Predicting Soil Influence on the Performance of Metal Detectors: Magnetic Properties of Tropical Soils

Mine detection and clearance are costly and time-consuming procedures necessary to benefit the communities these weapons affect. A complication surrounding mine detection is the influence of the soil on landmine detection, but little research has been done on the subject. This article discusses how soil can affect mine detectors and research plans to improve mine-detection efficiency.

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It is commonly known that many soils negatively affect landmine detection when metal detectors are used. Until now, however, there has been a lack of geoscientific studies on magnetic soil properties with regard to this issue. Therefore, we investigated magnetic susceptibility on a set of tropical soil samples gathered from 15 countries on five continents. We deduced a classification system that can be used for predicting soil influence on metal detectors, anticipating more than one-third of the samples would likely have a severe or very severe impact on the performance of metal detectors. As a result of our investigation, we identified two factors that have an influence on soil magnetic properties: the parent rock of the soils and their degree of weathering.

Introduction

Anti-personnel mines affect nearly 90 countries worldwide, many of them located in the tropics. Soils of these regions are often known to have a negative effect on the performance of metal detectors. Such detectors are commonly used for the detection of landmines, unexploded ordnance and improvised explosive devices, all of which may be buried in soil. The demining community is well-aware that certain soils cause problems for landmine clearance. However, there is confusion about the physical cause and the appropriate nomenclature of these soils. Conductive soils, lateritic soils, red soils, iron-rich soils and mineralized soils are some of the unspecific terms used. According to "Soil Properties Database for Humanitarian Demining: A Proposed Initiative,"[1] the impact of these soils on the performance of metal detectors can be the following:

1. The detector's sensitivity can be so reduced that an object may no longer be detected at the required depth.
2. It may generate false alarms.
3. In extreme cases, the soil may render some detectors totally unusable.

The most important soil properties influencing the performance of metal detectors are magnetic susceptibility and electric conductivity.

Metal Detectors and Soil Influence

Metal detectors are the most widely used device for landmine detection. This technology is based on the principle of electromagnetic induction. An alternating current is fed to a transmitter coil, which excites a magnetic field called the primary field. If the MD is operated in air, there is no field other than the primary field. If there is a metallic object, such as the fuze of a mine, in the vicinity of the detector, a current is induced within this object. This current in turn induces a secondary field, which is measured with a second coil and, depending on its strength, may trigger an alarm.

Besides metallic objects, the soil itself may also excite a secondary field as a reaction to the detector's primary field. The strength of the soil signal depends on its magnetic susceptibility and, to a lesser degree, on its electric conductivity. If the soil signal is strong, it can mask the mine signal and detection becomes difficult. The problem is getting worse with the decreasing metal content of modern mines and the rising magnetic susceptibility of soils. The extent of deterioration in detector performance depends on its basic layout and the specific model that is used.[2, 3] In this study we concentrate on characterizing the soil that is causing the problem.

Magnetic Properties of Soils

The magnetic susceptibility of a material describes how likely this material is to become magnetized when it is placed in a magnetic field. The higher the susceptibility, the more easily a material is magnetized. The magnetic susceptibility of matter depends on its structure on the atomic scale. One can assign minerals and materials to different categories of magnetic behavior:

- Diamagnetic: weak negative susceptibility
- Paramagnetic: weak positive susceptibility
- Ferromagnetic: strong positive susceptibility
- Ferrimagnetic: strong positive susceptibility
- Anti-ferromagnetic: moderate positive susceptibility

The magnetic properties of some minerals and materials are listed in Table 1 (on the next page). One can see that, due to their high susceptibility, even small amounts of ferro- and ferrimagnetic minerals or materials substantially determine the magnetic behavior of soil. Ferromagnetic materials like pure iron, nickel and cobalt do not occur in soils naturally. Their presence is due to anthropogenic input in the form of metallic clutter, which often causes false alarms.

Soil is the uppermost layer of the solid earth. It is the product of the weathering of rocks by physical, chemical and biological processes over very long time periods. Soil is a mixture of mineral and organic matter, whereby the first is generally the major constituent, which also determines soil magnetic properties. During soil genesis, minerals are dissolved and other new minerals may crystallize depending on the alteration of temperature, water content, pH-value and redox potential. Magnetic soil minerals can either be of lithogenic origin (i.e., they originate from the parent rock from which the soil was formed by weathering), or of pedogenic origin (i.e., they are formed during soil genesis).

When magma cools, it solidifies and forms igneous rocks. The types of minerals which crystallize during this process depend on the chemical composition of the magma. The higher the iron content of the mag-

Mineral/element	Chemical formula	Magnetic susceptibility kappa [10^{-5} SI]	Origin
Diagmagnetic			
Quartz	SiO_2	-15	lithogenic
Feldspar	$[Ca,Na,K]\ [Al,Si]_4O_8$	-13	lithogenic
Calcite	$CaCO_3$	-12	lithogenic
Paramagnetic			
Dolomite	$CaMg[CO_3]_2$	100	lithogenic
Olivine	$[Fe,Mg]_2SiO_4$	100	lithogenic
Ferromagnetic			
Iron	Fe	220,000,000	anthropogenic
Cobalt	Co	180,000,000	anthropogenic
Nickel	Ni	61,000,000	anthropogenic
Ferrimagnetic			
Magnetite	Fe_3O_4	200,000–570,000	lithogenic, biogenic
Maghemite	gamma Fe_2O_3	140,000–220,000	pedogenic
Titano-magnetite	Fe_3O_4-Fe_2TiO_4	85,000–150,000	lithogenic
Pyrrotite	Fe_7S_8	23,000	lithogenic
Antiferromagnetic			
Hematite	alpha Fe_2O_3	100–900	pedogenic, lithogenic
Goethite	alpha FeOOH	100–400	pedogenic

Table 1: Magnetic susceptibility of some elements and minerals and their origin in soils.
Lithogenic: deriving from the parent rock material; pedogenic: deriving from neoformation of minerals during soil genesis/weathering of the soil; biogenic: deriving from neoformation due to bacterial activity; anthropogenic: deriving from humanitarian (susceptibility values are from diverse sources).
ALL GRAPHICS COURTESY OF THE AUTHORS

ma, the more ferromagnetic minerals are formed during cooling. A higher amount of these magnetic minerals result in a higher magnetic susceptibility of the formed rock. Basic and ultrabasic rocks (e.g., basalt) have the highest susceptibilities, whereas acidic igneous rocks (e.g., granite) have intermediate to low values in general. Besides the igneous rocks, there are the groups of metamorphic and sedimentary rocks, with the latter (e.g., limestone) showing very small susceptibilities in general.

The most common minerals that determine the magnetic properties of soils are magnetite, titano-magnetite and maghemite. The first two usually are of lithogenic origin, i.e., they crystallized during cooling and solidification of magma and are part of many igneous rocks. Large quantities are often found in basic rocks such as basalts. Magnetite can also be formed as a result of bacterial activity.[4] Maghemite is formed during weathering and soil genesis by oxidation of magnetite[5] or as a new mineral by crystallization of dissolved iron.[6] Thus, the parent material, i.e., the rock from which the soil developed, as well as soil forming processes, may have an influence on soil magnetic properties.

Soil Samples

Currently, a large database of magnetic properties of soils in mine-affected countries does not exist.[1] This need was our motivation to investigate a large number of tropical soil samples archived in a collection of the Federal Institute for Geosciences and Natural Resources in Hannover, Germany. The study aims to analyze what influencing factors, such as parent rock and soil genesis, have on magnetic properties.

Figure 1. Detailed picture of the laterite sample collection of the Federal Institute for Geosciences and Natural Resources in Hannover, Germany.

A total of 511 soil samples were selected from the soil archive (see Figure 1 above). The sample collection consists of lateritic soils from many countries of the world's tropical belt. Lateritic soils are prevalent in tropical regions and are characterized as being enriched with iron, aluminum and other metals while simultaneously being depleted in silica. The analyzed samples include topsoils and subsoils from various depths as well as weathered parent rock. As most of the landscapes where laterites occur are subject to strong erosion processes; topsoil, subsoil, and weathered parent rock may appear side by side at the surface and form the material in which landmines are likely to be embedded. The samples were grouped according to their parent material:

- Ultrabasic igneous rocks, e.g., phonolite and serpentinite
- Basic and intermediate igneous rocks, e.g., amphibolite, basalt and gabbro
- Acid igneous rocks, e.g., gneiss and granite
- Clays and clay slate, e.g., slate, shale and tertiary sediments
- Phyllites
- Sandstone, e.g., sandstone and quartzite

The rock denotations are used in geological and other geoscientific maps, for example, which should be consulted when planning a demining campaign in an unknown area.

Magnetic Susceptibility Measurements

All samples were dried, mechanically crushed and homogenized, and filled into 10 ml plastic boxes before the analysis was carried out. Volumetric magnetic susceptibility was measured with a Bartington MS2B laboratory apparatus at a frequency of 465 Hz and a magnetic field strength of approximately 80 A/m. Three measurements were carried out by rotating the boxes by 120 degrees. Anisotropy inside the homogenized samples was found to be very low and the average of the three readings was used for further analysis.

Classification	Magnetic Susceptibility [10^{-5} SI]
neutral	0–50
moderate	50–500
severe	500–2,000
very severe	>2,000

Table 2: Classification of magnetic susceptibility with respect to its effect on the performance of metal detectors (CEN, 2003).

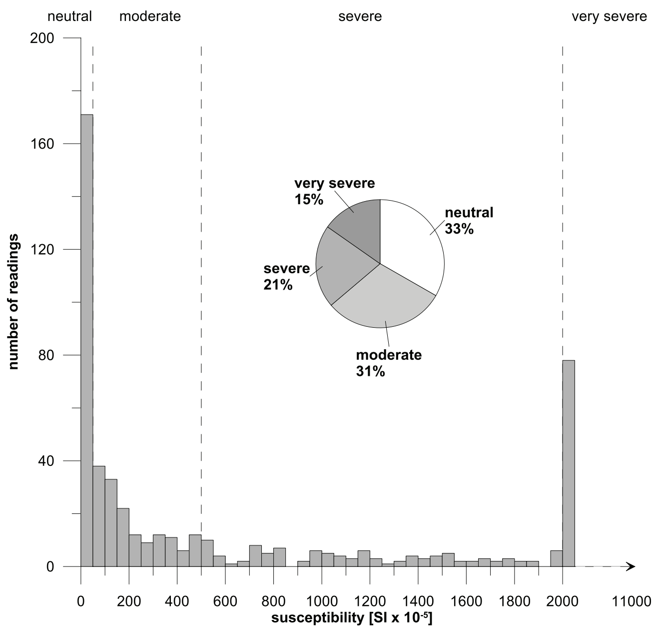

Figure 2: The pie chart shows the proportion with respect to the influence on metal detectors according to Table 2. Histogram of measured magnetic susceptibilities.

Interpretation

To evaluate the susceptibility values, we used the classification in Table 2 from CEN (2003) assigning soils a neutral to very severe impact on the performance of metal detectors. Figure 2 shows the histogram of the measured susceptibilities whereby the classification limits are indicated with dashed lines. The data show an asymmetric distribution and highest susceptibility values are in the range of $10{,}000 \times 10^{-5}$ SI. The pie chart in Figure 2 depicts the proportion of measurements with respect to the classes of Table 2. More than one-third of the samples have either "severe" or "very severe" impact on metal detectors. This result underlines the fact that lateritic soils quite often cause problems for landmine detection with MDs.

In Figure 3 the samples are grouped according to their parent material. The median susceptibility of soils derived from ultrabasic and basic rocks is around $1{,}000 \times 10^{-5}$ SI and higher. This finding can be attributed to the iron-rich magma that formed these rocks and favored the crystallization of magnetite. Since magnetite is a weather-resistant mineral, it is still present in soils even if they are old and strongly altered. The soils derived from other parent materials that primarily possess low magnetite contents show median susceptibilities of less than 50×10^{-5} SI. Thus, on average they have no negative influence on MDs. Nevertheless, the variability is very high for all parent-material classes. Within the group of soils deriving from basic rocks, some samples possess low susceptibilities, which are unlikely to have an influence on MDs. In contrast, some soils derived from acid rocks or sandstones (which are generally associated with low susceptibilities) show very high susceptibilities and may have a very severe impact on MDs. One reason is the natural variability of mineral components within each individual parent rock group. Another factor is the degree of soil development and the associated enrichment of existing magnetic minerals or the formation of new minerals.

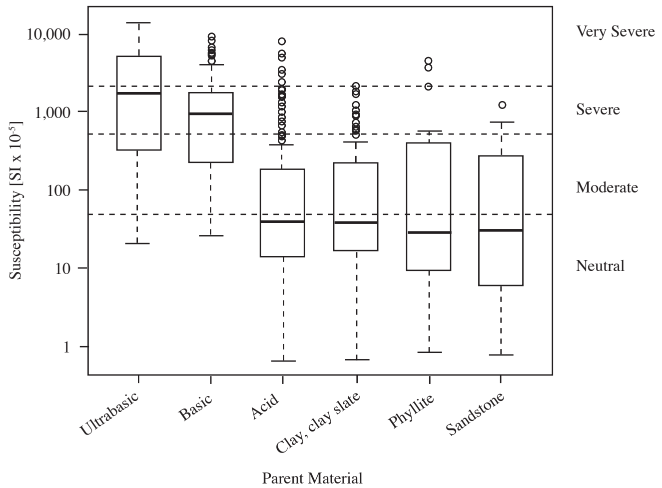

Figure 3: Magnetic susceptibilities depending on parent material of the soil. The bars in the boxes correspond to the most frequent value (median) and the boxes comprise 50% of the values. The whiskers extend to the extreme data points.

Laterites are highly weathered soils. Lateritization signals the depletion of silica and the accumulation of iron and aluminum oxides. Thus, the amounts of SiO_2, Fe_2O_3, and Al_2O_3 can be used to describe and compare the intensity of soil development. Here, the ratio of SiO_2 and (Fe_2O_3 + Al_2O_3) is used as an index to quantify the degree of weathering: the smaller the index, the higher the degree of weathering. In Figure 4 the susceptibility is plotted against the degree of weathering for all samples. Low susceptibilities occur over the whole range of weathering. The more weathered the soil (i.e., the smaller the index), the higher the maximum values of susceptibility. Values larger than $2{,}000 \times 10^{-5}$ SI, which are particularly problematic for metal detectors, are only found in

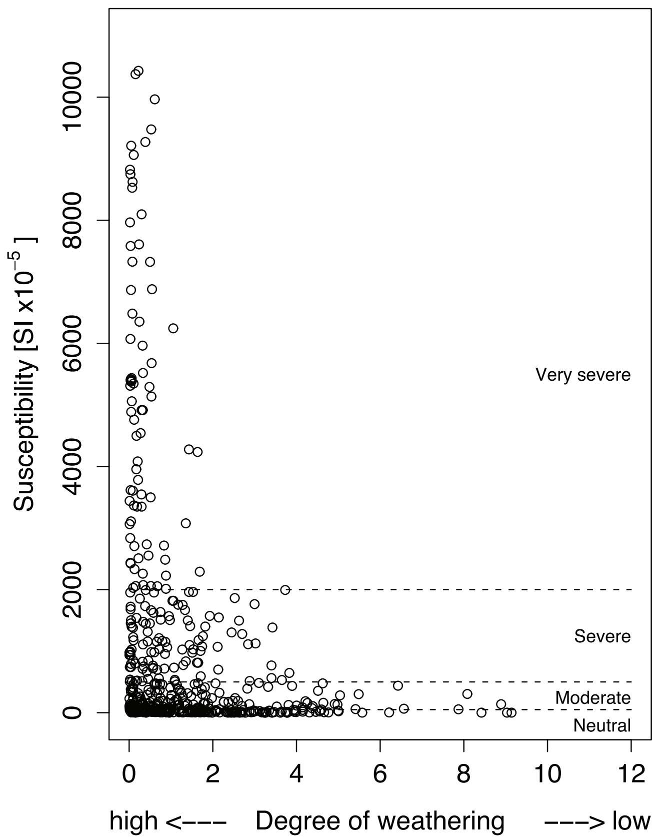

Figure 4: Magnetic susceptibility depending on the degree of weathering of the soil. All groups of parent material are depicted in the plot which covers 511 samples.

highly weathered soils with indices < 2. The same trend can be recognized when examining the soils separately according to their parent material: the highest susceptibilities can only be found in highly weathered soils.[7] This phenomenon may be explained either by relative enrichment of weathering-resistant magnetite originating from the parent rock during weathering,[8] or the formation of maghemite (and possibly magnetite) from pedogenic iron.[9]

Classification and Prognosis System

In the previous section, we have shown that both factors—parent material and degree of weathering—play a crucial role for the susceptibility of tropical soils. We have to take both factors into consideration when classifying soils with respect to the detectability of landmines. For the classification, we group the soils according to their parent material and their degree of weathering. The weathering index is subdivided in three classes:

- 0–1: very strongly weathered
- 1–3: strongly weathered
- > 3: moderately weathered

To characterize the magnetic properties of these groups, we determine the average (median) and extreme (90%-quartile) susceptibility values (Table 3). For some combinations of parent material and degree of weathering, the number of samples is too small for reliable values to be determined. Based on this table and the thresholds given in Table 2 (see previous page), we deduce a classification system (Table 4, below) to predict soil influence on MDs. The first symbol corresponds to the average (median) influence of the soil on MD and the second to the maximum impact that has to be expected. Thus, classifying a soil according to the second symbol is a more conservative appraisal than using the first symbol.

The degree of weathering was calculated from the results of a chemical analysis.[7] Usually, such an analysis is not available. However,

Parent Material	Ignoring Weathering		Degree of Weathering					
			0-1		1-3		>3	
	Median	90% - q	Median	90% - q	Median	90% - q	Median	90% - q
Ultrabasic	1496	8018	2706	8793	508	2266	187	1014
Basic/Intermediate	937	3187	743	3962	1051	1963	–	–
Acid	44	733	78	2506	23	273	46	474
Clay/Clay State	40	710	54	716	28	713	11	37
Phyllite	28	2059	21	3100	61	317	–	–
Sandstone	32	572	715	1077	122	432	4	108

Table 3: Average and extreme values of the susceptibility (10^{-5} SI) of the soils grouped according to their parent material and degree of weathering.

Parent Material	Ignoring Weathering	Degree of Weathering		
		0-1	1-3	>3
Ultrabasic	3-4	4-4	3-4	2-3
Basic/Intermediate	3-4	3-4	3-3	–
Acid	1-3	2-4	1-2	1-2
Clay/Clay State	1-3	2-3	1-3	1-1
Phyllite	1-4	1-4	2-2	–
Sandstone	1-3	3-3	2-2	1-2

Table 4: Classification of susceptibilities with respect to soil influence on metal detector performance. 1: neutral, 2: moderate, 3: severe, 4: very severe. The first index corresponds to the median and the second to the 90%-quartile.

the level of weathering can be estimated by the scheme in Table 5 (next page), which accounts for soil coloration and the presence of a crust.

Short Instruction for Using the Concept

Our classification system is intended to be used prior to demining activities for planning purposes and as a way to help select appropriate equipment. The first step is to look at a geologic map or to consult a geologist and determine the soil parent material, which is commonly the underlying rock. This information can be used to assess soil influence on MDs by looking at the first column of Table 4. If there is specific information on the soil in the mine-affected region, Table 5 may be used to determine the degree of weathering. Then, columns 2–4 of Table 4 can be used for a more sophisticated prediction.

Degree of Weathering	Condition of Soil
0-1	Presence of an Fe-Al crust or crust fragments
1-3	Intense red coloration of the soil
>3	Weak red coloration of the soil or any other color

Table 5: Scheme to appraise the degree of weathering of a soil in the field.

The first symbol stands for the most likely soil impact on the used detector. The second symbol is a worst-case appraisal, i.e., the most negative influence to be expected in some places within a region.

Consider the following example: If we know the parent material is an acid rock (e.g., granite), without knowing the degree of weathering, we can assess that soil will most likely be neutral toward a metal detector, but in rare cases there might be a severe influence. If, in addition, we know that the soil is deeply red-colored and there is a crust on top of it, we extract from Table 5 that the soil is very strongly weathered and we see from Table 4 that there will be most likely a severe influence and in rare cases there might be a very severe soil influence on detector performance.

Plans for Future Work

The next step will be to merge our classification system with geological and pedological maps of mine-affected countries in the tropics. This work will result in maps that can be used to appraise soil magnetic susceptibility over wide areas. By using Table 5 we can get a map that predicts soil influence on MD performance in terms of a probability. At the moment we are working on such a map for Angola. These maps may help demining organizations choose an adequate detector for the region where they plan to carry out a clearance campaign. In some regions a simple and cheap detector may be sufficient, but in other regions these detectors may be doomed to fail and a sophisticated detector with good ground compensation has to be used. In the worst case, MDs might not be the appropriate technique for mine clearance.

So far, we have analyzed the magnetic susceptibility that influences the performance of MDs. Beside the absolute value, the frequency dependence of magnetic susceptibility also has an influence on the detector signal.[10, 11] We plan to analyze the frequency dependence on the set of soil samples that we studied here and to deduce a comparable classification system.

See Endnotes, Page 115

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News Brief

Over 100,000 Explosive Disposal Charges Made in Cambodia

Golden West Humanitarian Foundation's Explosive Harvesting System team in Cambodia, funded by the U.S. Department of Defense, has harvested over 100,000 disposal charges from unexploded ordnance in Cambodia. The Explosive Harvesting System began in 2005 as a joint project between the Golden West Humanitarian Foundation and the Cambodian Mine Action Centre.

Most research and development projects are constructed and developed in Western countries and shipped abroad, but the Explosive Harvesting System was constructed directly in Cambodia. The system is designed to safely remove ordnance from anti-tank mines and large-caliber projectiles, and convert them into disposal charges for demining teams. These charges are produced at a low cost and provide an effective and environmentally safe method for clearing landmines and unexploded ordnance. Recovered explosives are provided at no charge to the humanitarian mine-action nongovernmental organizations working in Cambodia.