PHYSICAL CHARACTERISTICS OF SOIL COLLECTED IN IRAQ AND AFGHANISTAN RELATED TO REMOTE SENSING

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ABSTRACT

Interrelationships among soil and environmental properties are typically nonlinear. They are affected by environmental conditions such as air temperature, soil temperature, wind speed, and solar radiation. Military engineering research programs are investing extensively in quantifying the effects of each soil property and environmental property on signal attenuation, magnetic susceptibility, reflectance, and ultimately on sensor performance.

In support of joint military interests, the U.S. Army Engineer Research and Development Center (ERDC) conducted soil testing and sampling in Iraq in 2008 and in Afghanistan in 2009. Data sets from each sampling site were spatially coincident and were geo-located using a global positioning system (GPS) to provide the fidelity required for multiple realizations of scene parameters.

This paper discusses some initial findings from analyses of the soil samples and data. Soil at the surface and in the underlying subsurface layers could be differentiated based on textural, spectral, chemical and electrical properties. Disturbed soil could be identified, as expected, with remote sensing technology. A regular arrangement of soil characteristics existed in the arid soil in both Iraq and Afghanistan.

A comprehensive database including these soil properties is on a secure server located at the U.S. Army Corps of Engineers Reachback Operations Center (UROC) at the ERDC. The soils data and all other properties are available for download through the UROC's secure web site and are incorporated into site-specific geospatial viewers. This access and retrieval portal allows for user-defined data selection for custom development and validation of technologies to model, measure, and mitigate the effects of geo-environmental factors that impact the detection capabilities of sensors.

1. INTRODUCTION

Geophysical techniques such as ground-penetrating radar (GPR), electromagnetic induction (EMI), resistive imaging (RI), and magnetic profiling (MP) are used in investigations of the surface and near-surface to counter munitions threats in forward areas. Sensors that employ these technologies are impacted by soil properties such as magnetic susceptibility, electrical conductivity, clay mineralogy, density, thermal and hydraulic properties, and *in situ* moisture content. Efforts to protect and sustain DOD assets in forward areas have been hampered by the lack of pertinent soil data and *in situ* properties.

In support of joint military interests, the U.S. Army Engineer Research and Development Center (ERDC) conducted soil testing and sampling in Iraq in 2008 and in Afghanistan in 2009. Sampling sites (Fig. 1) were chosen on the basis of military interest, geomorphic setting, surface-soil characteristics, and field-expedient conditions. Properties measured *in situ* included soil density and moisture, spectral characteristics, surface

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14. ABSTRACT

Interrelationships among soil and environmental properties are typically nonlinear. They are affected by environmental conditions such as air temperature, soil temperature, wind speed, and solar radiation. Military engineering research programs are investing extensively in quantifying the effects of each soil property and environmental property on signal attenuation, magnetic susceptibility, reflectance, and ultimately on sensor performance. In support of joint military interests, the U.S. Army Engineer Research and Development Center (ERDC) conducted soil testing and sampling in Iraq in 2008 and in Afghanistan in 2009. Data sets from each sampling site were spatially coincident and were geo-located using a global positioning system (GPS) to provide the fidelity required for multiple realizations of scene parameters. This paper discusses some initial findings from analyses of the soil samples and data. Soil at the surface and in the underlying subsurface layers could be differentiated based on textural, spectral, chemical and electrical properties. Disturbed soil could be identified, as expected, with remote sensing technology. A regular arrangement of soil characteristics existed in the arid soil in both Iraq and Afghanistan. A comprehensive database including these soil properties is on a secure server located at the U.S. Army Corps of Engineers Reachback Operations Center (UROC) at the ERDC. The soils data and all other properties are available for download through the UROC?s secure web site and are incorporated into site-specific geospatial viewers. This access and retrieval portal allows for user-defined data selection for custom development and validation of technologies to model, measure, and mitigate the effects of geo-environmental factors that impact the detection capabilities of sensors.

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roughness, electrical conductivity, and magnetic susceptibility.

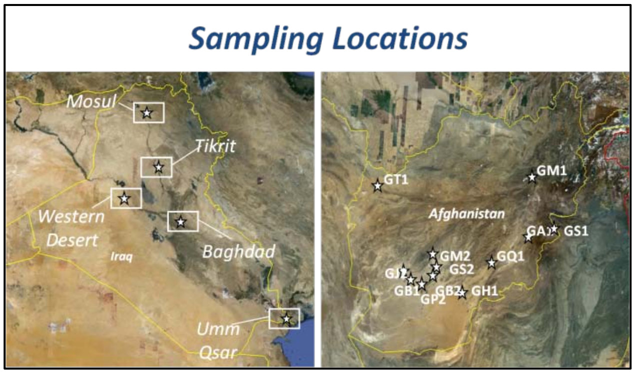

Fig. 1 Engineering soil properties from sites sampled in 2009 and 2010. Some sites were sampled by British Military personnel.

Soil samples were collected and shipped to the ERDC for further testing in the laboratory to quantify the mechanical properties of geo-typical theater soils. Test results were used for developing constitutive model fits of the soil properties for input into hybrid-elastic-plastic (HEP) modeling and ground-shock codes. Theater soil samples were used to determine particle size distribution, thermal and hydraulic properties, mineralogy, and chemistry.

2. STEPS IN FIELD DATA COLLECTION

Field data collection represents a large investment of time and talent, and may involve personal risk. Generally, a field team will collect soil samples for multiple purposes by multiple methods. The multicomponent data set resulting from a given field effort will include, but is not limited to, field geomorphic data; geo-environmental data such as air and soil temperature at multiple levels, wind speed, and solar radiation; surface spectra and other data from nondestructive methods; data from light detection and ranging (LiDAR) to quantify surface roughness; and positional data for sampling locations. All of these data are collected in addition to field-measured properties of soils and physical soil samples.

2.1. General Site Selection

Selection of sampling locations is a complex process that involves information about current military interest; knowledge of regional geology, geomorphology, and soils; expert judgment about soil conditions and disturbance at each site; and response to operational constraints.

Site selection for data gathering must represent a broad base of geologic conditions. However, limiting factors such as personal safety, availability and transport of field equipment, and time will always influence the success of the effort.

2.1.1. Topography and General Site Description

Once a site is selected for sampling, its geomorphic context is determined using imagery and existing documentation. All pertinent information on landforms and soil types (rock types if the area has minimal soil cover) in the sampling area and its surrounding region must be considered. This allows for the anticipation of complicating factors such as extremely coarse-grained soils, very thin soil cover, and huge local variability in soil type. A geographic information system (GIS), using available imagery, topographic, soil and geology maps, is initiated for future input of data points where sampling activities occur.

2.2. Sampling at the Selected Location

The least-disturbed area that is available should be chosen for sampling. A fresh, undisturbed soil column best represents soil mineralogy, density, moisture and chemical processes in the area at that time. Final decisions about exact sampling locations are a compromise between judgment about places that are geologically appropriate, physical access to the site and to excavation equipment, and judgments regarding personal safety.

Before excavation at a site, a 20-m by 20-m area is measured on the surface. Because of the need for co-located datasets, soil samples are collected within the upper 4 cm from the surface at mission-specified locations within the surface-sampling area. Ideally, a trench and other surface measurements (including some soil sampling, reflectance measurements, LiDAR scanning, EM, and magnetic susceptibility measurements) will be performed within this area. This description is for the ideal distribution of trench and surface sampling, and has always been the goal. The actual sampling effort was always limited by logistical complications in Iraq and Afghanistan.

2.2.1. Surface Sampling

Surface sampling includes both collecting surface data using nonintrusive technologies and taking physical samples of soil at the surface. The four corners of the measured 20-m by 20-m “surface grid” are surveyed and coordinates are recorded. Each sampling subset will have grid numbering designations so that the sampling location can be determined.

2.2.2. Trench sampling

Collection of physical soil samples includes vertical and horizontal sampling, plus geomorphic description and measurement of exposed trench walls. Soil samples are collected from trenches (Fig. 2) excavated by backhoe in step intervals to total depths of 2 m. Each trench is stepped down to allow safe access to the bottom. Prior to trenching, the site is described geologically and geomorphically, and photographed.

The sidewall of each trench is sampled down a vertical column that best represents the soil stratigraphy at that location. Soil is collected at 10-cm-depth increments by driving 3-in-diameter rings/cylinders using a density drive sampler. One end of each sampling cylinder is beveled to improve penetration into the soil. Samples collected in this method are used for field (in situ) measurements of water content, porosity, and soil density. This type of sample represents the so-called "undisturbed" soil, in that the original density, orientation, and texture are maintained as much as possible. One cylinder at each 10-cm depth is used for the in situ density and moisture measurements. Two additional cylinders are collected at 20-cm intervals for laboratory analysis of hydraulic, chemical, and thermal properties.

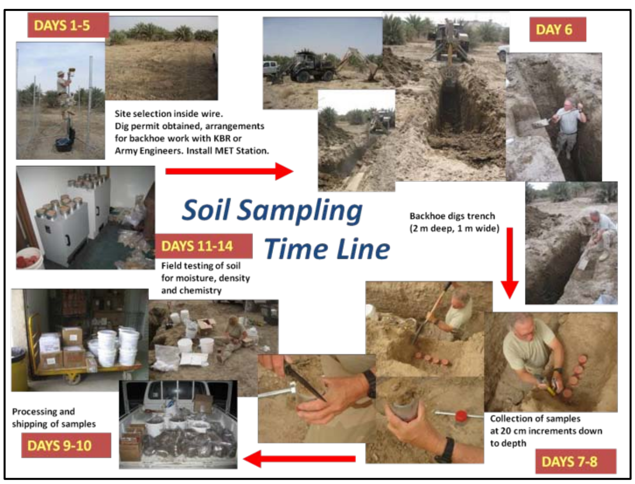

Fig. 2 Typical trench sampling activities.

Sampling with the drive cylinder is difficult and may not be possible in gravelly soils. If much resistance is met during sampling or if the cylinder is bent during the process, alternative methods must be used. The "steel-shot density test" (Freeman et al. 2008, 2010) used to determine determining in situ soil density prove to be suitable, as it is simple and requires few extra pieces of equipment. The procedure is a hybrid between the sand cone method (i.e., ASTM D 1556 - 07) and a simpler sand replacement test (ASTM D 4914 - 08). The method was used during construction of expedient airfields in theater and at surrogate sites in the United States.

2.2.3 Other In Situ Data Collection

Geo-environmental conditions such as soil moisture and temperature vary in response to daily and seasonal changes in solar radiation, precipitation, and wind speed. As soil moisture and temperature change, so do the electrical properties, surface roughness and spectral properties of the soil. A good "snapshot" in time of the soil conditions provides the basic information necessary to understand these relationships. Ideally, data should be collected for up to a year after field sampling to document seasonal changes.

2.3.1. Surface Spectral Measurements

The reflectance characteristics of a surface feature are quantified by measuring the amount of incident energy that is reflected. The spectral reflectance curve of soil (or measure of the diffuse reflectance properties of that material) in general shows much less variation in reflectance as a function of wavelength than other surface features (such as plants). Factors that can affect soil reflectance are mineralogy, moisture content, texture, surface roughness, and the amount of organic matter present in the soil.

Spectral measurements, such as those collected by a hand-held Analytical Spectral Devices, Inc. (ASD) Field Spec Pro full-range spectrometer (spectral range of 350 to 2500 nm) provide information such as surface reflectance and radiance/irradiance in dozens of narrow spectral bands in the visible to near infrared (VIS-NIR) portions of the electromagnetic spectrum (ASD, 1999).

The A2 Technologies, Inc. developed another portable field spectrometer (EXOSCAN) that uses Fourier Transform technology (spectral range of 2500 to 15,385 nm) to measure in the mid-infrared (MIR) electromagnetic spectrum. The combined use of both instruments is intended to provide broad sampling of the spectral characteristics of the soil over the VIS-NIR to MIR ranges of the electromagnetic spectrum.

2.3.2. Light Detection and Ranging (LiDAR)

A ground-based 3-D laser scanning system was used to collect high-resolution point data sets to depict surface roughness (disturbed soil areas), microtopography, and vegetation height. Detailed point clouds were collected, creating a 3-D representation of as many sites as possible to allow for dynamic landscape visualization, including any naturally inherent components or in-place objects. Using these data, targets of interest can be modeled to provide near real-time discrimination under contrasting surface conditions. Terrain models provide detailed background phenomenology and enable analysts to measure topographic variations within the area of interest.

2.3.3. Collection of Electromagnetic Data

At some field sites, the ERDC team conducted ground-conductivity surveys using a Geonics EM38-MK2 instrument. The EM38 is a portable device weighing about 3 kg and is carried by the operator with one hand such that it is positioned several centimeters above the ground surface.

Ground conductivity is affected by soil mineralogy, particularly the presence of magnetic minerals and salts. Soil grain size, water content, and density also impact conductivity. Certain geophysical and remote sensing instruments do not perform well in highly conductive soils. The electromagnetic signal they emit becomes scattered, or attenuates, and cannot penetrate the soil.

A portable magnetic susceptibility meter, the SM-30, developed by Z.H. Instruments, Inc., was used to gather in situ magnetic susceptibility information over the surface grids at each site.

Depending on the expertise of deployed ERDC personnel, additional geophysical testing, such as ground penetrating radar and seismic refraction, was conducted at some sites in Afghanistan.

2.3.4. Environmental Physical Properties Sensing System (EPPSS)

Background characterization at a study site requires more than a snapshot look at the soil conditions. The ERDC team uses an environmental sensing system designed to collect and record soil conditions over an extended period of time to gain an adequate understanding of fluctuating soil conditions in response to weather changes. An environmental physical properties sensing system (EPPSS) was installed at some sites close to the trench and surface-sampling area as part of a complete data-collection effort.

Types of environmental data that are obtained from a sensing system can include, but are not limited to, global and net solar radiation, wind speed, air temperature, soil temperature, and soil thermal flux (Peyman-Dove et al. 2007). Results of statistical analysis of the environmental data are among the many input variables used for realistic simulations. Combined with spectral reflectance and LiDAR, environmental data are critical to computational realizations of the air-soil interface and of the ground itself.

Each sensing system is designed to operate and record data at a sampling site for up to 1 year, providing a background of daily and seasonal variations in critical near-surface properties. In current operations, data acquired by the sensing systems are collected periodically by personnel on site and transferred by data-storage card to ERDC for analysis. The sensing systems in Afghanistan are equipped with an iridium phone that allows daily data transmissions to ERDC.

2.4. Soil Analyses

Any complete soil background characterization must have a clear snapshot of soil conditions and all variables possible at a given time. Important relationships among mineralogy, soil moisture retention, electrical properties, and soil surface response to precipitation, wind, and solar energy cannot be understood unless all are considered together. Gathered information must be spatially coincident.

2.4.1. In Situ Soil Analyses

Soil moisture changes rapidly after sampling, therefore, it is ideal for soil moisture and density to be calculated on site. The American Society for Testing and Materials standards (i.e., ASTM D 2216-05 and ASTM D 2937-04) are used to determine the in situ values. A small conventional soil oven is required to dry the soil and is part of the field equipment used by ERDC sampling teams.

Although the use of a small microwave oven would make soil drying easier in the field, it is not recommended because arid soils may contain gypsum, a mineral that has water molecules bound in crystal structure. Microwave drying can force some of the water molecules out of the gypsum (Turk and Bounini, 1984), and will result in significant errors in water content measurements. Oven temperature is kept at 30 degrees Celsius and soil is dried for 36 hours. This process preserves the bound water within the gypsum crystal lattice and targets the water between the grains in the soil matrix.

2.4.2. Laboratory Analyses

Soil collected at military field sites was sent to various laboratories for particle-size distribution, mechanical properties, thermal, hydraulic, electrical, and magnetic properties, as well as mineralogy and chemistry. Spectral data were re-analyzed in the ERDC lab on samples to verify field data measurements. These data support various research programs including blast-effects modeling, sensor performance modeling, and the development of appropriate surrogate test sites.

3. GENERAL FINDINGS

3.1. General Comments on Soil Properties

Engineering soil properties are outlined for sites in both Iraq and Afghanistan (Fig. 3 and 4). Soil was finer grained than expected in most places, with more silt and clay than sand-sized soil grains.

Five sites in different geologic settings were sampled in Iraq. Very little to no gravel was present at the surface at most locations. Most soil contained gypsum that had been reworked from existing soil layers. Gypsum was partially cemented in the soil samples, giving the soil a gravelly texture. However, when the soil was tested in the lab, the gypsum crystals broke apart, dissolved, or broke mechanically into clay-sized particles.

The soil in and around Baghdad was moist and contained large amounts of clay, making it very conductive. The water table was less than 2 m beneath the surface and was encountered in all trenches. Instruments such as ground penetrating radar (GPR) did not perform well in this wet, highly conductive environment.

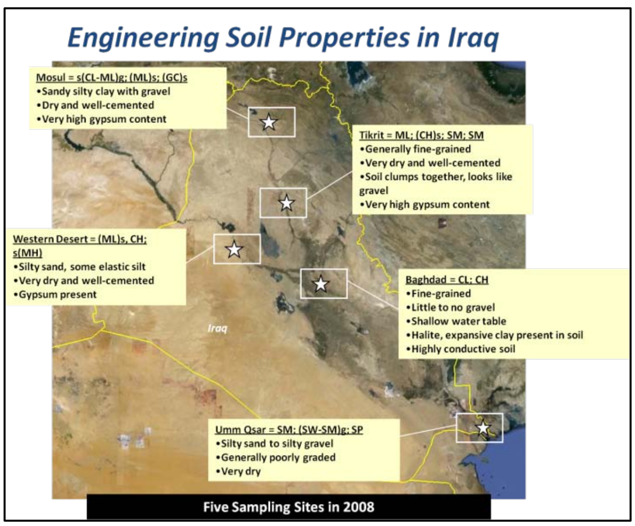

Fig. 3 Engineering soil properties from Iraq sites sampled in 2008. Soil predominantly silt and clay.

A total of twelve sites were sampled in Afghanistan. The ERDC team sampled seven of the sites, collecting soil and data and the UK Royal Engineers sampled the remaining five sites and collected soil samples only.

Soil in Afghanistan contained more gravel than the soil sampled in Iraq. Also, calcium carbonate was the dominant evaporite mineral found in the soil layers. Gypsum was found in significant amounts only in the Helmand Province.

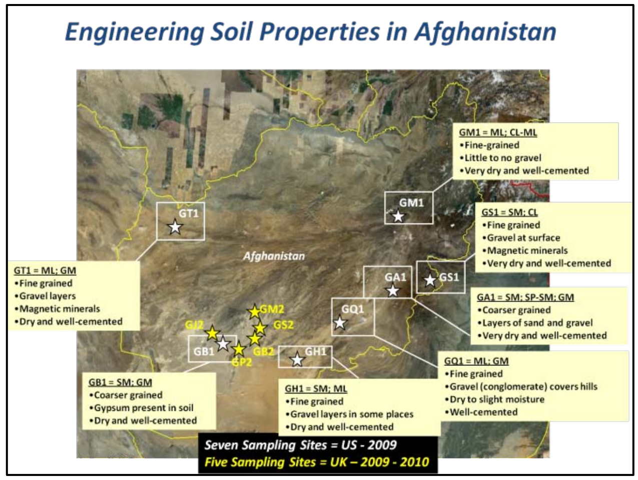

Fig. 4 Engineering soil properties from Afghan sites sampled in 2009 and 2010. Sites in yellow were sampled by British Military personnel.

One site in Afghanistan, GS1, had soil with magnetic minerals such as magnetite and chromite. Several types of sensors will be affected by magnetic minerals in the soil.

3.2. Complex Layering and Mineralogy

It is common to see zones of mineralization (soil horizons) in arid soil where concentrations of calcium carbonate or gypsum are deposited by evaporating groundwater. This soil will have a different density, moisture content, reflectance value, and thermal signature than the surface soil.

Soils in the shallow subsurface in both Iraq and Afghanistan were layered. Generally, there was a crust (duricrust) on the surface from a few millimeters to centimeters in thickness (Fig. 5). When disturbed, the crust broke apart into blocky pieces. Lichen was sometimes present in the duricrust layer. An unconsolidated layer of silty sand usually was present below the duricrust. This layer was not more than 50 cm in thickness and lacked evaporite minerals. Below the unconsolidated layer, the soil was cemented with either calcium carbonate or gypsum. White concretions of evaporite minerals were usually encountered in this layer. The evaporite minerals were once dissolved in the ground water and recrystalized in the soil as water evaporated from the soil. Exceptions to this were in areas where the water table was encountered within the first two meters of the surface, and the evaporite minerals were still in solution.

Fig. 5 Duricrust is common on the surface.

A good example of mineralized zones was at site GB1 (Fig. 6) in the Helmand Province. A gypsiferous zone was encountered at a depth of 40 cm. Gypsum crystals formed in porous spaces and on the lower surfaces of rocks. Soil in this zone was lighter colored, moister, and less dense than soil above and below the zone. Calcium carbonate was the more prevalent evaporite mineral just under the surface.

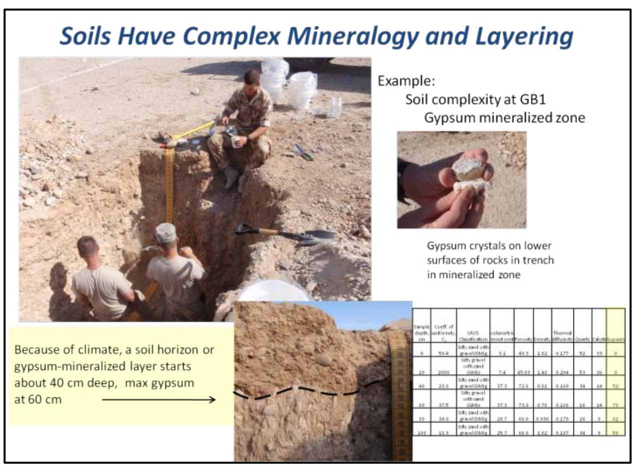

Fig. 6 Gypsiferous soil encountered in the trench at a depth of 40 cm.

Soil samples from the trench wall at GB1 were measured with the ASD VIS-NIR spectrometer in the laboratory at ERDC. Prior to testing, the samples were dried in a conventional oven. Therefore, reflectance values were measured on highly disturbed soil and in situ moisture, density, and porosity were all removed. The reflectance values in the VIS-NIR from the soil layers plots into three groups (Fig. 7). The data grouping with the highest reflectance is the gypsum rich layer from 40 cm to 100 cm. The transition layer that was at 30 cm in depth plots separately with less reflectance. The surface down to 20 cm also plots separately and has the lowest reflectance values. Mineralogy differences produce different reflectance values.

The lowest values in the VIS-NIR wavelength are at the surface where gypsum is absent. The zone with the highest reflectance is from 40 cm to 100 cm, the zone dominated by gypsum.

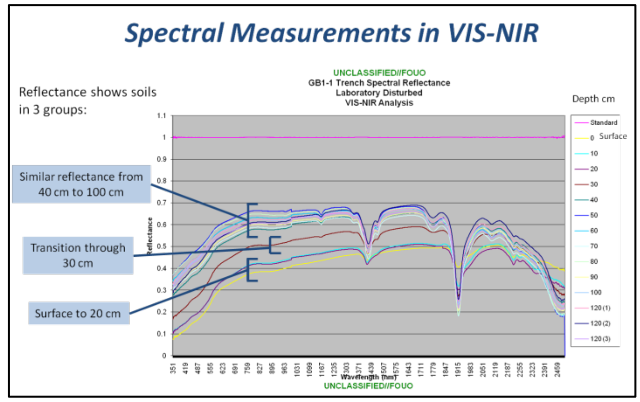

Fig. 7 Reflectance values from the trench at GB1. Layers plot in groups due to mineralogy.

3.3. The EPPSS and Surface Soil Moisture

Soil moisture and temperature vary in response to daily and seasonal changes in solar radiation, precipitation, and wind speed. The installation and placement of an environmental monitoring system within close proximity to an area of soil sampling is part of a complete data collection effort. Five Environmental Physical Properties Sensing Systems (EPPSS) were installed in Iraq and two were installed in Afghanistan.

Each EPPSS has the capability to monitor soil temperature and temperature flux as well as soil moisture down to a depth of 30 cm. There are two sets of soil parameter sensors, group numbered, with the goal of monitoring an undisturbed area and a disturbed area.

In undisturbed areas at many locations, the surface layer was duricrust. It was generally drier, and had a lower porosity and higher density than the soil in the next layer. When disturbed, the duricrust broke apart into blocky pieces and would eventually turn to a fine powder after repeated crushing.

An example of soil response to precipitation in an undisturbed and a disturbed area is seen in data from the EPPSS at GA1 in Afghanistan (Fig. 8). After a small rain event, the disturbed soil took up the moisture more easily than the undisturbed soil with the duricrust layer still intact.

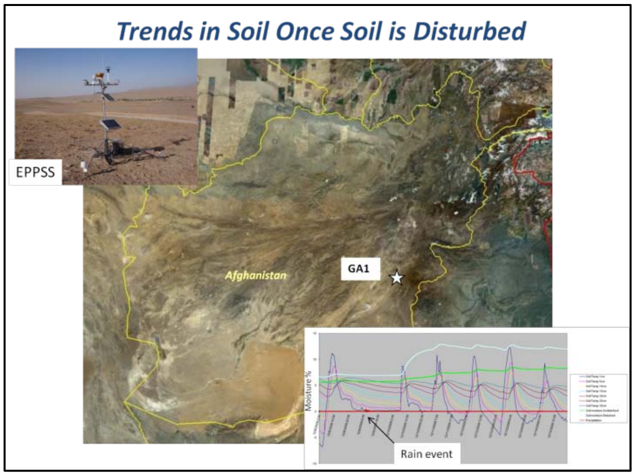

Fig. 8 Disturbed soil takes up moisture better (light blue line) than undisturbed soil (green line) after a rain event.

3.4. Reflectance Changes in Disturbed Soil

Undisturbed soil is expected to have different spectral properties than disturbed soil due to differences in mineralogy in the soil layers and increased moisture with depth. Measurements were taken with the EXOSCAN FTIR spectrometer at the field sampling site in Afghanistan on soil that was first undisturbed and then disturbed with a shovel and pick. Additional measurements were taken on the same sample after it was oven-dried in the ERDC lab. In the MIR, there were variations in reflectance, with the oven-dried sample having the highest reflectance values (Fig. 9).

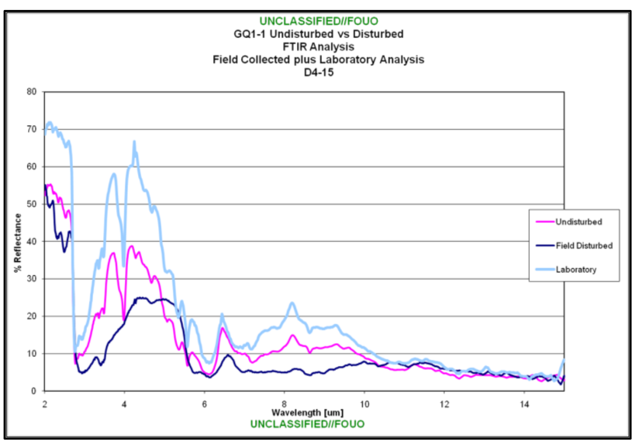

Fig. 2 Reflectance values in the MIR on soil that was field undisturbed, field disturbed and oven-dried.

4. DATABASE FOR DATA RETRIEVAL

All soil properties and data from other surface measurements are available through a secure online database on the web site of the U.S. Army Corps of Engineers Reachback Operations Center (UROC) at the ERDC. Datasets can be downloaded from the web site or displayed interactively through site-specific geospatial viewers allowing pan, zoom, measurement, and overlay functions with various spatial data layers that are geo-located with sampling locations. Integrating data into an accessible geospatial web portal provides wide dissemination for use as input to the development and validation of technologies to model, measure, and mitigate the effects of geo-environmental factors on the detection capabilities of sensors. The data are being used to define and identify meaningful surrogate test beds and to support hybrid-elastic-plastic (HEP) modeling for increased safety of ground vehicles. The database supports research, development, and modeling to improve the realism of munitions-effects calculations, and to improve detection of surface and subsurface targets across a wide range of geo-environmental conditions and complexities. The ERDC maintains a duplicate set of archived soil samples for additional research as needed.

5. CONCLUSIONS

In support of joint military interests, the ERDC conducted soil testing and sampling at five sites in Iraq in 2008 and twelve sites in Afghanistan in 2009 and 2010. Sampling sites were georeferenced spatially and represented a wide range of electrical and physical properties of soil from natural geo-environments in theater.

In general, soils from both Iraq and Afghanistan are finer grained than expected, with silt and clay more prevalent than sand. Mineralogy is extremely important, affecting reflectance values, moisture retention, density, porosity, and thus, electrical properties of the soil.

Although layering of the soil in the shallow subsurface is complex, it is often similar and even predictable at many locations. Most places with undisturbed soil in the arid to semi-arid environment in Iraq and Afghanistan have a duricrust layer on the surface. The duricrust is underlain by a loose, unconsolidated, windblown layer of soil with little to no evaporite minerals. Below the windblown layer, a mineralized layer with either calcium carbonate or gypsum is usually present. Reflectance values of each layer are distinctive and are related to mineralogy. When soil is disturbed and the duricrust is destroyed, reflectance and electrical properties on the surface change. Disturbed soil is able to absorb moisture more easily than undisturbed soil.

Data provided from this effort are essential input for developing and validating technologies to model, measure, and mitigate the effects of geo-environmental factors that impact the detection capabilities of sensors. The data are made available to the research community through a secure online database on the web site of the UROC at the ERDC.

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