Worldwide distribution of soil dielectric and thermal properties

Jan M.H. Hendrickx*, Remke L. van Dam, Brian Borchers
New Mexico Tech, Socorro, NM

John Curtis
Waterways Experiment Station, Vicksburg, Mississippi

Henk A. Lensen
TNO Physics and Electronics Laboratory, The Hague, The Netherlands

Russell Harmon
U.S. Army Research Office, Durham, NC

ABSTRACT

Ground penetrating radar and thermal sensors hold much promise for the detection of non-metallic land mines. In previous work we have shown that the performance of ground penetrating radar strongly depends on field soil conditions such as texture, water content, and soil-water salinity since these soil parameters determine the dielectric soil properties. From soil physics and field measurements we know that the performance of thermal sensors also strongly depends on soil texture and water content. There is it critical that field soil conditions are taken into account when radar and thermal sensors are employed. The objectives of this contribution are (i) to make an inventory of readily available soil data bases world wide and (ii) to investigate how the information contained in these data bases can be used for derivation of soil dielectric and thermal properties relevant for operation of land mine sensors.

Keywords: soils, soil dielectric property, soil thermal property, soil data base, land mines

1. INTRODUCTION

Most if not all land mine sensors are affected to some degree by soil conditions. The performance of a specific sensor under specific soil conditions can be predicted using our understanding of the physics of the soil-mine-sensor system. In this study we will focus on soil properties that affect the performance of ground penetrating radar and thermal sensors. Previous and current work by our research team and other investigators has shown how these sensors are affected by field soil conditions[1,2,3,4,5,6,7].

For example, the real part of the relative permittivity (ε_r) of water shows little frequency dependence ($\varepsilon_r \sim 80$) up till 3 GHz, after which it drops. The imaginary part of ε_r starts frequency dependent behavior at around 1 GHz, increasing its value steadily up to 17 GHz[8]. In fact, the commonly used model to relate dielectric soil properties to volumetric water content and vice versa[9] decreases in accuracy with increasing frequency[10]. We have shown with field experiments that the combined effects of soil texture and soil water content lead to soil conditions where non-metallic mines are best detected in wet sand soils and dry clay soils[5,11]. The dependence of soil thermal properties on soil texture and water content has been documented in many text books[12,13]. With increasing soil water content the thermal conductivity and volumetric heat capacity of all soils will increase.

* hendrick@nmt.edu

A major finding of our research is that simple models can be used to evaluate the effect of soil dielectric and thermal properties on land mine sensor performance. We have evaluated the models of Dobson *et al.*[14] and Peplinski *et al.*[15] for the prediction of soil dielectric properties as a function of soil texture and soil water content and found good agreement with field measurements. Using the predicted soil dielectric properties we used a simple analytical radar wave propagation model for the prediction of radar signatures from anti-tank land mines under a wide range of soil conditions[1]. These predictions for detection of non-metallic and metallic land mines agreed well with our field measurements[5,11]. Many investigators have determined relationships for the prediction of thermal soil properties from soil texture and water content[16,17]. Recently, we have found that these relationships combined with simple analytical models for prediction of soil surface temperatures perform as well as complicated numerical models for the evaluation of thermal land mine signatures[18]. Thus, our research has shown that the performance of radar and thermal land mine sensors can be predicted better wherever we have access to basic soil data.

All over the world soil scientists have gathered a wealth of soil data during the last century. Until a few decades ago this information was buried in soil maps and reports by national soil surveys. However, the simultaneous developments in methods and instrumentation for soil data acquisition, storage, retrieval, analysis, interpretation, manipulation, modeling, simulation, accessibility, and distribution has given us an array of tools to extract useful, timely information for the assessment of field soil conditions[19]. Our goal is to explore how these tools can be used to improve land mine sensor performance. The specific objectives of this contribution are (i) to make an inventory of readily available soil data bases world wide and (ii) to investigate how the information contained in these data bases can be used for derivation of soil dielectric and thermal properties relevant for operation of radar based land mine sensors.

2. SOIL MAPS AND SOIL DATA BASES

Soil survey services worldwide have traditionally produced soil maps at different scales, consisting of delineations called mapping units. Each mapping unit is characterized by a "representative soil profile". A soil profile typically consists of a vertical succession of more-or-less distinct soil layers called soil horizons (Figure 1). The top layer, or A horizon, is the zone of major biological activity and is therefore generally enriched with organic matter and typically darker in color than the underlying soil. Its thickness can vary from 1-2 cm to 15-30 cm. Beneath the A horizon we often find a B horizon, where some of the materials (e.g. clay or carbonates) that are leached from the A horizon by percolating water tend to accumulate. The B horizon is generally thicker than the A horizon. Underlying the B horizon is the C horizon which is the soil parent's material. In some cases the C horizon consists of weathered and fragmented rock material. In other cases, the C horizon may consists of sedimentary deposits, e.g. alluvial, aeolian, or glacial. Obviously, for land mine detection the composition of the A horizon and –for deeper mines- the B horizon are of most interest.

The boundaries of a mapping unit are not based on a large number of soil profile descriptions but on external above ground features of the soil and the landscape that can be seen in the field or on air photos or other remote sensing images[20]. In other words, a soil surveyor develops a conceptual model about soil changes in the landscape and only then selects the observation points to dig a soil pit for inspection and sampling of "representative soil profiles". There is a direct relation between the density of representative soil profiles sampled in the field and map scale, which is defined by the number of representative soil profiles per square centimeter of the final map. Buringh *et al.*[21] recommend sampling four representative soil profiles per square centimeter while Dent[22] recommends only one. Thus, a detailed soil map at scale 1:10,000 is based on approximately one to four representative soil profiles per hectare (100x100 m) while a soil map with coarser resolution at scale 1:1,000,000 is based on approximately one to four representative soil profiles per 100 km^2. Therefore, the information on a soil map represents at best the average condition over each mapping unit but contains little or no information about soil variability. For that reason the legends of a soil map are often qualitative covering a range of possible values.

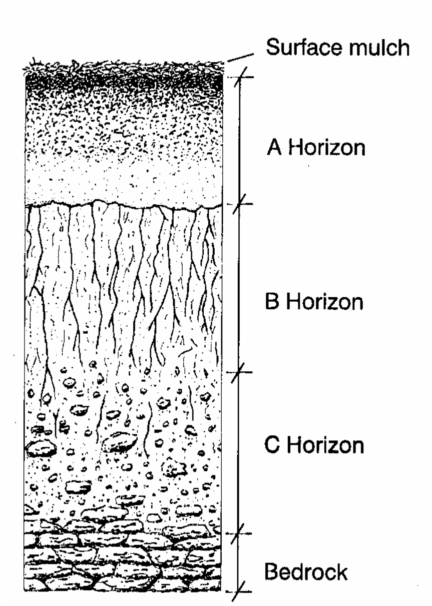

Figure 1. Schematic presentation of hypothetical soil profile[23].

Soil texture is a soil attribute or property that is qualitative but also contains quantitative information. The textural designation of a soil is determined on the basis of the mass ratios of three particle size classes: sand (0.05-2.0 mm), silt (0.002-0.05 mm), and clay (below 0.002 mm). Soils with different percentages of sand, silt, and clay are assigned different classes as shown in the textural triangle (Figure 2). However, an A horizon assigned textural class "sand" can have a range of clay and silt percentages varying from, respectively, 0-10% and 0-15%.

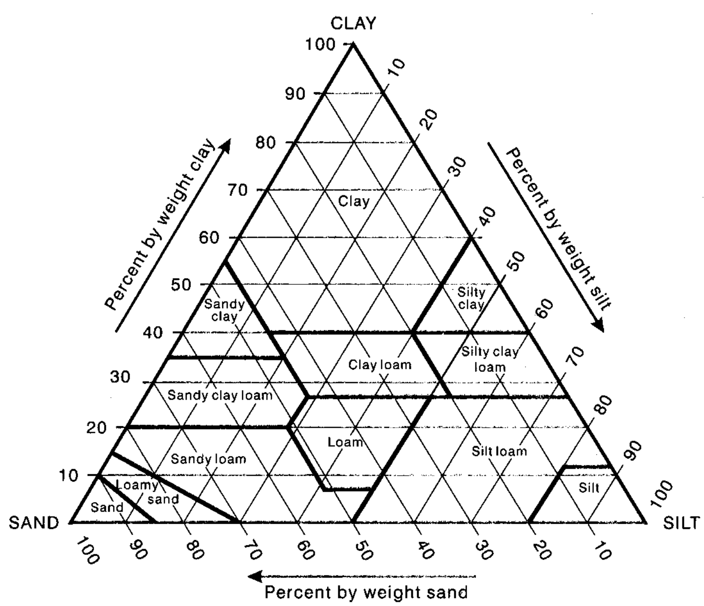

Figure 2. Textural triangle and the conventional soil textural classes based on percentage clay (below 0.002 mm), silt (0.002-0.05), and sand (0.05-2.0)[23].

Traditionally soil data were stored in archives in paper form. The accessibility of these archives is often quite limited, even by the survey organization themselves. Fortunately, the development of Geographical Information Systems makes it now possible to store soil data in computers so that they can be quickly retrieved. We distinguish between point and area data. Point data are detailed descriptions of representative soil profiles, often including chemical, physical, and mechanical analyses. Soil maps and mapping units are regarded as area data.

Many national and international organizations and agencies have made soils databases accessible on the internet. Additions and changes in electronic accessibility of soils data are occurring continuously. The websites presented in Table 1 contain much information about the world soil resources and have linkages with other global, national, and regional databases. A compendium of on-line soil survey information is available at http://www.itc.nl/~rossiter/research/rsrch_ss.html by D.G. Rossiter. At this moment FAO's Soil Map of the World is the best geographic source on global soil resources at a scale of 1:5,000,000. Work is underway to update the world's information on soil resources at a scale of 1:1,000,000 in SOTER, the World Soil and Terrain Database program[24].

Table 1. Four major soil databases[19].

Soils Data	Agency	Website
SOTER, WISE other soil databases	International Soil Reference and Information Center Wageningen, The Netherlands	www.isric.nl
Digital Soil Map of the World	Food and Agriculture Organization (FAO) Rome, Italy	www.fao.org
World Soil Resources	Natural Resources Conservation Service U.S. Department of Agriculture Washington, D.C., U.S.A.	www.nhq.nrcs.usda.gov
Canadian Soil Information System	Agriculture and Agri-Food Canada Ottawa, Canada	www.res.agr.ca

The SOTER datasets mostly have a scale of 1:1,000,000 and information is available in the form of maps and tables. For characterizing soil components SOTER uses the FAO soil classification; for terrain classification it has developed its own classification. Terrain and soil are combined in a step-by-step manner, progressively defining terrain, terrain component and soil component. *Terrain* is based on the physiography and parent material; *terrain components* such as surface form, slope, etc.; *soil components* such as number of reference profiles, surface rockiness, types of erosion, rootable depth, etc. The SOTER databases contain geometric data (stored and handled by Geographic Information System, GIS) and attribute data (stored in a separate set of attribute files, manipulated by a Relational Database Management System, RDBMS). More than fifty attribute data are available including soil texture, bulk density, infiltration rates, soil salinity, etc. Although the mandatory attribute data do not include information on (magnetic) iron oxides, it does provide information on diagnostic horizons and properties, for example ferralic soils. A disadvantage of the SOTER system is that for large areas in the world the datasets are yet to be compiled. At this point, published datasets are available for Latin America and the Caribbean, Kenya, Eastern Europe, Tanzania, and Niger and Benin. Unpublished SOTER datasets include those for Mozambique, Namibia, Syria, Jordan, Zimbabwe, and Nepal.

The World Inventory of Soil Emission Potentials (WISE) dataset comprises information on soil profiles from all over the world that are considered representative for the soil units shown on the FAO digital soil map of the world. The WISE datasets include several thousands of soil profiles. Like in the SOTER database, use is made of geometric data, handled by GIS software and attribute data, manipulated by a Relational Database Management System. Although at a less detailed scale (½ degree longitude by ½ degree latitude) than SOTER, the soil profile information includes soil physical and chemical parameters like soil texture and Cation Exchange Capacity.

These soil databases and many other national databases provide much information about the composition of the top soil layer such as texture, organic matter content, bulk density, salt content, etc. However, as has been explained before no soil database will provide site specific information since the number of sampled representative profiles is only an infinitely small fraction of the entire worldwide soil volume. Yet, in many cases the databases will give a clear picture of average soil conditions that are found in a region and the associated soil variability. The need for the use of soil databases in humanitarian demining has been pointed out by Das *et al*.[25]. We recommend that soil scientists be consulted to extract relevant soil information from these databases for use in mine detection and removal.

3. PEDOTRANSFER FUNCTIONS FOR SOIL DIELECTRIC AND THERMAL PROPERTIES

Bouma[26] discussed "the challenge for soil science to translate data we have [readily available in soil databases] to data we need". For our purpose we need to translate information from soil databases on soil texture, bulk density, and soil water content into soil dielectric and thermal properties. This translation is performed by *pedotransfer functions*. A pedotransfer function is a mathematical relationship between two or more soil parameters which shows a high level of statistical confidence. It is used to estimate a non-measured soil parameter from one or more measured ones.

Pedotransfer functions for soil dielectric properties. For the determination of the real (ε') and imaginary (ε'') parts of the dielectric coefficient (ε) of a soil we have used the 1995 model of Peplinski *et al*.[15] which has been calibrated by fitting the model to a set of experimental observations with a variety of soil textures, water contents, and frequencies from 0.3 to 1.3 GHz.

$$\varepsilon = \varepsilon' - \varepsilon'' i$$

$$\varepsilon' = 1.15\left[1 + \frac{\rho_b}{\rho_s}(\varepsilon_s^{\alpha} - 1) + \theta^{\beta'}\varepsilon_{fw}'^{\alpha} - \theta\right]^{1/\alpha} - 0.68$$

$$\varepsilon'' = \left[\theta^{\beta''}\varepsilon_{fw}''^{\alpha}\right]^{1/\alpha}$$

$$\varepsilon_s = (1.01 + 0.44\rho_s)^2 - 0.062$$

$$\varepsilon_{fw} = \varepsilon'_{fw} - \varepsilon''_{fw} i$$

$$\varepsilon'_{fw} = \varepsilon_{w\infty} + \frac{\varepsilon_{w0} - \varepsilon_{w\infty}}{1 + (2\pi f \tau_w)^2}$$

$$\varepsilon''_{fw} = \frac{2\pi f \tau_w (\varepsilon_{w0} - \varepsilon_{w\infty})}{1 + (2\pi f \tau_w)^2} + \frac{\sigma_{eff}}{2\pi\varepsilon_0 f}\frac{\rho_s - \rho_b}{\rho_s \theta}$$

$$\beta' = 127.48 - 0.519S - 0.152C$$

$$\beta'' = 1.33797 - 0.603S - 0.166C$$

$$\sigma_{eff} = 0.0467 + 0.2204\rho_b - 0.4111S + 0.6614C$$

Where θ is volumetric water content, *f* is frequency, *S* is fraction of sand, *C* is fraction of clay, ρ_s is specific density of soil particles (2660 kg m^{-3} for most soil minerals), ρ_b is bulk density of the soil, σ_{eff} is effective dielectric conductivity of soil, ε_{fw} is the dielectric constant of free water, , ε_0 is the dielectric permittivity of free space, ε_{w0} is the static dielectric constant of water (80.1 at 20 ºC), $\varepsilon_{w\infty}$ is the high frequency limit of ε_{fw}' (4.9), ε_s is the dielectric constant of soil particles, and τ_w is the relaxation time of water (9.23x10^{-12} s at 20 ºC). Using this pedotransfer function we find the unknown real (ε') and imaginary (ε'') parts of the dielectric coefficient (ε) of a soil using the known fractions of sand (*S*) and clay (*C*), the bulk density (ρ_b), and the particle density (ρ_s) for different soil water contents.

Pedotransfer functions for soil thermal properties. The soil thermal properties needed to model soil surface temperatures above and away from mines[18] are the volumetric heat capacity (c) and the thermal conductivity (λ). The volumetric heat capacity of soil is often expressed as the weighted sum of the heat capacities of the various soil constituents. Since the volumetric heat capacity of air is about three orders of magnitude less than that of the other soil constituents it can be neglected so that

$$c = \rho_b (c_s + c_w \theta_g)$$

where c_s and c_w are the specific heat of soil (0.73 kJ kg^{-1}K^{-1}) and water (4.18 kJ kg^{-1}K^{-1}), ρ_b is the dry bulk density, and θ_g is the gravimetric soil water content[17].

Soil thermal conductivity (λ) can be determined from an empirical equation[16].

$$\lambda = A + B\theta_v - (A - D)\exp[-(C\theta_v)^E]$$

where θ_v is the volumetric soil water content and *A, B*, *C*, *D*, and *E* are soil dependent coefficients which are related to soil properties that are usually fairly readily available. The relationships are

$$A = \frac{0.57 + 1.73\phi_q + 0.93\phi_m}{1 - 0.74\phi_q - 0.49\phi_m} - 2.8\phi_s(1 - \phi_s)$$

$$B = 2.8\phi_s$$

$$C = 1 + \frac{2.6}{m_c^{0.5}}$$

$$D = 0.03 + 0.7\phi_s^2$$

$$E = 4$$

where φ is the volume fraction of a particular component, subscripts “q”, “m”, and “s” indicate quartz, minerals other than quartz, and total solids, and m_c is the clay mass fraction. The thermal conductivity predicted by this equation is the total conductivity which includes the sensible and the latent heat components.

An example. In New Mexico we have taken radar measurements in three different field top soils. The properties of these soils are presented in Table 2. Similar soil properties can be obtained from the soil databases discussed above or from other sources such as national soil survey agencies. We have used these soil properties together with the pedotransfer functions for soil dielectric and thermal properties to predict those for the three soils over the entire range of water contents from bone dry to saturation. The results are presented in Figures 3-5. These results can be used in simple radar and thermal models for the analysis of land mine signatures as demonstrated by Miller[11] and Van Dam *et al*.[18].

Table 2. Properties of three field top soils in New Mexico[11].

Soil Type	Texture			Bulk Density
	% Sand	% Silt	% Clay	g/cm^3
Sand	95	2	3	1.6
Silt	2	66	32	1.3
Clay	1	27	72	1.5

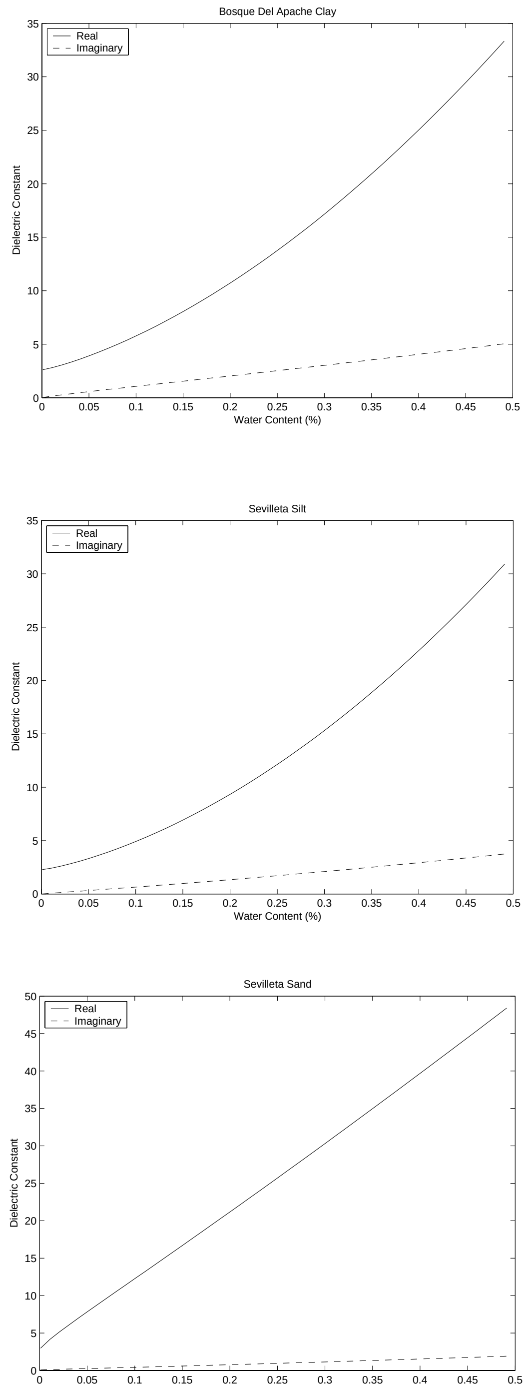

Figure 3. The real and imaginary part of the dielectric coefficient as a function of water content in three New Mexico field soils.

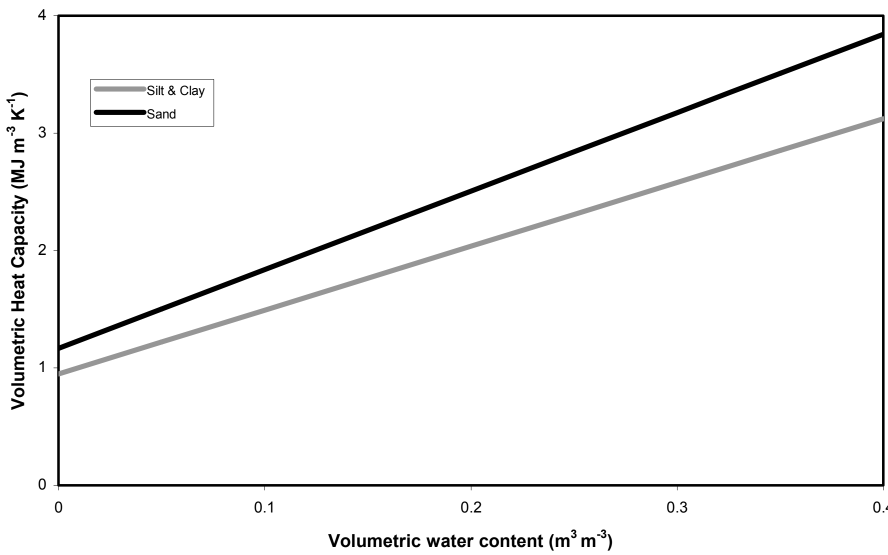

Figure 4. The volumetric heat capacity as a function of water content in three New Mexico field soils.

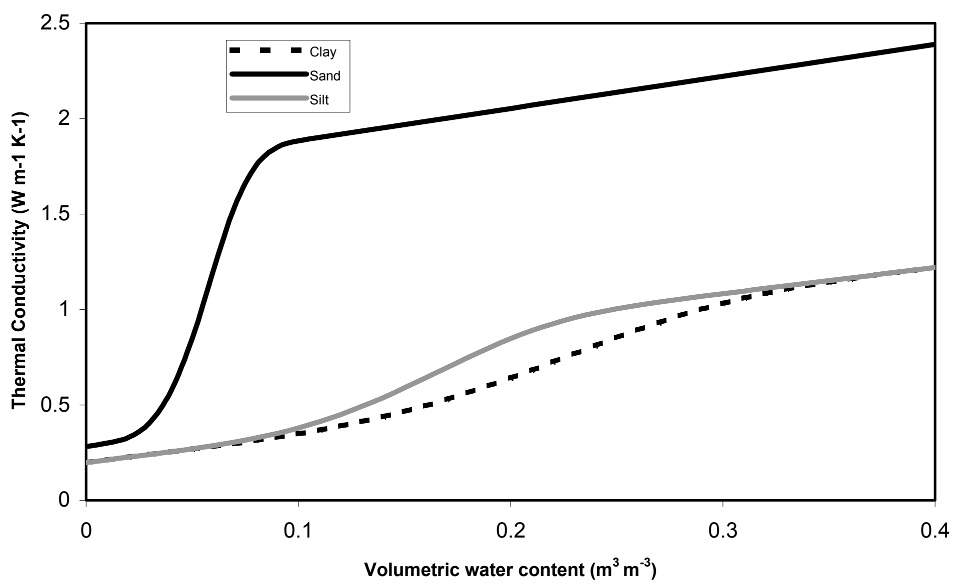

Figure 5. The thermal conductivity as a function of water content in three New Mexico field soils.

4. EVALUATION OF SOIL CONDITIONS IN MINE FIELDS WORLDWIDE

Our overall research goal is to develop a procedure that informs deminers about the effects of soil conditions on land mine sensors. We recognize two distinct phases in this procedure: the mobilization phase and the field operation phase. During the *mobilization phase* one has to decide what kind of sensors can be employed in a mine field and what kind of soil effects may enhance or hinder sensor operation. It is during mobilization that the information of soil databases is most useful. Soil databases (Table 1) provide immediate information about the texture, bulk density, organic matter, salinity status, and sometimes iron contents of the soils in the region of interest. This information can be used as input into pedotransfer functions to obtain soil dielectric and thermal properties over the entire range of soil water contents. Combining these properties with simple models as shown by our research team[1,3,4,5,7,11,18] will provide immediate feedback on sensor performance for a large number of soil-mine-sensor combinations. This information can be used to have sensor experts instruct deminers how to deal with the expected soil conditions before they enter the mine field. One might also construct mine testing lanes to better train deminers for specific soil conditions.

During the *field operation phase* the information contained in soil databases or even in detailed national soil maps will be of limited to no value. The reason is that soil variability is so large that one can not rely on soil maps to predict soil conditions at a specific location. For example, in a study by the former Netherlands Soil Survey Institute it was found that average soil map purities ranged from 60-70% even for maps with scale 1:10,000[27]. This means that only 60-70% of the soil profiles sampled within a mapping unit exactly meet all the criteria of the classification used. Clearly, these odds are not acceptable for mine clearing operations. We conclude that therefore the deminer should have some capability to evaluate the soil conditions in his mine field as these change from place to place due to variability of soil and land use, and from day to day due to atmospheric conditions (precipitation, net radiation, wind speed, etc.).

We see two possible approaches to obtain *in-situ* information on soil conditions in mine fields. One approach is the use of soil sensors for determination of soil dielectric and thermal properties. The other approach is to develop tests that can be conducted with the land mine sensor itself. For example, with ground penetrating radar sensors it is common to bury a metal object at some depth to obtain information about attenuation of the radar signal in the soil. Using soil sensors will have the advantage that detailed information is obtained about soil properties. However, it may become a burden for the deminer to take these measurements and process the information. Therefore, the most promising approach seems to be to develop simple test objects that can be used with the sensor of interest for determination of current soil conditions in the mine field. A test object that immediately comes to mind is the use of land mine simulants similar to the ones expected in the mine field.

5. SUMMARY

The objectives of this contribution are (i) to make an inventory of readily available soil data bases world wide and (ii) to investigate how the information contained in these data bases can be used for derivation of soil dielectric and thermal properties.

We have found that a wealth of soil information is readily available worldwide. Although many areas still need to be surveyed, sufficient information appears available for most –if not all- regions of the world for an evaluation of the effect of prevailing soil conditions on land mine sensors. The soil evaluation is performed by using information on soil texture and bulk density in pedotransfer functions for the prediction of soil dielectric and thermal properties. This evaluation takes place during the *mobilization phase*. The results of this evaluation are used to better instruct deminers on how to deal with expected soil conditions in the mine field and to prepare an optimal suite of sensors.

During the *field operation phase* soil data bases are of little or no value since it is impossible to predict the exact soil conditions in a mine field. Therefore, we recommend that field tests are developed for *in-situ* evaluation of soil conditions in the mine field.

ACKNOWLEDGMENTS

The work at New Mexico Tech was funded by a grant from the Army Research Office (DAAD19-02-1-027).

REFERENCES

1. Borchers, B., J.M.H. Hendrickx, B.S. Das, and S.-H. Hong. 2000. Enhancing dielectric contrast between land mines and the soil environment by watering: modeling, design, and experimental results. Proc. of SPIE - The International Society for Optical Engineering (SPIE). Vol. 4038 (2):993-1000.
2. Hendrickx, J.M.H., B. Borchers, J. Woolslayer, L.W. Dekker, C. Ritsema, and S. Paton. 2001. Spatial Variability of Dielectric Properties in Field Soils. *In* Detection and Remediation Technologies for Mines and Minelike Targets VI, A.C. Dubey, J.F. Harvey, J.T. Broach, and V. George, editors, Proceedings of the SPIE 4394:398-408.
3. Hong, S.-H., T. Miller, H. Tobin, B. Borchers, J.M.H. Hendrickx, H. Lensen, P. Schwering, and B. Baertlein. 2001. Impact of Soil Water Content on Landmine Detection Using Radar and Thermal Infrared Sensors. *In* Detection and Remediation Technologies for Mines and Minelike Targets VI, A.C. Dubey, J.F. Harvey, J.T. Broach, and V. George, editors, Proceedings of the SPIE 4394:409-416.
4. Hong, S.-H., T.W. Miller, B. Borchers, J.M.H. Hendrickx, H.A. Lensen, P.B.W. Schwering, and S.P. van den Broek. 2002. Land mine detection in bare soils using thermal infrared sensors. *In* Detection and Remediation Technologies for Mines and Minelike Targets VII, J.T. Broach, R.S. Harmon, and G.J. Dobeck, editors, Proceedings of the SPIE 4742:43-50.
5. Miller, T.W., B. Borchers, J.M.H. Hendrickx, S.-H. Hong, H.A. Lensen, P.B.W. Schwering, and J.B. Rhebergen. 2002. Effect of soil moisture on land mine detection using ground penetrating radar. *In* Detection and Remediation Technologies for Mines and Minelike Targets VII, J.T. Broach, R.S. Harmon, and G.J. Dobeck, editors, Proceedings of the SPIE 4742:281-290.
6. Sendur, I.K. and Baertlein, B.A., "Numerical simulation of thermal signatures of buried mines over a diurnal cycle", in *Detection and Remediation Technologies for Mines and Minelike Targets*, A.C. Dubey, J.F. Harvey, J.T. Broach, and R.E. Dugan, eds., Proceedings of the SPIE Volume 4038, 156-167, SPIE, Orlando, 2000.
7. Simunek,S., J.M.H. Hendrickx, and B. Borchers. 2001. Modeling Transient Temperature Distributions Around Landmines in Homogeneous Bare Soils. *In* Detection and Remediation Technologies for Mines and Minelike Targets VI, A.C. Dubey, J.F. Harvey, J.T. Broach, and V. George, editors, Proceedings of the SPIE 4394:387-397.
8. Curtis, J.O. 2001. A durable laboratory apparatus for the measurement of soil dielectric properties. IEEE transactions on instrumentation and measurement 50(5): p. 1364-1369.
9. Topp, G.C., Davis, J.L., and Annan, A.P. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resources Research, 1980. 16(3): p. 574-582.
10. Curtis, J.O. 2001. Moisture effects on the dielectric properties of soils. IEEE transactions on geoscience and remote sensing 39(1): p. 125-128.
11. Miller, T.W. 2002. Radar detection of buried land mines in field soils. M.S. Thesis, Dept. of Earth and Environmental Science, New Mexico Tech, Socorro, NM.
12. Van Wijk, W.R., *Physics of plant environment*, 382 pp., John Wiley & Sons, New York, 1963.
13. Jury, W.A., W.R. Gardner, and W.H. Gardner. 1991. *Soil physics*. John Wiley and Sons, New York, U.S.A. pp. 328.
14. Dobson, M. C., F. T. Ulaby, M. T. Hallikainen, and M. A. El-Rayes. 1985. Microwave dielectric behavior of wet soil - Part II: Dielectric mixing models. IEEE Trans. Geosci. Remote Sens., GE 23:35-46.
15. Peplinski, N. R., F. T. Ulaby, and M. C. Dobson. 1995. Dielectric properties of soils in the 0.3-1.3GHz range. IEEE Trans. Geosci. Remote Sens., 33(3):803-807.
16. Bristow, K.L. 2002. Thermal conductivity. *In*: J.H. Dane and G. C. Topp (eds.), Methods of Soil Analysis. Part 4. Physical Methods. Soil Science Society of America Book Series #5, Madison, Wisconsin. pp. 1209-1226.
17. Kluitenberg, G.J. 2002. Heat capacity and specific heat. *In*: J.H. Dane and G. C. Topp (eds.), Methods of Soil Analysis. Part 4. Physical Methods. Soil Science Society of America Book Series #5, Madison, Wisconsin. pp. 1201-1208.

18. Van Dam, R.L, B. Borchers, J.M.H. Hendrickx, and S.-H. Hong. 2003. Soil effects on thermal signatures of buried nonmetallic land mines. This Volume.
19. Baumgardner, M.F. 2000 Soil databases. *In*: M.E. Sumner (Ed.), Handbook of soil science. CRC Press, Boca Raton. H1-H94.
20. Bregt, A.K. 1992. Processing of soil survey data. Doctoral Thesis. Wageningen Agricultural University, Wageningen, The Netherlands. 167 pp.
21. Buringh, P., G.L. Steur, and A.P.A. Vink. 1962. Some techniques and methods of soil survey in The Netherlands. Netherlands Journal of Agricultural Science 10:157-178.
22. Dent, D.L. 1986. Acid sulphate soils: a baseline for research and development. Publication 39, International Land Reclamation Institute, Wageningen, The Netherlands.
23. Hillel, D. 1998. *Environmental Soil Physics*, Academic Press, San Diego.
24. Van Engelen, V.W.P. 2000. SOTER: the World Soils and Terrain Database. *In*: M.E. Sumner (Ed.), Handbook of soil science. CRC Press, Boca Raton. H19-H28.
25. Das, Y., McFee, J.E., and Cross, G. 2002. Soil properties database for humanitarian demining: a proposed initiative", in 17th World Congress of Soil ScienceThe International Union of Soil Science, Bankok, Thailand.
26. Bouma, J. 1989. Using soil survey data for quantitative land evaluation. *In*: B.A. Stewart (Ed.), Advances in Soil Science, Vol. 9. Springer-Verlag, New York, NY. pp. 177-213.
27. Marsman, B.A. and J.J. de Gruijter. 1986. Quality of soil maps. A comparison of survey methods in a sandy area. Soil Survey Papers, No. 15. Netherlands Soil Survey Institute, Wageningen, The Netherlands.