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Influence of Soil Properties on the Performance of Metal Detectors and GPR

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Influence of Soil Properties on the Performance of Metal Detectors and GPR

This article examines the effects of four soil types on metal detector and GPR performance and proposes the development of a classification system based on soil type to aid in the selection of effective methods for manual demining.

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Although landmine clearance employs various techniques, manual demining still accounts for a large part of mine-removal operations. The metal detector is the most common tool used in manual demining. Ground-penetrating radar was studied and tested as a complementary tool to the metal detector, because it can identify buried objects and accelerate operations. As the metal detector and GPR employ electromagnetic techniques, the soil's magnetic, electric and dielectric properties influence both devices. If the influence is significant, these tools may not provide reliable information and the safety of operations cannot be assured. Studying how soils affect detection and how the detectability of the mines is influenced is important. In this article, field experiment results illustrate soil influence on detection performance.

	Laterite	Magnetic Sand	Humus A	Humus B
Humus [% of total soil]	0.8	<0.5	2.7	12.4
Clay [% of mineral soil]	31.5	1.3	16.6	17.1
Silt [% of mineral soil]	39.4	7.0	48.4	40.7
Sand [% of mineral soil]	29.1	91.7	35.0	42.2

Table 1. Texture and humus content of the test soils.
All graphics courtesy of the authors.

Influential Soil Properties on Sensors

Magnetic susceptibility is the most influential soil property affecting metal detectors.[1] In general, the value of magnetic susceptibility at a certain frequency affects continuous wave metal detectors, and frequency dependence has more influence on pulse-induction detectors.[2] Soil with a high susceptibility or frequency dependence generates additional responses to metal detectors. These responses can be misinterpreted as metal detection and/or interfere with responses from landmines so that the signature of the mine is changed. This can result in false alarms or missed mines. Although magnetic susceptibility theoretically affects GPR, it must be extremely high to influence the signal. For example, reportedly, susceptibility must be greater than 30,000 x 10-5 SI to be influential compared to dielectric permittivity.[3] Values in this range are exceptional even for tropical soils, which are often highly susceptible, making the influence of magnetic susceptibility on GPR practically negligible.[4]

Electromagnetic induction-based devices can easily measure magnetic susceptibility at a single frequency. The measurements at multiple frequencies may require soil sampling and laboratory setups.

If the electric conductivity of soil is extremely high, then it also influences metal detectors, though to a lesser extent than magnetic susceptibility.[1] In contrast, the normal range of conductivity influences GPR. This property relates primarily to the attenuation of electromagnetic waves; a radar signal cannot propagate a long distance in a highly conductive medium. Anti-personnel mines are often shallower than 20 cm; thus the soil influence on radar signals may not be so critical. For example, electric conductivity of 60 mS/m, which is very high for normal soils unless they contain salt or clay, attenuates radar signals to $1/e$ (~-8.7 dB) at a 20-cm depth in relatively wet soil (volumetric water content of 35%).

Dielectric permittivity also greatly influences GPR, and it directly relates to water content in the soil.[5,6] In most soils, the permittivity contrast between two materials mainly defines the reflectivity of radar signals. The difference in permittivity between soil and a buried object generates reflected signals, which are interpreted to identify a target. However, a permittivity change within the soil also generates reflected GPR signals, and they can be misinterpreted as an object. Additionally, a change may confuse signals reflected from a target. Therefore, dielectric permittivity is the most influential soil property on GPR performance.

A time-domain reflectometry probe can easily measure permittivity at a single location in the field. The spatial distribution can be obtained by repeating TDR measurements at various locations. A reliable determination of frequency dependence requires soil sampling and laboratory measurements.

Testing Metal Detectors and GPR

The International Test and Evaluation Program for Humanitarian Demining tested metal detectors and a dual sensor in Germany in 2009 to evaluate their field performance. Kazunori Takahashi and Dieter Gülle reported details of the test conditions and general considerations.[7,8] This test used the following four soil types:

- Laterite: an iron-rich tropical weathered soil, a red-colored clay loam with stone content of approximately 2–5%.[9]
- Magnetic sand: an artificial mixture of coarse sand and engineered magnetite with low fine-gravel content (2–5%).

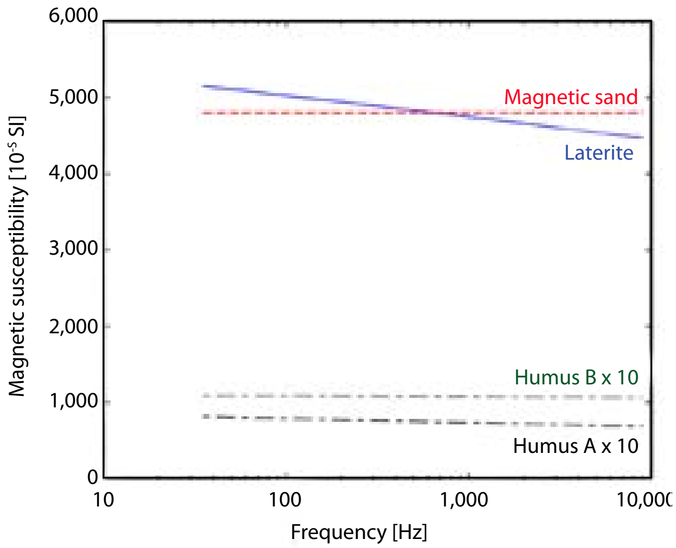

Figure 1. Frequency dependence of magnetic susceptibility of the test soils. Note that the magnetic susceptibility of humus A and B was multiplied by a factor of 10 for visibility.

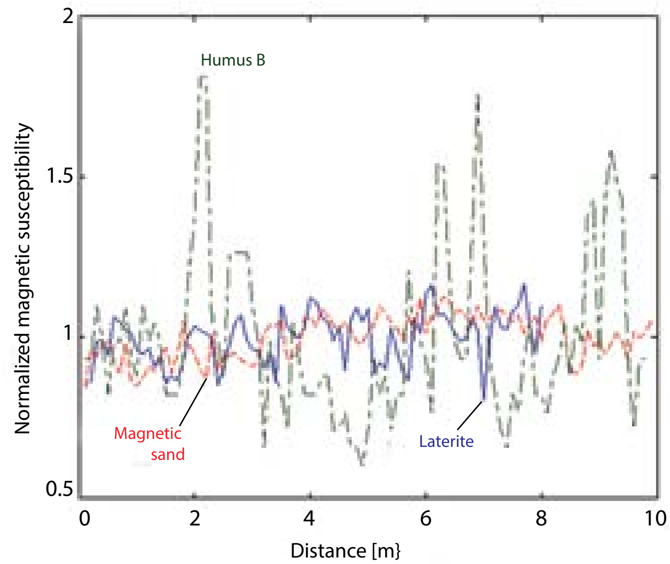

Figure 2. Spatial distribution of magnetic susceptibility for the test soils measured in 10-m long profiles at a frequency of 958 Hz. Values in this figure were normalized by the mean.

- Humus A: a humus loam originated from loess.[10,11]
- Humus B: a loamy humus forest soil with high stone content (about 30–40%) and high humus content.

Table 1 (page 52) summarizes the texture and humus content of the test soils. In these soils, blind tests of various detector models were used to calculate the following performance measures:

- Probability of detection: the number of targets detected relative to the total number of targets
- False alarm rate: the number of false alarms produced
- False alarm rate reduction: the number of metal junk the GPR correctly identified
- Probability of detection loss: the number of mines the GPR falsely identified as metal junk [7,8]

Analyzing Soil Properties

A susceptibility bridge (Magnon VFSM) measured the frequency dependence of magnetic susceptibility on soil samples at the laboratory. Figure 1 (page 53) shows the results. Both laterite and magnetic sand showed very high magnetic-susceptibility values; however, only laterite exhibited significant frequency dependence. Humus A and B had much lower values, but only humus A demonstrated a relatively high frequency dependence. Figure 2 (page 53) shows the spatial variation of the normalized magnetic susceptibility in a 1-D profile measured at a frequency of 958 MHz in the field using a susceptibility meter (Bartington MS2 and its field loop MS2D). Only humus B exhibited remarkable spatial variation; however, the absolute level in humus B was very low (Figure 1 on page 53), and the absolute variation was thus small. Based on this result and classification systems of soil influence dependent on magnetic susceptibility, laterite is expected to significantly influence metal detectors because of the very high susceptibility values and frequency dependence of magnetic susceptibility.[12,13] In contrast, the easiest soil for metal detectors was humus B. All soils showed magnetic susceptibility much lower than 30,000 x 10^{-5} SI, and no significant influence on GPR was expected in any type of soil.

The spectral-induced polarization method (Radic-Research SIP Fuchs Lab) measured the frequency dependence of electric conductivity in the laboratory, and 3-D resistivity imaging (DMT Resecs) obtained the spatial distribution in the field. Figures 3 (page 53) and 4 (page 54) show the results. Conductivities in all soils were in the normal range and not particularly high. For example, a depth that attenuates radar signal to 1/*e* is more than 1 m in humus B, which exhibits the highest conductivity among all. Some amount of spatial variation can be observed in Figure 4, but again, the level is not high. Therefore, the influence of electric conductivity on metal detectors and GPR was expected to be negligible in these soils.

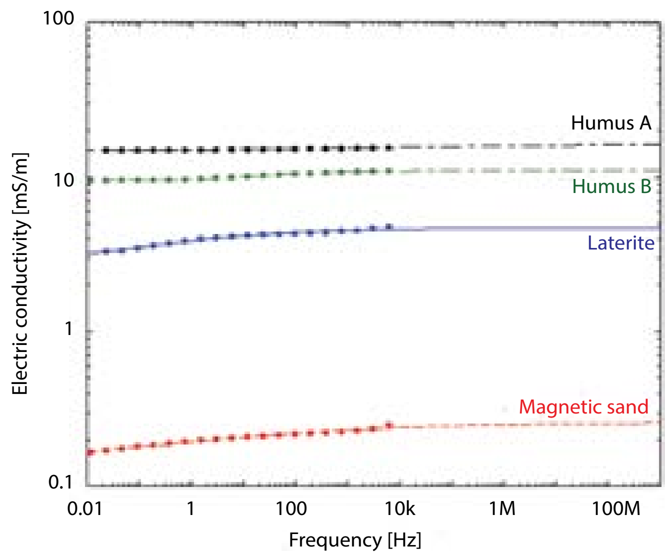

Figure 3. Frequency dependence of electric conductivity of the test soils. The dots and lines show the measured values and model fits, respectively.

Spatial changes in dielectric permittivity were measured in the field every 10 cm along 10 m profiles with a time-domain reflectometry (FOM/mts, Institute of Agrophysics of the Polish Academy of Sciences), as Figure 5 (page 55) indicates. Magnetic sand showed a low and constant permittivity. Mainly because of the very small variation, clear radar signatures of targets were expected in magnetic sand. However, laterite and humus showed higher permittivity (higher water content) and larger spatial variations. The spatial variation causes additional response to GPR, which disturbs the signatures of targets. Therefore,

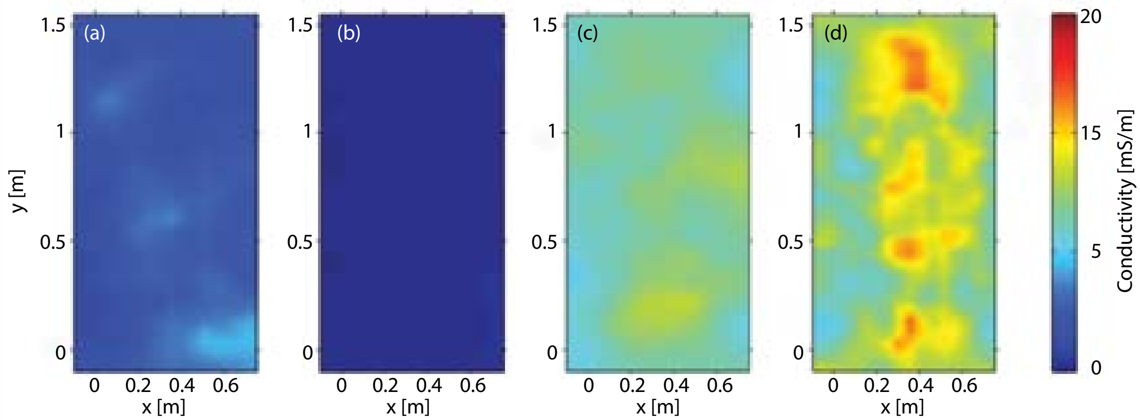

Figure 4. Spatial distributions of electric conductivity at a depth of 5-10 cm in (a) laterite, (b) magnetic sand, (c) humus A, (d) humus B.

	Laterite	Magnetic Sand	Humus A	Humus B
κ at a certain frequency	Very high	Very high	Very low	Very low
Frequency dependence of κ	Very high	Low	High	Low
Spatial variation of κ	Small	Small	N/A	Very large
σ at a certain frequency	Low	Very low	Low	Low
Spatial variation of σ	Large	Very small	Small	Large
Absolute level of ϵ_r	High	Low	High	High
Spatial variation of ϵ_r	Large	Very small	N/A	Very large
ϵ_r at a certain frequency	Very severe	Moderate	Moderate	Neutral
Impact on GPR	Moderate	Neutral	Moderate/severe	Very severe

Table 2. Qualitative evaluation of measured soil properties and comprehensive estimation of soil impact on the performance of detectors. κ, σ and ϵ denote magnetic susceptibility, electric conductivity and dielectric permittivity, respectively.

laterite and humus may be problematic for GPR. Especially in humus, the correlation length, which describes dimension of the variation cycle in space and was determined by further analysis, was similar to the target dimension. Therefore, humus was expected to more severely impact GPR than laterite.

Table 2 (page 54) summarizes the qualitative evaluation of soil-property measurements and provides a comprehensive estimation of soil impact on metal detectors and GPR.

Soil Properties and Detector Performance

The performance of metal detectors (probability of detection and false alarm rate) calculated from the test results is shown in Figures 6 and 7 (page 55) with respect to soil difficulty shown in Table 2 (page 54). In Figure 6 (page 55) the performance measures are the average of all metal detector models tested. This figure clearly exhibits that POD (positive feature) decreased and FAR (negative feature) increased as soil became more difficult. In Figure 7 (page 55) the averaged performance measures of metal detectors are plotted for pulse-induction detectors and continuous wave detectors separately. A significant difference between PI and CW detectors is observed in FARs in magnetic sand. The FAR of a PI detector is lower than the FAR of a CW detector in magnetic sand, which showed a high magnetic susceptibility but no frequency dependence. This result confirms that the susceptibility value at a certain frequency influences CW metal detectors more than PI detectors.[2]

Figure 8 (page 55) shows the identification performance of GPR (FAR reduction and POD loss) with respect to soil difficulty. Note that the order of soil types in the horizontal axis according to the estimated soil impact is different for GPR (Figure 8, page 55) and metal detectors (Figures 6 and 7, page 55), since the test-soil difficulties were graded differently for each. In the case of GPR performance, FAR reduction (positive feature) was nearly constant for all test soils, and POD loss (negative feature) increased with soil difficulty. Therefore, GPR performed poorly in soils classified as difficult. These results demonstrate that comprehensive soil characterization and classification, according to the geophysical analyses, agreed with the performance of detectors.

Discussions

Soil characterization, based on geophysical measurements, agreed with detector test results: high POD and low FAR in unproblematic soil, and low POD and high FAR in difficult soil for metal detectors; low POD loss in easy soil, high POD loss in difficult soil and constant FAR for GPR. The results indicate that the performance of detectors can be predicted qualitatively by analyzing soil properties obtained by geophysical measurements.

As shown, heterogeneity and spatial distribution of soil properties are necessary to assess detector performance, especially for GPR. The soil characterization for sensors shown in this article is very general, and the criteria for grading soils can be applied to all detector models. However, because each metal detector and dual-sensor model is unique, the amount of soil influence on performance (i.e., the slopes of curves in Figures 6–8, page 55)) may differ.

Detector performance can be assessed during clearance through soil characterization as follows: Geophysical measurements can be carried out on a representative area, other than the minefield, before actual

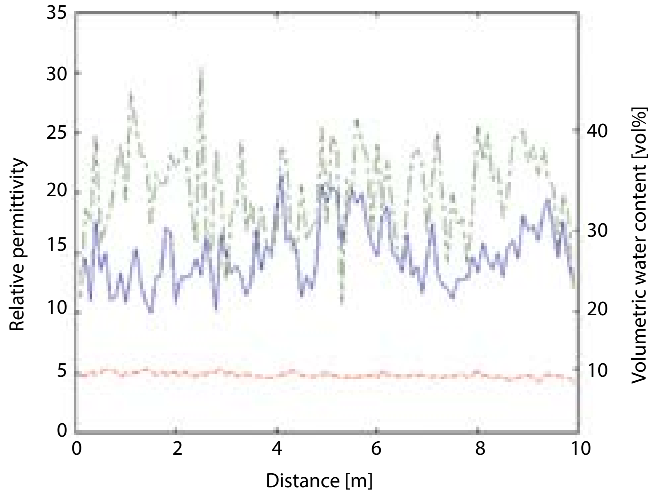

Figure 5. Spatial distribution of relative permittivity of the test soils measured in 10-m long profiles and corresponding water content determined by an empirical equation.[11]

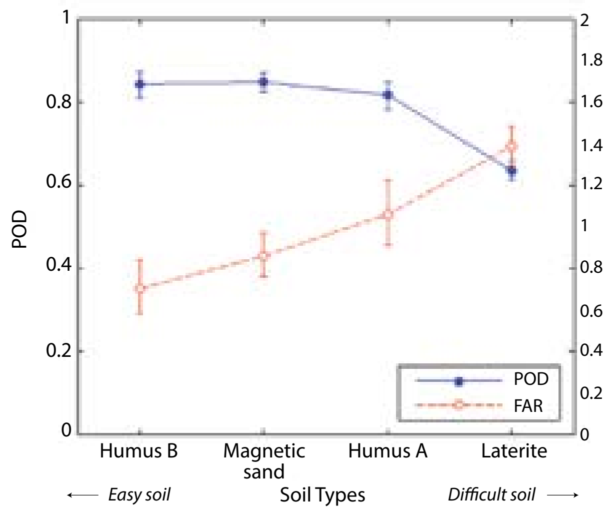

Figure 6. Performance of metal detectors in terms of POD (blue dots with solid line) and FAR (red circles and dashed line) averaged over all models tested. Soil on the left side is considered to be easy and soil on the right side is considered to be difficult. The error bars show 95% confidence bounds.

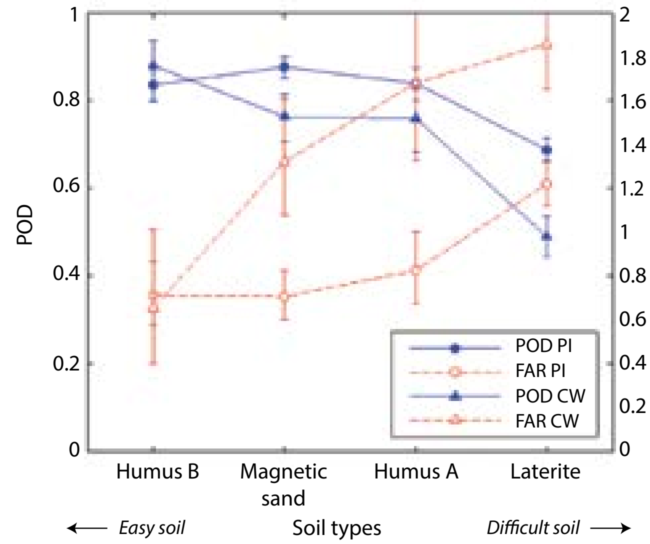

Figure 7. Performance of metal detectors in terms of POD (blue solid lines) and FAR (red dashed lines), separately calculated for pulse induction (PI, plotted with circles) and continuous wave (CW, plotted with triangles) detectors. Soil on the left side is considered to be easy and soil on the right side is considered to be difficult. The error bars show 95% confidence bounds.

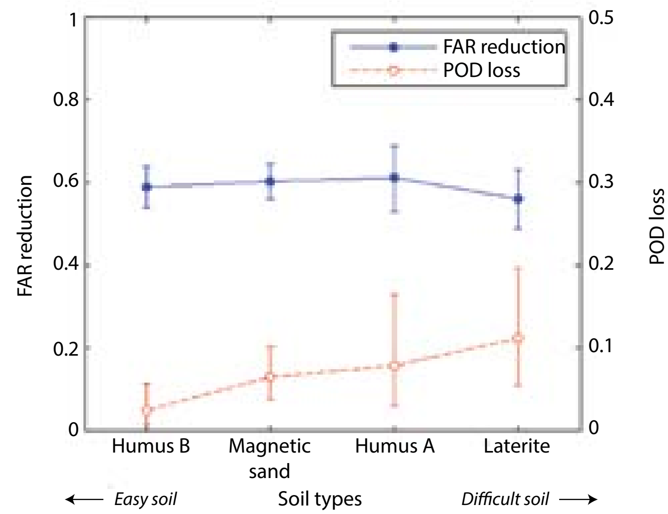

Figure 8. Performance of GPR in terms of FAR reduction (blue dots with solid line) and POD loss (red circles and dashed line). Soil on the left side is considered to be easy and soil on the right side is considered to be difficult. The error bars show 95% confidence bounds.

demining operations, i.e., in the stage of Technical Survey. The soil characterization allows for the selection of appropriate clearance techniques. For example, if soils in an area are assessed as easy for GPR, the use of a dual sensor in this area may accelerate clearance operations. However, if soils are assessed as difficult for GPR, a dual sensor should not be used because the operations may not be safe and/or effective. Furthermore, if soils are expected to be difficult for metal detectors, manual prodding should be used. Such performance assessment and selection of detection techniques can reasonably be made by analyzing soil properties. As a complementary survey, geophysical measurements are very useful for mine clearance with detectors.

Only four soil types were available for this study, although these soils were selected to represent a wide variety of natural soil types in mine-affected countries. By collecting more samples, a classification system based on soil magnetic and dielectric properties may be established. Such a classification system will advance the benefit and safety of using metal detectors and GPR for clearance.

Detailed results of geophysical measurements shown in this article can be found in Preetz et al., and a more technical, detailed discussion of the analysis can be found in Takahashi et al.[15,16,17,18]

See endnotes page 66

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News Brief

Poland Ratifies the APMBC

On 4 December 2012 Poland became the 161st state to ratify the 1997 *Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti-personnel Mines and on Their Destruction* (Anti-personnel Mine Ban Convention or APMBC).[1] Poland originally signed the APMBC in 1997.[1] The Undersecretary of State at the Ministry of Foreign Affairs, Maciej Szpunar, made the announcement at the 12th Meeting of the States Parties to the APMBC, which took place in Geneva, Switzerland, on 3–7 December 2012.[2]

Explosive remnants of war and a small number of landmines from World War II and the Soviet occupation heavily contaminated Poland. However, the Polish Ministry of Defense states that mined areas or areas suspected of mine contamination no longer remain, eliminating the need for regular clearance or mine risk education programs.[3] Nonetheless, Polish armed forces conduct landmine and ERW clearance in response to emergency requests for explosive ordnance disposal and in routine checks on former Soviet and Polish military bases before they are handed over to local civilian communities.[4]

The APMBC will take effect in Poland on 1 June 2013. Remigiusz Henczel, Poland's ambassador to the U.N. in Geneva stressed Poland's commitment to a world without landmines, stating that Poland is "ready to actively participate in endeavors promoting the universal adherence to the Convention and its humanitarian impact."[1]

See endnotes page 67

~ Sarah Peachey, CISR staff

ENDNOTES

Influence of Soil Properties on the Performance of Metal Detectors and GPR by Takahashi, Preetz and Igel [from page 52]

1. Das, Yogadhish. "A Preliminary Investigation of the Effects of Soil Electromagnetic Properties on Metal Detectors." *IEEE Transactions on Geoscience and Remote Sensing* 44 (2006): 1444–1453. http://bit.ly/LENsu0. Accessed 9 July 2012.
2. Cross, G. "Soil Electromagnetic Properties and Metal Detector Performance: Theory and Measurement." *Defence* R&D Canada. http://1.usa.gov/Ne0Bpp. Accessed 9 July 2012.
3. Jol, Harry, ed., *Ground Penetrating Radar: Theory and Applications*. Amsterdam: Elsevier B.V., 2009.
4. Preetz, Holger, Sven Aitfelder and Jan Igel. "Tropical Soils and Landmine Detection – An Approach for a Classification System." *Soil Science Society of America Journal* 72, no. 1 (January 2008): 151–159. http://bit.ly/OtQM6F. Accessed 10 July 2012
5. Lampe, B. and K. Holliger. "Effects of Fractal Fluctuations in Topographic Relief, Permittivity and Conductivity on Ground-Penetrating Radar Antenna Radiation." *Geophysics* 68, no. 6 (November 2003): 1934–1944. http://bit.ly/LENYIA. Accessed 9 July 2012.
6. Igel, Jan. "On the Small-Scale Variability of Electrical Soil Properties and Its Influence on Geophysical Measurements." PhD diss., Frankfurt University, *Frankfurt am Main*, Germany, 2007. http://bit.ly/Ngj72O. Accessed 9 July 2012.
7. Takahashi, Kazunori and Dieter Gülle. "ITEP Dual Sensor Test in Germany." *International Symposium "Humanitarian Demining 2010."* (April 2010): 10–14. http://bit.ly/L61z5p. Accessed 9 July 2012.
8. Takahashi, Kazunori and Dieter Gülle. "ITEP Evaluation of Metal Detectors and Dual-Sensor Detectors." *The Journal of ERW & Mine Action 14.3* (2010): 76–79. http://bit.ly/LcXCR9. Accessed 10 July 2012.
9. Loam is a mixture of soil containing clay, sand and silt in fairly even amounts.
10. Humus is organic material in soil, which decomposed from plant and animal substances (usually rich in nutrients, e.g., soil containing manure). "Humus." *Encyclopædia Britannica Online*. http://bit.ly/IPsgz6. Accessed 6 December 2012.
11. Loess is a recent sedimentary deposit of silt or loam, often deposited by wind. "Loess." *Encyclopædia Britannica Online*. http://bit.ly/JVq6Ky. Accessed 6 December 2012.
12. "CEN Workshop Agreement: Humanitarian Mine Action – Test and Evaluation – Part 1: Metal Detectors." *European Committee for Standardization*. http://bit.ly/MfzJtO. Accessed 9 July 2012.
13. "CEN Workshop Agreement: Humanitarian Mine Action – Test and Evaluation – Part 2: Soil Characterization for Metal Detector and Ground Penetrating Radar Performance." *European Committee for Standardization*. http://bit.ly/NdjPhZ. Accessed 9 July 2012.
14. Topp, G.C., J.L. Davis and A.P. Annan. "Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines." *Water Resources Research* 16, no. 3 (1980): 574–582. http://bit.ly/MinusK. Accessed 10 July 2012.
15. Preetz, H., K. Takahashi and J. Igel. "Physical Characterisation of the Test Lanes in the ITEP Dual Sensor Test Oberjettenberg/Germany 2009." *Leibniz Institute for Applied Geophysics*. http://bit.ly/Milocb. Accessed 9 July 2012.
16. Takahashi, Kazunori, Holgar Preetz and Jan Igel. "Soil Properties and Performance of Landmine Detection by Metal Detector and Ground-Penetrating Radar – Soil Characterisation and its Verification by a Field Test." *Journal of Applied Geophysics* 73, no. 4 (2011): 368-377.
17. Takahashi, K., H. Preetz and J. Igel. "Performance of Demining Sensors and Soil Properties [8017-31]." Proceedings - SPIE - *The International Society for Optical Engineering* 8017, (2011): 80170X.
18. Takahashi, Kazunori, Holgar Preetz and Jan Igel. "Soil Characterisation and Performance of Demining Sensors." *International Symposium "Humanitarian Demining 2010:" 27 to 30 April 2010, Šibenik, Croatia.* (2010): 47–52. http://bit.ly/L61z5p. Accessed 9 July 2012.