INTRODUCTION

Human suffering caused by antipersonnel (AP) landmines left over from previous conflicts has received considerable public exposure in the past few years. By some accounts [1], the problem of landmines and other unexploded ordnance (UXO) affects some 90 countries spanning Africa, the Americas, the Asia-Pacific, Europe and Central Asia, and the Middle East and North Africa. Although estimates of the severity of the problem vary, there are many publications that describe this global problem. The nature, the extent and the impact of this problem can be found in the Landmine Monitor [1], which provides a particularly extensive discussion.

In this paper we will be concerned with only a small but crucially important aspect of the landmine problem, namely, their detection and the effect of soil properties on the functioning of current and proposed detection technologies. We will first describe the detection problem in general terms in order to familiarize soil scientists with the difficulty of detecting landmines. This will be followed by a brief description of the various detection technologies as an introduction to the relevant soil properties that affect the various technologies. A knowledge of these soil properties in various landmine-affected areas will thus be of significant importance to landmine detection efforts both in the development and selection of equipment as well as in predicting their performance in a given region. The primary objective of this paper is to present to the world soil science community the requirements for information on soil properties and to seek their advice, guidance and assistance in establishing a framework for getting such information.

2. LANDMINE DETECTION PROBLEM

Although research on how to detect and deal with buried landmines was initiated as early as the Second World War, the search for solutions still continues.

Landmine detection is part of a more general problem, namely, the detection and neutralization of buried unexploded munitions, which also includes the detection of unexploded ordnance (UXO). UXO items include artillery shells, bullets, mortars, bombs and other such ammunition, and are relatively large metallic objects usually made of steel. Landmines are of two broad types: larger antitank (AT) landmines and the smaller AP landmines, and could have nonmetallic (wood or plastic) or metallic cases. AT landmines, which are designed to damage tanks and vehicles, can be up to 35 cm in diameter and may contain a few kilograms of explosives. AP landmines are meant to hurt people and are small, containing a few

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grams of explosives. The common explosive fill in landmines is TNT, but RDX and other compounds are used as well. There are hundreds of varieties of landmines. Whereas UXO could be buried as deep as 10 m, landmines are usually buried in the first 30 cm of soil.

Although countries with landmine problems usually have significant UXO problems, most current UXO detection activities are aimed at clearing domestic land previously used as military training ranges in developed countries (e.g., U.S.A. and Canada). Landmine problems comprise two distinct scenarios: (1) peacekeeping and countermine, which involve dealing with landmines in a military environment; and (2) humanitarian demining, which deals with clearing land for civilian use. Despite some common characteristics, the three problems (UXO clearance, countermine and humanitarian demining) have many differences and warrant different approaches to their solution.

The reason that the search for solutions to landmine detection still continues is due to the very complex nature of the problem and the high degree of effectiveness required. Typically, very poor or no records are kept of where landmines were planted; this is particularly true in the case of humanitarian landmine problems where the cause has been nonconventional warfare. Since landmines are designed to maim or kill, extreme care is needed in approaching them, which makes invasive detection techniques unsuitable and demands near 100% accuracy in detection. Landmines,even those laid on the surface, can easily blend into the background vegetation. The problem is further exacerbated by the fact that the soil is a very complex medium. The contrast between properties of a landmine and those of the soil are often very low, particularly for so-called “plastic” mines (mines with very small amounts of metal). The soil is lossy to many probing energy forms and it is inhomogeneous on the scale required for landmine detection. Added to these is the presence of vegetation and other natural and man made clutter which produce many false targets.

3. LANDMINE DETECTION TECHNOLOGIES

This section gives a brief background of technologies which have been considered for landmine detection. Landmine detection techniques can be divided into two general categories: (1) techniques to detect the casing (certain physical properties of its explosive content may also have some influence) and (2) techniques for direct detection of the explosive contents. Techniques investigated to implement these two general approaches span almost the entire electromagnetic spectrum and a wide variety of other technologies. Detailed reviews of these technologies can be found in [2–5]. In the rest of this Section, we will briefly describe the operating principles of the various detection technologies proposed to date indicating, where appropriate, the particular properties of the soil that may have an effect on their operation. A list of the technologies along with soil properties that could potentially affect their operation is given in Table 1.

3.1. Detection Technologies Which Do Not Detect Explosives

The first major group of mine detection methods includes those that do not specifically detect explosives, but rather attempt to identify the munition based on properties of the entire landmine or portions of it, such as its casing. Frequently, this is equivalent to void/anomaly detection, that is, detection of the absence of or discontinuity in a soil property.

3.1.1. Magnetostatics and Electrostatics

In magnetostatic techniques which are also known as magnetic anomaly detection, the disturbance caused by ferrous objects in the earth’s relatively uniform and static magnetic field are measured by magnetometers of various designs. Since the technique can only detect ferrous metal, it is not suitable as a landmine detection method because many mines have only nonferrous or stainless steel parts. However it is very relevant for UXO detection. Magnetic properties of soil will affect the operation of this technique.

In analogy with magnetostatics, electrostatic techniques would measure the anomaly caused by objects in the ambient electrostatic field. Hence the technique should be able, in principle at least, to detect both metallic and nonmetallic objects. It is thought that this method would not be viable for this purpose because the ambient electrostatic field near the ground is expected to be very inhomogeneous. Because of this, there has been very little research effort in this area.

3.1.2. Direct Current (DC) Conduction Methods

DC conduction methods (also called resistivity method or surveying) are active techniques and involve measuring an effective electrical impedance of the host medium, by injecting current into the medium and measuring surface potentials. Impedance tomography or conductivity imaging is an extension of the resistivity method where surface potentials, at points on a grid, corresponding to a number of current injection sites (analogous to the number of "views" in X-ray tomography) are measured. This ensemble of surface potential measurements are then used to solve the associated electromagnetic inverse problem to estimate the underlying impedance distribution (an image, in other words) which could have caused the measured potentials. Soil conductivity will influence the operation of this approach, which is still in an early research phase.

3.1.3. Electromagnetic Induction Techniques

Metal detectors which, with the possible exception of the mechanical prodder, are the only detection devices widely used in demining operations, are based on the principle of electromagnetic induction. In this technique, metal objects are detected by sensing the eddy currents induced in them by an external time-varying magnetic field. It is known that the magnetic susceptibility of soil and, to a lesser extent, its electrical conductivity affect the operation of metal detectors. Since metal detectors are the most widely used tools in demining operations, these two soil properties are of the greatest interest in the short term.

3.1.4. Microwave Techniques

Active One of the extensively researched topics in the detection of buried landmines is the use of active microwave systems often discussed in the literature under the names ground probing radar (GPR) or subsurface radar. Active systems of various designs (e.g., impulse, continuous wave (CW), frequency modulated continuous wave (FM-CW), step frequency, separated aperture or waveguide beyond cutoff, balanced bridge and so on) have been developed over more than three decades for the detection of buried landmines. Although these systems can detect buried antitank nonmetallic landmines under certain conditions and form a part of some multisensor military systems [6], the detection of antipersonnel landmines continues to be one of the most difficult problems for this technology and no operationally satisfactory system exists. Soil inhomogeneity, low target contrast, uneven soil surface, vegetation and nuisance targets such as rocks are the basic problems.

Passive Passive microwave or microwave radiometric techniques involve the measurement of natural blackbody radiation, in the microwave band, coming from an object or region of interest. In simple terms, detection of buried landmines with radiometric techniques relies on the assumption that the presence of a landmine causes a temperature anomaly at the surface of the host medium of uniform emissivity or that the soil disturbance causes an emissivity and/or temperature change. Reflection of sky radiation can also be used to detect surface laid landmines. Application of passive microwave to landmine detection is considered to be in an early research phase.

Soil electromagnetic properties of relevance to both active and passive microwave techniques are permittivity, conductivity and, to a lesser degree, magnetic susceptibility. Permittivity and conductivity will depend strongly on soil moisture content. A review of soil electromagnetic properties can be found in [7].

3.1.5. Optical Technologies

Since the penetration of optical wavelength electromagnetic radiation in opaque materials is less than 1 mm, the only optical techniques to consider are those which measure a soil surface property that is affected by the presence of the buried landmine.

Infrared (IR) Thermal infrared detection or infrared radiometry relies on measuring the change, compared to undisturbed soil, in spectrum or intensity of infrared radiation emitted or reflected by the soil over a buried landmine. The change in radiation is usually quoted as an equivalent change in surface temperature. The cause of the radiation change is the alteration of the heat flow by the landmine and disturbed soil and the change in surface emissivity of the disturbed soil. Infrared imagers of sufficient temperature resolution ($\sim 0.1°$C) and spatial resolution to detect the anomalies due to a landmine are commercially available and are used in some multisensor military systems [6]. Soil parameters relevant to the operation of IR systems include thermal resistivity, thermal diffusivity and specific heat capacity, all of which are expected to depend on soil moisture content.

Visible Wavelengths Visible wavelengths will measure surface optical properties, such as reflectance or polarization characteristics, of the disturbed ground above a landmine which may differ from the properties of undisturbed soil. In addition, vegetation growing above buried landmines may have different spectral characteristics than that growing above undisturbed soil. The signal due to thermal emission is negligible compared to reflection at these wavelengths.

Current research in detection using optical technologies is directed towards hyperspectral imagers which have many more and much narrower spectral bands than older multispectral imagers. It may be possible to use pattern recognition methods with such imagers to distinguish between disturbed/undisturbed soil and to detect vegetative changes. Research is in the early phases.

Ultraviolet (UV) Measurement of UV reflection from the ground surface, using either solar radiation or artificial sources, will measure only surface properties of the ground. These properties may differ between disturbed soil over a landmine and undisturbed soil, but the effect should decrease with burial time. The magnitude of the difference and the rate of decrease of the effect is unknown. The signal due to thermal emission is negligible compared to reflection at these wavelengths.

3.1.6. Acoustics/Seismic

Active acoustic methods are based on injecting acoustic energy into the ground and then measuring reflections of acoustic energy caused by the difference between the acoustic impedance of the landmine and/or disturbed soil and that of the surrounding undisturbed soil. Current research efforts measure ground vibrations over a buried landmine as an approach to detecting it. Acoustic techniques have had mixed success to date.

Since acoustic impedance depends on mass density and bulk modulus, knowledge of these properties of soil will be relevant to acoustic techniques. These properties will also depend on soil moisture content.

3.2. Detection Technologies Which Detect Explosives

Explosives detection methods are classed as either bulk detection or trace detection methods. Bulk detection, which includes radio frequency resonance absorption (with the exception of microwave molecular absorption) and nuclear radiation methods, look for a property present in explosives which is not present in natural soil or vegetation. Explosives have a much higher percentage of nitrogen (10 to 40%) than soils ($< 0.1\%$). Also, the effective atomic number of explosives is between 5 and 7, which is similar to organic material, as compared to 11 to 12 for soil. However, typical mass density of soil (1.0 to 2.5 g/cm^3) and of explosives (1.6 to 1.8 g/cm^3) are similar. Trace detection involves identifying the specific explosives molecules themselves by sampling the air or soil in the vicinity of the landmine.

3.2.1. Radio Frequency Resonance Absorption Spectroscopy

Radio frequency resonance absorption spectroscopy (RRAS) methods all involve selective absorption of energy from an electromagnetic field due to resonances formed by interactions between the electric or magnetic moments of nuclei or electrons of atoms and external or internal fields. There are four basic methods: nuclear magnetic resonance (NMR); nuclear quadrupole resonance (NQR); electron paramagnetic resonance (EPR); and microwave molecular absorption (MMA). Of these, the only one being seriously considered for landmine detection at present is NQR, which can uniquely identify a specific explosive. Since the NQR technique involves interaction, through soil, of bulk explosives in landmines with electromagnetic field in the hundreds of kHz to MHz range, soil properties having the most influence would be magnetic susceptibility, electrical conductivity and, to a lesser degree, electrical permittivity.

3.2.2. Nuclear Radiation Methods

Since the 1940s, an enormous amount of research has been performed on nuclear detection of landmines. Nuclear techniques look at a return radiation characteristic of nitrogen or an intensity change of a noncharacteristic scattered radiation, which is a function of a parameter that differs between soil and explosives. Noncharacteristic radiation methods are essentially anomaly detectors, that is, they detect inhomogeneities in the medium and inclusions in addition to landmines. Examples of noncharacteristic radiation techniques are X-ray Backscatter and Neutron Moderation. Thermal Neutron Activation (TNA) is based on detecting γ-rays characteristic of ^{14}N. While X-ray Backscatter and Neutron Moderation techniques are at a research stage, a vehicle-mounted TNA device is already a part of a fielded military system [6].

Soil properties of relevance to X-ray Backscatter will include effective atomic number, weight, and mass density. Since Neutron Moderation detects landmines by detecting hydrogen content anomalies, a property of direct relevance will be moisture content of soil. Because of the potential effect on the background signal and possible interference with the γ-line due to ^{14}N, contents of elements such as Fe, Ti, Cd, B, Gd, O, C, N, Si in soil are important for detection by TNA.

3.2.3. Trace Explosive Detection (TED)

This technology involves sensing particles emanating from the buried landmine and then separating the constituent molecules, atoms or ions for identification. A viable method must have sufficient sensitivity to explosives and sufficient selectivity to reject particles from naturally occurring materials.

Nonbiochemical There are many nonbiochemical detection technologies that can be used to detect explosive vapours. These include mass spectrometry (MS), ion mobility spectrometry (IMS), laser/optical techniques, gas chromatography (GC), solid state detectors (resistive film, metal oxide field effect transistor or MOSFET), differential Raman spectroscopy and photothermal deflection spectroscopy. There are also combined detectors such as GC/MS, MS/MS and IMS/MS.

Biochemical Detection Biochemical detection is a trace explosive detection method which uses chemical processes derived from biological systems. Biochemical detection can be divided into two general classes - *in vivo* and *in vitro*. *In vivo* detectors include animal olfaction and bioluminescent bacteria.

The success of all TED systems, biochemical as well as nonbiochemical, will depend on the amount of explosive available for detection at or near the soil surface over a landmine. The soil parameters needed to model the migration of explosives through the soil will be of interest. To the best of the authors' knowledge, such modelling is relatively new [8] and it is not possible to produce a definitive list of relevant soil parameters. However, such parameters will likely include factors related to porosity, moisture content, organic matter and cation exchange capacity.

3.3. Mechanical Detection Technologies

To date, mechanical systems for dealing with landmines usually have been machines to unearth and move the landmines (ploughs) or trigger and detonate them (flails and rollers). There appears to have been little work done on mechanical systems for landmine detection without destroying the landmine. The current technology employed for the mechanical detection of buried landmines is limited to the use of a prodder, inserted manually into the ground at about 30 degrees. The operator virtually "feels" around with the prodder for buried objects. As such, the parameters that may indicate the ease with which a prodder could be inserted in a given soil will be relevant to the operation of the prodder.

Instrumented Prodder The standard prodder relies on the dexterity of the operator. With instrumentation, the prodder could make acoustic or electromagnetic measurements during insertion. The echo would give information about the mechanical impedance of the material near (or in contact with) the tip, making discrimination between rock, wood, plastics and metal possible. Such a device has been under development with considerable success.

In addition to the parameters that may indicate the ease of inserting a prodder in a given soil, depending on the auxilliary sensors used, other parameters such as acoustic and electromagnetic properties of soil would be relevant to the operation of an instrumented prodder.

Table 1. Landmine Detection Technologies and Relevant Soil Properties. Many of the soil properties (e.g., permittivity, thermal and acoustic properties) will depend strongly on soil moisture content and their values may have to be specified at a number of selected moisture contents.

Detection Technology	Main Relevant Soil Properties
Magnetostatics	Magnetic susceptibility
Electrical Impedance Tomography	Electrical conductivity
Electromagnetic Induction	Magnetic susceptibility Electrical conductivity
Nuclear Quadrupole Resonance	Magnetic susceptibility Electrical conductivity Electrical permittivity Piezoelectric materials (e.g. quartz content) Magnetostrictive materials
Active and Passive Microwaves	Electrical permittivity Electrical conductivity Magnetic susceptibility
Infrared	Thermal resistivity Thermal diffusivity Specific heat capacity
Thermal Neutron Activation	Content of elements such as Fe, Ti, Cd, B, Gd, Si, O, C, N, H
X-ray Backscatter	Effective density Effective atomic number and weight
Neutron Moderation	Content of H
Trace Explosives Detection	Porosity and moisture content Cation exchange capacity Other chemicals and parameters affecting absorption and adsorption of explosives
Acoustic/Seismic Techniques	Density and bulk modulus
Prodders	Hardness Acoustic and electromagnetic properties

4. GENERAL REQUIREMENT FOR INFORMATION ON SOIL PROPERTIES

Landmines are buried typically in the top $\sim$ 50 cm of soil. From the foregoing discussion and Table 1 we have seen that various physical, chemical and electromagnetic properties of this top layer of ground will potentially affect landmine detection as well as other technologies devised to deal with landmines. Thus as much information as possible on these properties of soil would be beneficial to the development and operation of landmine detection technologies. To the best of the authors' knowledge, such information is not available. Although there is information related to conventional soil classification which addresses agricultural and environmental issues, such as the FAO-UNESCO soil map of the world, little or no information exists in a form directly relevant to landmine detection and other demining technologies. There is, thus, a general need for the development of an information database and maps of such soil properties. Such an information database will serve the following purposes:

1. It will help demining organizations select equipment and predict its performance in their particular environment.
2. It will help equipment developers and researchers assess the potential of their proposed technologies in various parts of the world.
3. It will help researchers develop test facilities that simulate realistic demining environments existing in different parts of the world.

We should note that a number of databases exist on the landmine targets themselves. The proposed database will complement this information.

Even if we consider only the landmine-affected countries, the task of obtaining information on all the properties discussed above would be almost impossible. With this in mind, we describe below a potential initiative of much reduced scope but of immediate and direct use to humanitarian demining operations as well as research.

5. SOIL MAGNETIC SUSCEPTIBILITY AND ELECTRICAL CONDUCTIVITY DATABASE

In spite of the many technologies being researched and developed as previously discussed, the metal detector remains the most commonly used detection tool in humanitarian demining. The operation of the metal detector is based on the principle of electromagnetic induction. The signal produced in a detector by a metal object depends on many factors including the object's size, shape, orientation, material and parameters of the detector electronics. One of the other important factors that has an the effect on this signal is the host soil. It is generally known (although the authors feel that the subject needs much more study) that soil magnetic susceptibility and, to a lesser degree, electrical conductivity influence this signal and thus have an effect on the depth of detection of buried objects.

The adverse effects of some soils on metal detectors were known as early as the Second World War. But the user community seems to have forgotten this in the intervening period. Users are once again finding that certain soils (1) can reduce the sensitivity of detectors to an extent that they cannot detect targets to desired depths; (2) can cause false targets and (3) in extreme cases can render some detectors totally unusable. This so-called "Soil Problem" may be much more severe at the present time than during previous conflicts. This is because antipersonnel landmines which contain minimal amount of metal are presently very common and are widely used. Although they know that certain soils are a problem, there is much confusion in the user community and even in the research community about what causes the problem or how to characterize it. One often hears people use terms like "conducting soil", "lateritic soil", "red soil", "iron bearing soil", "mineralised soil" and so on to describe the problem. In an attempt to characterize the effect investigators often carry out only a texture and chemical analysis of the soil, instead of measuring the electromagnetic properties.

Currently a large variety of metal detectors in the market are being aimed at the humanitarian demining arena. The capability and performance of these detectors vary widely. Some of the better detectors (less than 5 in total) can adequately detect small mine targets in "problem" soils. This is an area of detector performance which is currently of great importance and impacts heavily on the selection of new detectors by demining organizations and by the military. Manufacturers are competing to design detectors that can deal with "problem" soils in a better way.

The scientific community can do the following to assist:

1. Provide further clarification and data on the effect of electromagnetic properties of soil on metal detectors. A fair bit of information, some dating back to the 60's, already exists on this topic, but there is need for much more, particularly with reference to minimum metal mines.

2. Assuming that magnetic susceptibility and electrical conductivity are the relevant soil properties as far as metal detectors are concerned, there is room for developing measurement protocols and suggesting practical instrumentation to characterize these properties both in the field and in the laboratory. A limited number of affordable instruments exist in the market to measure these properties directly.

3. Develop or suggest a methodogy to relate detector performance to measured soil properties.

4. Lastly, provide data on properties of soils present in the landmine affected countries. This information, in conjunction with the work described under the previous items, will help predict and/or compare detector performance in the types of soil to be expected worldwide. This data will also be useful in setting up laboratory test soil lanes that could represent conditions in different parts of the world.

   The required information could take the form of a database and/or soil maps.

The work described under items 1, 2 and 3 above would involve analytical and experimental research in the areas of interest to the R&D community involved in electromagnetic induction technology. However, major involvement and assistance from the soil sciences and other branches of the earth sciences would be needed to carry out the work under item 4, that is, the development of a database of relevant soil properties. Organizations that plan demining operations, such as the United Nations and the demining organizations in the mine-affected countries, could use this information in their planning and equipment selection. Manufacturers of detectors could also use such information in improving their detectors. R&D organizations such as ours, which are engaged in research, test and evaluation, would benefit from such data in developing detectors as well as in setting up test soil lanes and test plans for performance evaluation of detectors. As well, although the information on magnetic susceptibility and electrical conductivity would be of immediate benefit to the development, test and evaluation, and application of metal detectors, such information is also needed for other technologies being researched as seen from Table 1.

It is understood that a comprehensive database of properties of soils of the world would be beyond the resources likely to be available to the demining research community. In the following we present some issues, specific to the humanitarian demining problem, that may help reduce the magnitude of the task while still providing some useful data. These issues are included here for assessment by soil and other earth scientists who can determine the validity of the points raised.

1. **Parameters:** The number of soil properties on which information is gathered will severely influence the scope of the work. Since soil magnetic properties have the most dominant effect on metal detectors, the database could be initially restricted to magnetic susceptibity data only. This parameter is also expected to be relatively independent of soil moisture content and short term climatic variations, thus reducing the number of variables to take into account.

2. **Areas and Resolution:** Initially information requirement could be restricted to the mine-affected countries which are expected to have strongly magnetic soils. The amount of surface area to include can be reduced if a country can be divided into areas of "representative" soil types. The desired parameters of a number of these representative areas could then be characterized at an affordable spatial resolution. It may be possible to further reduce the number of areas to be surveyed by focusing on areas expected to have magnetic soil. The degree of local spatial variation of magnetic susceptibility, in addition to its magnitude, has an effect on the performance of a metal detector. Hence, at each survey site within the representative areas one should gather some high resolution (of the order of a few cm) data over a relatively small area (a few square meters). Such complementary high resolution data should provide an adequate idea of the expected spatial variation of magnetic susceptibility in a given country.

   An alternative area reduction approach would be to concentrate only on the known and suspected mined areas of a country and characterize soils typical of those areas only. As well, initial work could consider only a very small (possibly ≤ 3) number of countries as a pilot project.

   The idea of representative soil areas may also be applicable in some cases across country boundaries. This would allow any available information on soils of one country to be used to deduce information about soils from another.

3. **Existing Resources:** We may be able to draw upon the existing infrastructure and resources of the mine action centres in the various mine-affected countries to assist in the gathering of data. As well, national organizations responsible geological and soil surveys in mine-affected countries may be approached for assistance and any existing data.

   Soil and other earth scientists may be able to point to existing data from which the information we seek can be derived, thus reducing the need for data collection. They may be able to suggest suitable on-going international initiatives, an example being the one described in [9], on which we could "piggyback" to obtain the required information with incremental effort. As well, it may be possible to add a soil properties component to the on-going Global Landmine Survey initiative currently being managed by the Survey Action Center *.

6. STATUS

The work envisioned would certainly involve multiple disciplines and resources of many organizations. Various organizations have expressed a verbal interest in the work; however, at this moment, there is no established funding nor an official project or initiative. Once a project plan is established, organizations could be approached for possible funding. We are currently in the process of approaching various scientific organizations to make them aware of the information requirement and to seek their advice, guidance and assistance in establishing a viable approach to obtaining the information and in determining the scope of the needed effort. It is against this background that this paper is presented to the Council of the International Union of Soil Science.

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*Information about the initiative can be found in http://www.icbl.org/lm/2001/appendices/sac.html