Advances in Military Geosciences

Eric V. McDonald
Thomas Bullard
Editors

Military Geosciences and Desert Warfare

Past Lessons and Modern Challenges

Springer

Military Test Site Characterization and Training Future Officers—An Integrated Terrain Analysis Approach

Steven Fleming, Eric V. McDonald and Steven N. Bacon

Abstract U.S. military equipment has become more sensitive to environmental conditions than ever before, especially with increasing application of sophisticated microprocessors, wireless connectively, and sensors commonly employed on highly maneuverable armored vehicles. Increasing development of military technology requires considerably more comprehensive information about the extreme testing environment (i.e., natural environmental test sites) than was required nearly a half century ago. An all-encompassing research, development, and testing program for current and new designs of tracked and wheeled military vehicles, the primary means of transport for U.S. ground forces, depends on the use of an extensive network of vehicle mobility and durability (i.e., endurance) test courses located in a variety of temperate, tropical, desert, and cold region environments. Most of these test courses consist of unimproved, dirt or gravel roads, primarily developed on the native soil and landscape. Although several of these test courses have been in use for nearly 50 years, many of their geotechnical attributes have not been characterized. In support primarily of the Army's Test and Evaluation Command (ATEC) mission, the Department of Geography and Environmental Engineering (GEnE) from the United States Military Academy (USMA) at West Point and the Desert Research Institute (DRI) characterized numerous test courses at various geographic locations. Since 2007, multiple teams from West Point, primarily consisting of Cadets with supervising officers, have worked in collaboration with DRI to characterize geotechnical attributes of soils along test courses in desert, arctic, temperate and tropical landscapes. These data collection activities also support the Army in providing future officers with field training associated with sample collection and data

S. Fleming (✉)
Spatial Sciences Institute, Dornsife College of Letters, Arts, and Sciences,
University of Southern California, 3616 Trousdale Parkway,
AHF B55, Los Angeles, CA 90089, USA
e-mail: s.fleming@usc.edu

E. V. McDonald · S. N. Bacon
Division of Earth and Ecosystem Sciences, Desert Research Institute,
2215 Raggio Pkwy, Reno, NV 89512, USA
e-mail: Eric.Mcdonald@dri.edu

S. N. Bacon
e-mail: Steven.Bacon@dri.edu

E. V. McDonald, T. Bullard (eds.), *Military Geosciences and Desert Warfare*,
Advances in Military Geosciences, DOI 10.1007/978-1-4939-3429-4_18

management. The characterization activities focused on making geotechnical measurements, sampling soils, collecting imagery, generating map data, and developing geospatial databases. This effort also included the preparation of databases of in situ geotechnical properties along test courses at representative locations to a depth of ~0.3 m (1 ft) that included the measurements of: soil stiffness and modulus, penetration and shear resistance, bulk density, and particle size distribution. These new data sets will assist the Department of Defense (DoD) and the Department of the Army (DA) in maintaining a varied and detailed inventory of characterized soil-landform assemblages in different fundamental environments from various test sites throughout the U.S. and abroad. In addition, the data collected and the information compiled through these site studies will also benefit the DoD community that tests emerging technologies for the detection and defeat of Improvised Explosive Devices (IEDs), which require significant understanding of the natural variability of both physical and chemical soil attributes.

Keywords Terrain · Mobility · Operational testing · Soil · Tropic · Desert · Temperate

1 Introduction

A growing challenge facing development and testing of current and future military equipment (vehicles to electronics) is the requirement that equipment must work across all global military operating environments: deserts, tropics, temperate, and cold regions. Increased awareness of sensitivities to extreme environmental conditions is needed especially given the expanding dependencies of military weapon systems on microprocessors and sensors that are inherently more affected by climate and other factors (such as atmospheric aerosols, diurnal temperature fluctuations and frequent shock and vibration during transport and deployment) than are mechanical parts. Going forward, military test and evaluation strategies will require greater detail and understanding of the structure, function, and complex interrelationships of the combined landscape and ecosystem. The Department of Defense (DoD), specifically, the U.S. Army Test and Evaluation Command (ATEC), through the Yuma Proving Ground (YPG) is increasingly adapting current scientific knowledge of soils and landforms to improve Technical Operating Procedures (TOP) in developing and testing of military equipment and soldier systems (YPG 2012, YTC 2012). The incorporation of important soil and other detailed terrain information from selected sites across YPG (and other ATEC and foreign) test sites into current and future testing programs has been a major focus of on-going data collection since the early 1990s (ATEC 2014).

For over a decade, GEnE has supported YPG with test site evaluations, terrain characterizations, and soil and image data collection. Many of these evaluations

Table 1 Locations of test sites evaluated by USMA, ARO, and DRI

Test site or military installation[a]	Military operating environment	Integrated activity
Cold Regions Test Center (CRTC): Ft Greely, AK[ab]	Cold regions	Map, soil and terrestrial image data collection
Tropics Regions Test Center (TRTC): Panama[ac]	Tropic	Map, soil and terrestrial image data collection
Mocoron, Honduras[c]	Tropic	Site characterization
Yuma Test Center (DTC): Yuma Proving Ground[ad]	Desert	Map, soil and terrestrial image data collection
Aberdeen Proving Ground (APG), MD[a]	Temperate	Map, soil data collection
Southern Cayo in Western Belize	Tropic	Map, soil and terrestrial image data collection
Fort A.P. Hill (VA)[a]	Temperate	Map, soil and terrestrial image data collection
Afobaka Test Track, Suriname	Tropic	Map, soil and terrestrial image data collection
Camp Pendleton Marine Corps Base, CA[a]	Temperate	Map, soil and terrestrial image data collection

[a] Test site locations where data collected by USMA cadets
[b] Additional test site characterization: Harmon et al. 2008
[c] Additional test site characterization: King et al. 2009
[d] Additional test site characterization: King et al. 2004

also included the participation of DRI subject matter experts from DRI and Army Research Office (ARO) researchers, all working in collaboration with the USMA Cadets and their GEnE supervisors. Test site evaluations conducted since 1998 (summarized in Table 1) involved a range of activities across all major military operating environments. The objective of many of these activities, and part of the focus of this paper, was to integrate training of USMA Cadets in performing geotechnical site characterizations at a variety of test sites that include georeferenced and efficiently organized data, and for YPG (and ATEC) in support of their testing programs. Collected geotechnical data and site evaluations have become and remain critically important to supporting testing of military vehicles and technologies for the detection and defeat of enemy activity (including Improvised Explosive Devices—IEDs), as well as for vehicle endurance testing.

The focus of this paper is threefold: (1) to discuss the need for natural environmental testing using "lessons learned" from U.S. military activities in the tropics of Southeast Asia; (2) to describe the integrated training activities involving the field collection of geotechnical soil data by USMA Cadets; and (3) to evaluate some of the geotechnical soil data collected by Cadets from three diverse environmental settings representing temperate, desert, and tropic biomes.

2 The Need for Environmental Testing Research—A Tropical Climate Example

The history of conflict has documented the challenges for armies to conduct military operations in unfamiliar environments. This is recorded in detail and evidenced through the work of the United States and its coalition partners to successfully adapt operations to the desert climate and landscapes over the period of recent military operations in the Middle East and Southwest Asia from 2001 to 2014. A more striking (and some would argue, worrisome) example of a complex, "unaccustomed" environment, the heat, humidity, and dense biologic setting that characterize the tropical environment have proven a significant "thorn in the side" to U.S. fighting forces for much more than the past decade. History reinforces that the tropics have challenged the U.S. military for over half a century. The U.S. experience during World War II in the Southwest Pacific, in Southeast Asia during the Vietnam War, and, albeit limited, in Panama during Operation Just Cause (1989–1990) clearly demonstrated the hazards to personnel and equipment posed by the extreme tropical environment. From this, two clear lessons emerge: (1) equipment must be tested to assure it can stand up to and perform under a variety of variable and demanding environmental conditions; and (2) units must train in the harshest settings (in this example, tropical climates) to be prepared to accomplish full spectrum operations within these unique domains.

Roughly 15% of the earth's land mass is classified as tropical, primarily using parameters of climate and land cover; however, 75% of all international and internal conflicts since 1960 have been in countries whose borders are totally or partially within the wet, tropical environment (King et al. 2009). Researchers examining past conflicts to better understand the security threats of the future have reached the conclusion that the countries lying within the tropics are the most likely locations for future conflicts (King et al. 2009). Further, studies examining the sources of insecurity posed by global environmental degradation regard the tropical regions of Africa, Asia, and the Americas as the most likely locations of instability in the future. Recent operations in Somalia, Rwanda, Haiti, Panama, East Timor, and elsewhere have only reinforced the need to be prepared for tropical conditions. Clearly, by any metric, the DoD must be prepared to deploy and operate successfully in the tropical environment.

2.1 *A History of Testing in Tropical Environments*

The U.S. and several of its military allies have a long history of operating testing and/or training facilities in the hot, humid tropics (e.g., the United Kingdom in Belize, France in French Guiana, and Australia in its state of Queensland). Guided by requirements in numerous performance military standards (MIL STDs), environmental conditions and their effects are to be given realistic consideration in the research, development, test, and evaluation (RDT&E) process for equipment used in combat by the U.S. military. As a result, testing and evaluation in a variety of environments of equipment and systems, as well as human performance, is well established. The mission of testing in extreme natural environments for the Army resides with the ATEC and is vested with YPG. Presently, this mission is accomplished at desert, cold region (arctic), sub-tropical and tropical test facilities in the United States and abroad. Principal U.S. Army test centers, all operating under the command of the YPG, include: Cold Regions Test Center (CRTC) at Fort Greeley, Alaska (CRTC 2014); desert conditions at the Yuma Test Center (YTC), Yuma Proving Ground, Arizona; and sub-tropical conditions at Schofield Barracks, Hawai'i and routinely in Panama through the Tropics Regions Test Center (TRTC). Most recently, testing through TRTC has been expanded to include testing of heavy tactical vehicles in Suriname and Belize. Testing in temperate and sub-tropical environments is primarily the responsibility of the Aberdeen Test Center (ATC) located at the Aberdeen Proving Ground (APG), Maryland.

Testing of equipment and systems, together with human performance evaluation under tropical conditions, took place in the Canal Zone area of the Republic of Panama as far back as WWI. This mission evolved into the Tropic Test Center (TTC) in 1962, which supported specific Army test functions in response to evolving military needs through the 1990s. In parallel, the Army's Jungle Operations Training Center (JOTC) was operated at Fort Sherman in Panama, conducting individual soldier and collective unit training for the Army and land forces from all services within the DoD. The tremendous value of the JOTC experience- preparing units for missions in the tropics and to develop troop leading skills- was well respected throughout the Army; however, under the terms of the Carter-Torrijos Treaty of 1977, the U.S. military mission in Panama was required to relocate from the country by December 31, 1999.

In 1998, at the request of YPG, the Army Research Laboratory's Army Research Office convened an expert panel to undertake a study to identify areas across the globe that could replace the tropical test environment that was being lost as a result of the Army's departure from Panama. The initial product (first phase) of the study panel examined the DoD (Army) tropical test mission to define the conditions that best provide the environmental challenges needed for tropical testing in the 21st century (King et al. 2009). This study defined the climatic, physical, and biological characteristics of the "ideal tropical test environment" and identified regions of the world that best provided the combined parameters for such an ideal location. Worldwide, 16 areas were identified as suitable localities for DoD tropical testing (Fig. 1). The first group of six geographic areas, ordered in terms of their relative proximity to the continental U.S., included: northern Honduras, the Isthmus of Panama, French Guiana/coastal northeastern Brazil (including Suriname), the southwestern New Guinea lowlands, low-moderate altitude areas of the East Indies in east-central Java and southeastern Borneo, and the Isthmus of Kra in Malaysia. The premier localities in this group for tropical testing were the Isthmus of Panama and the Isthmus of Kra because both areas offer a spectrum of tropical conditions and environments within a compact geographic area. A second group of 10 loca-

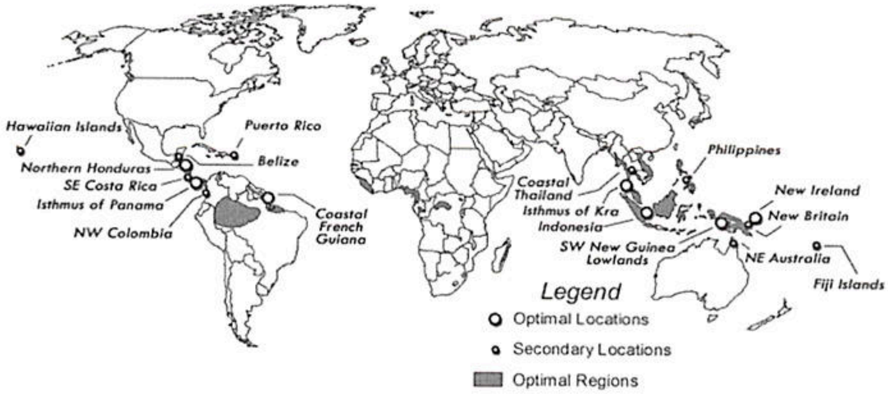


Fig. 1 Optimal locations for developmental and operational tropical testing of military equipment, vehicles, and weapon systems. (from King et al. 2009)

tions was identified that exhibited the general physiographic and biotic character, but failed to provide one or more of the critical elements considered requisite of the ideal tropical environment for DoD testing. This group consisted of coastal Belize, Puerto Rico, southeastern Costa Rica, northwestern Colombia, portions of the Hawai'ian Islands and the Fiji Islands, the Philippines, New Britain-New Ireland, the coastal region of northern Queensland in Australia, and the Bangkok area of coastal Thailand.

2.2 *Developing a New Suite of Tropical Test Sites*

The second phase of the ARO-led study followed on from the conclusion of King et al. (2009) that no ideal tropical test location existed in the U.S. or in U.S. controlled properties, therefore, a suite of sites should be developed to better support a broad range of environmental requirements for tropical testing and training. The primary product of the second set of tropical testing studies (King et al. 2009) was a geographic characterization model which subsequently was used to evaluate the suitability of candidate sites to the ideal conditions for tropical testing. This model allowed candidate sites to be examined and rated against the critical and important environmental criteria applicable for each type of test to be conducted.

As of 2012, DoD is actively engaged in tropical testing; now employing a suite of sites that has evolved from the results and recommendations of the ARO-led studies conducted from 1999 to 2007. Sites include locations in Hawai'i and capability for selected test studies in Panama, Honduras, Suriname, and, most recently, Belize. The requisite characteristics of the ideal environment for a tropical test facility are derived from complex interrelationships among the key factors of climate, terrain, and vegetation. Climate is the defining characteristic of a tropical region, whereas physiographic and geologic factors are closely associated, and the biologic manifestations (land cover/vegetation type) are a direct function of the combination of climate, physiography, and geology within a given region. Climatic criteria for the humid tropics are defined in Army Regulation, AR 70-38 (Department of the Army 1979), which broadly classifies world climates into four "basic climatic design types." Each of these design types is characterized by one or more daily weather cycles. Two daily cycles in the 'basic climatic type' represent the humid tropics.

According to AR 70-38, the ideal setting for a tropical test facility would lie in a hot and humid tropical climate regime to provide extremes of high relative humidity (RH) in a very high rainfall and near-constant high temperature environment. As such, the area encompassing the site should have annual precipitation in excess of 2000 mm, monthly-averaged minimum temperature and RH in excess of 18–20 °C and 60 %, respectively, and mean monthly temperatures and RH of at least 25 °C and 75 %, respectively. Average rainfall would not fall below 100 mm in any single month, nor exceed 6000 mm per year. These precipitation requirements address a desire for minimal seasonal variability and no impact on vegetation growth patterns (i.e., a preference for no absolute dry season). Regions experiencing tropical cyclone (hurricane or typhoon) activity should be avoided, unless all other physical factors indicate the site to be an optimal location. Ideally, a relatively compact area would exhibit variable conditions of climate (e.g., frequency/distribution of precipitation and temperature) across the spatial domain encompassing a landscape varying from coastal lowlands to steep mountainous relief.

The requirements defined in the ideal test environment are best met by an area of sufficient size to contain the test mission, possessing significant variations in slope and relief across the site, with surface streams sufficiently large to support a variety of tests, surrounding land use that is compatible with the testing mission, and the absence of cultural/historical resources or conservation pressures that could infringe on testing. The area should not be a high-risk zone in terms of frequency of natural hazards (e.g. tropical storms, volcanic activity, earthquakes, landslides, flooding, etc.). Also, it should not be affected by significant adverse anthropogenic activities (e.g. high adjacent population density, upstream pollution from urban, industrial, and/or farming activities). Soils need not be a specific type, but must be of sufficient thickness and health to support a diverse suite of lush tropical vegetation and offer significant challenges to the mobility of troops and vehicles.

Given the specific climatic, topographic and geographic constraints listed above, the major biological considerations for a tropical testing site are specific tropical vegetation characteristics, soils unique to tropical landscapes, and the presence of a diverse community of tropical above- and below-ground organisms. Today, as in the past, military interest in tropical vegetation is based on the forest structure and distribution in both horizontal and vertical dimensions as challenges to vision, mobility, communication, and performance of personnel and equipment. For other organisms, especially microbes, concerns focus primarily on sufficient density to produce high rates of the metabolic processes and by-products that foul physical material and interfere with equipment and systems. According to the model developed by King et al. (2009), the ideal tropical environment has been defined by 14 variables related to climate, physical setting, and biologic conditions. The regional and site specific tropical environment studies conducted by King et al. (2009) and the desert and cold regions studies undertaken by King et al. (2004) and Harmon et al. (2008), respectively, have greatly advanced the ability of the DoD to understand the complexities of different extreme environments and, therefore, how best to test in them (King et al. 2009).

3 USMA Cadet Data Collection, Management Methodology, and Procedures

Lessons learned from the history of incorporating environmental considerations into test strategies indicate the current and future importance for a global-based approach in testing and evaluation. One of the issues confronted in conducting test site evaluations (Table 1) was lack of geotechnical terrain and soil data that would provide both local data for test operations, as well as a means to compare geotechnical data among major test sites. The need for comparative geotechnical data inspired DRI and YPG to develop a research project where USMA Cadets would use field collection of geotechnical data as a field training exercise that would support students in the GEnE program of study and provide YPG and ATEC with important test site information (Fleming et al. 2009a, Fleming et al 2009b).

A principal component of USMA and DRI efforts to provide geotechnical soil data to the U.S. Army is the training of Cadets in procedures in the collection and analysis of field data. Training activities included: (1) field identification and properties of soil and terrain features; (2) learning the operation of field equipment; (3) learning data preparation and sampling methodologies, including proper documentation to record field data; and (4) developing leadership skills among field team members in formulating a daily work plan for collection of data. Collection of geotechnical data primarily occurred over a three week operational period. Cadets were also required to efficiently organize and geo-reference geotechnical engineering (soil characterization) data and imagery data into a final report organized for efficient retrieval and future examination, analysis and test community use. Military installations selected for Cadet field activities included test and training areas (e.g., Fort Greely, Yuma Proving Ground, Camp Pendleton, Aberdeen Proving Ground, and in Panama) that are critically important to supporting testing of military vehicles and technologies for the detection and defeat of enemy activity (e.g., IEDs).

Specific information collected by the USMA Cadets at each test site included: (1) exact coordinate locations; (2) soil stiffness and modulus; (3) soil moisture and density; (4) soil penetration and shear resistance; (5) two physical soil samples (one at 0–6 in. (0–15 cm), and another at 6–12 in. (15–30 cm) deep); and (6) terrestrial imagery (see Tables 2 and 3 and the discussion that follows).

Table 2 Sample data collection sheet used during field data collection

Site no.	Proposed location		Actual location		Elevation (m)	Date of test	Start time	End time	Humboldt (0–6")		Humboldt (6–12")		Troxler						Samples collected	Comment
	Northing	Easting	Northing	Easting					Y (Mpa)	S (MN/m)	Y (Mpa)	S (MN/m)	Depth (")	DD (PCF)	WD (PCF)	WD (PCF)	M	%M (%)		
1																				
2																				
3																				
4																				
5																				
6																				
7																				
8																				

Table 3 Types of geotechnical data collected and methods or equipment used

Measurement or data collected	Equipment	Notes	Reference
Coordinate data	Trimble Nomad and Trimble GeoXT, Garmin GPSMap60Csx, Garmin Rino520HCx	GPS used to locate selected sites	Trimble 2009a; Trimble 2009b; Garmin 2007a; Garmin 2007b
		Data collected at each sample site	
		Time of collection, PDOP, weather conditions, trail/road classification	
Soil stiffness and modulus	H-4140 Humboldt GeoGauge	3–5 measurements at ~ 2 m separation parallel to direction of trail or road	Humboldt 2009a
		Measurements at surface, 6 in.	
		Loose surface material (gravel, litter, vegetation) removed from surface	
		Stiffness in MN/m	
		Young's modulus Mpa	
Moisture content and bulk density	Troxler Roadmaster nuclear density gauge	Readings at 0, 2, 4, 6, 8, 10, 12"	Troxler 2009; Humboldt 2009b
		Not used at all sites	
Soil penetration and shear resistance	Rimik digital static cone penetrometer (CP40)	Surfaced only	Rimik 2009
		Depth > 10	
		Refusals noted	
		10 measurements per site	
Physical soil samples	Shovel	Bulk soil samples: 0–6", 6–12"	
		Sampled from 1 Geogauge excavation	
ArcGIS geospatial database	ESRI's ArcMap	Maps produced showing sample locations	ESRI 2012; Li 1997
Terrestrial image collection	iPIX® system	Provides interactive 360° field of view	Minds-Eye-View 2009

3.1 Collection of Geotechnical Data

3.1.1 Site Selection

Collection sites were selected by DRI scientists to focus on soil and landform assemblages that provide the best analogs to terrain attributes present in current places of strategic interest to the U.S. military (e.g., Iraq, Afghanistan, Iran, North Korea, etc.). Locations were selected using existing map data (e.g. Bacon et al. 2008) when available and supplemented with field reconnaissance of each sample area. A complete list of sample sites with location and general landform-type attribute data were provided to the Cadets prior to the start of each project.

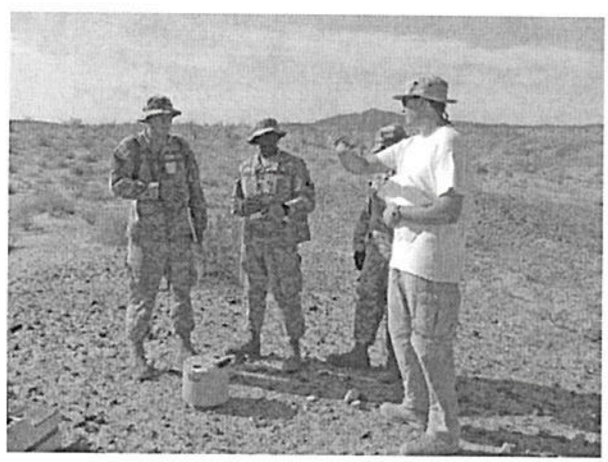
3.1.2 Coordinate Data

Coordinate data were collected at each sample site using Global Positioning System (GPS) technology with a Trimble Nomad (Trimble 2009a), Garmin GPSMap60Csx, or Garmin Rino520HCx receivers (Garmin 2007). Attribute data were also annotated on field collection sheets, including time of collection, PDOP (position dilution of precision), weather conditions, and trail classification and/or test course. When available, receiver accuracy was evaluated twice per day by comparing a point collection (as detailed above) to local survey control points. The commercial mapping software package from ESRI (e.g., ArcMap) was then used to create point shapefiles for each of the individual sites to be plotted on maps.

3.1.3 Soil Stiffness and Modulus

The H-4140 Humboldt GeoGauge (Humboldt Manufacturing Company 2009a) was used to record the stiffness and modulus at each site (Fig. 2). The GeoGauge measures the lift stiffness and soil modulus (i.e., elasticity) which is the ability of a soil to maintain its structural integrity under a given amount of applied force. At each sample location, two GeoGauge measurements were made at three different places, spaced about 2 m apart with one reading taken at the surface and a second reading at 15 cm below the surface (after hand-excavation). Loose organic litter (leaves, twigs, branches, etc) were removed from the top of the soil before measurements were taken. Soil strength (in terms of stiffness) was recorded in MN/m and Young's Modulus was recorded in MPa.

Fig. 2 West Point cadets and a DRI researcher prepares to record data with the Humboldt GeoGauge in Yuma, AZ



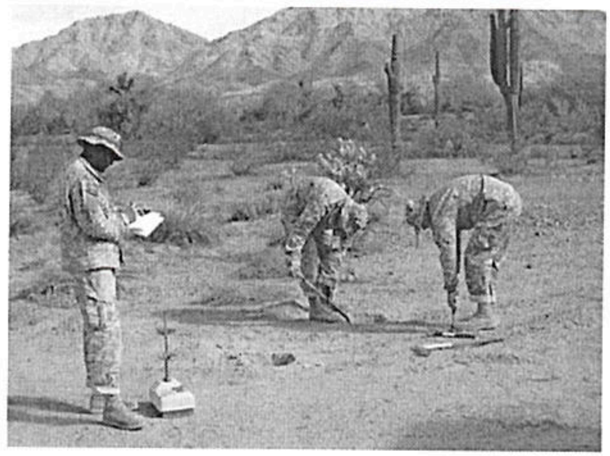


Fig. 3 Cadets collect data with a Nuclear Density Gauge in Yuma, AZ

3.1.4 Density and Moisture Content

In addition to soil stiffness and modulus, measurements of soil density and moisture content were also collected using a HS-50001EZ nuclear density gauge (Fig. 3; Humboldt Manufacturing Company 2009b). Specifically, the gauge produces readings for wet density, dry density, moisture content, percent of moisture, percent of compaction of a known Proctor or Marshall curve, void ratio and air voids. The instrument emits radiation from Cesium 137 within an external probe and the response by the soil target area is then directed back towards onboard sensors. Essentially, the strength of radiation returning back to the instrument sensors through the soil is proportional to the soil moisture content of the target area. Field measurements were taken at 12, 10, 8, 6, 4 and 2 in. deep by inserting the gauge's probe into a 12 in. deep hole in the ground created by Cadets. Surface measurements were also recorded. Five different sets of measurements were taken at each depth interval at each site that include: dry density (in pounds per cubic foot, PCF), wet density (PCF), water content by weight (lb water/lb soil), and percent moisture content (%).

3.1.5 Soil Penetration and Shear Resistance

Soil penetration and shear resistance were collected using a Rimik CP4011 cone penetrometer (Fig. 4; Rimik 2009) at TRTC and YPG. Essentially, the collection tool is used to analyze soil penetration resistance or bearing capacity. The cone is inserted into the ground by the operator applying a continuous downward force until the cone cannot penetrate any deeper. Penetration (in cm) was measured by applying steady pressure to the penetrometer and analyzing the depth of soil penetration by the cone. In addition, shear resistance (in kPA) was computed by the cone penetrometer system for each measurement. A total of ten measurements were taken at each site and stored in the penetrometer. The data was later extracted from

Fig. 4 Cadets collect soil data in Panama using the Cone Penetrometer

the penetrometer as part of the data post-processing procedures. The data from the penetrometer was identified and distinguished by site using the data/time stamps stored onboard the device. All data values were recorded if the instrument achieved a penetration depth of 10 cm or greater; otherwise, a re-test was conducted. After a re-test, the data was recorded if the minimum penetration was reached (10 cm) or "refusal" if the minimum depth was not obtained. For recorded data, the instrument displays a graph showing soil resistance by depth. In desert terrain, some of the sites had rocky or heavily compacted soil and resulted in a large number of readings not achieving the minimum penetration. Penetration resistance was also measured at APG, but with a different type of instrument, which consisted of a Humboldt HS-4210 digital static cone penetrometer (Humboldt Manufacturing Company 2009c).

3.1.6 Physical Soil Samples

Two separate bulk soil samples were taken from each site for laboratory analysis, primarily for particle-size distribution determination (i.e. texture) and soluble salts in desert terrain or iron oxides in tropical terrain and cold regions. One sample represented the soil from the surface to a depth of 0–15 cm (0–6 in.) (Fig. 5). The second sample represented the soil from a depth of 15–30 cm (6–12 in.).

3.1.7 Terrestrial Image Collection

The collection of terrestrial imagery was conducted with the iPIX® system (Minds-Eye-View Inc 2009) in order to provide interactive visual references of the sample locations. A Nikon CoolPIX 8700 or CoolPIX 6100 hand-held camera was used to collect the imagery (Fig. 6). The camera was equipped with a specialized fisheye lens which captured a 185° field of view (FOV) at the focal point. In addition, a cus-

Fig. 5 Cadets conduct a soil sample collection in a low area along a trail network in Alaska

Fig. 6 Cadets collect iPIX ® imagery in Alaska

tom-designed, tripod-mounted bracket held the camera in place which enabled two pictures to be taken from opposite. The result from this image collection method was two 185° FOV photos from the same focal point, pointed in the exact opposite directions. Before collection of imagery, the camera was adjusted to account for the fisheye lens attachment as well as the variability in lighting due to rotation of the camera during collection of image pairs. A north-facing orientation marker was placed on the ground in each scene in order to provide a directional reference within the imagery when post-processing. The two photos collected were then integrated ("stitched" together) using specialized software, producing a 360° interactive iPIX product. From this, a user is able to explore the entire 360° area captured in the photograph from the viewpoint of the camera, giving a complete all around view from where the iPIX system was located.

The geospatially-reference field data collected by the Cadets were then cataloged and entered into an ArcGIS geospatial database (ESRI 2012; Li 1997) for future analysis by the academic community and test/evaluation command. High spatial resolution satellite imagery was also used in generating the mapping products (DigitalGlobe 2004; Emap International 2002; Geoeye IKONOS 2009). Current GIS data standards (e.g., DIGEST) were used in the generation of these products to insure that the data was sharable with other DoD geodatabases (Chan 1999). This database is now accessible both on external hard drives, as well as from a secure, on-line portal for those conducting future research and testing on current and future landscapes of interest to DoD.

4 Examples of Geotechnical Data Collected from Tropical, Temperate, and Desert Test Sites

Geotechnical data collected by the USMA Cadets provides a means to compare soil properties illustrating differences between among the three very diverse test site settings represented at APG, YPG, and TRTC. The data collected from these sites reflect a range of soil conditions from engineered to disturbed and undisturbed native soils within temperate (APG), desert (YPG) and tropical (TRTC) environments (TRTC 2012). These three sites are selected for discussion because they have the most complete data that was collected by the Cadets, and when taken together, these sites illustrate important differences in geotechnical and soil properties between tropical test sites and the temperate and desert test sites in the U.S. where the majority of testing of military equipment occurs.

The geotechnical data for APG was collected from three principal vehicle test courses each composed of an improved, hard packed, road surface consisting of a layer of an engineered mix of imported soil consisting mostly of moderately-graded (moderately-sorted) silty sand with gravel from distant river burrow sources and lesser proportion of road surfaces composed of a mix of the important granular soil with fine-grained native soil. The APG test road conditions are basically an improved dirt road surface designed and maintained to minimize variation in surface characteristics and geotechnical properties over time related to frequent use. Geotechnical data from YPG was collected from a wide range of dirt and gravel roads used for testing vehicle durability, counter-IED technology, and transportation. Most of the measured sites are roads graded ("bladed") into the native alluvial gravelly soil and with minimal efforts to improve or maintain. The geotechnical data collected from the TRTC locations in Panama included a variety of dirt roads, footpaths, and firing ranges used for testing a wide range of military equipment. Most of the measured sites are either roadways or cleared surfaces graded into the native soil with minimal efforts to improve or maintain. Footpaths were largely developed based on frequent use (McDonald et al. 2006).

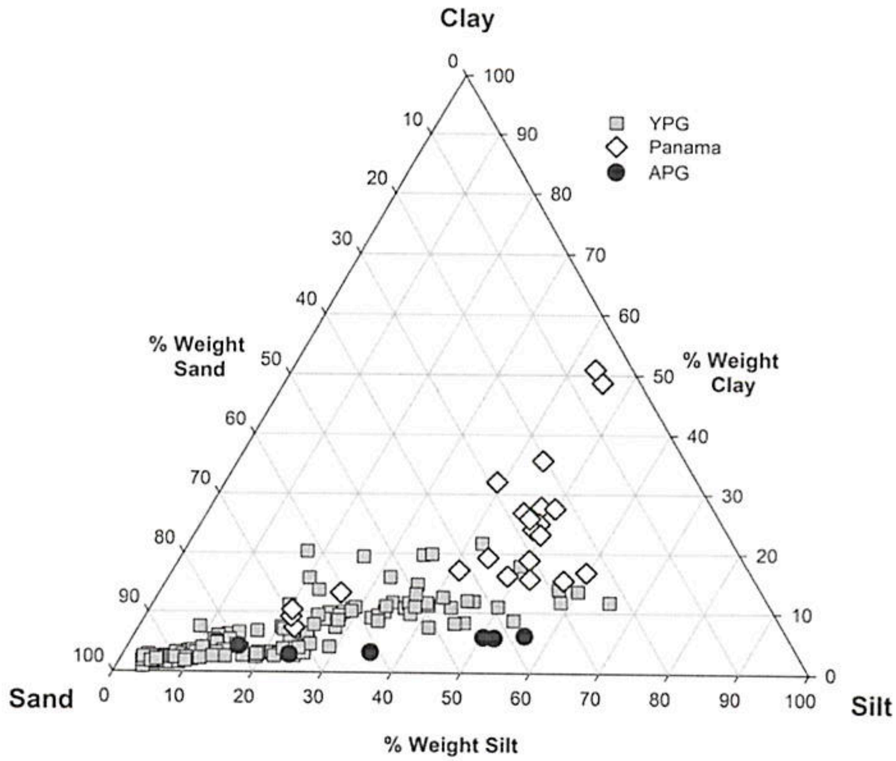


Fig. 7 Ternary diagram showing ratio of sand, silt, and clay content for soil samples collected from *APG, YPG*, and *TRTC*. Particle size measured using standard laser light scattering techniques. (ASTM 2000)

4.1 Soil Texture Results

Comparison of soil texture data illustrates how each test setting is different (Figs. 7, 8). Soils from the TRTC generally contain more silt and clay and less gravel relative to the soils at both YPG and APG. Soils at the TRTC are formed in strongly weathered volcanic rocks under high precipitation and high temperate, conditions that typically yield fine-textured soils. By comparison, soils at YPG are generally formed in poorly weathered gravel- to cobble-rich alluvium derived from igneous and metamorphic rocks under low precipitation and high temperature climatic conditions. Much of the silt and clay in the soils at YPG is from the long-term accumulation of desert dust that infiltrates into the shallow subsoil (McDonald and Caldwell 2005; Caldwell et al. 2008). Only a few of the samples from APG could be analyzed because of the hard consistency (soil strength) of the road surface. Clay content is low at APG, with variation largely in the sand, silt, and gravel content because of the gravelly sand barrow source. Native soils around the APG test roads are

s.fleming@usc.edu

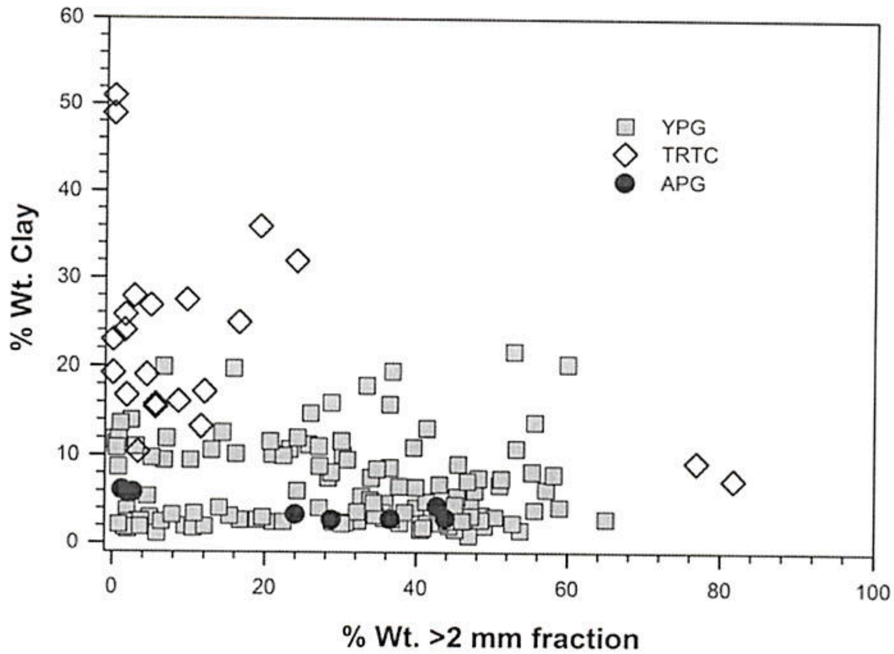


Fig. 8 Comparison between % weight gravel (>2 mm size fraction) and % weight clay for *APG*, *TRTC*, and *YPG*

primarily fine-textured, alluvial and estuarine deposits associated with the coastal plain that fringes Chesapeake Bay.

4.2 *GeoGuage Results*

GeoGuage measurements of Young's modulus and stiffness vary considerably among the three sites (Fig. 9). Generally, Young's modulus is a measure of a soils resistance to deform due to shear stress (i.e. soil strength) and stiffness is a measure of the resistance to bending (i.e. load capacity). The hard-packed, engineered soil surfaces of the test courses at APG have the highest mean value for Young's modulus relative to either TRTC or YPG due to compacted soils. In contrast, the mean value for stiffness at APG relative to either TRTC or YPG is similar (within uncertainty) and much lower, respectively. This is likely due to the roadbed at APG composed of relatively uniform and fine-grained soil that was not dry at the time of testing similar to TRTC, albeit with greater sand and lower moisture contents. By comparison, the soils (roads, firing ranges, and footpaths) at TRTC have low values of Young's modulus and stiffness reflecting the low resistance to deformation typical of the largely moist and gravel-poor character of clay-rich tropical soils. The

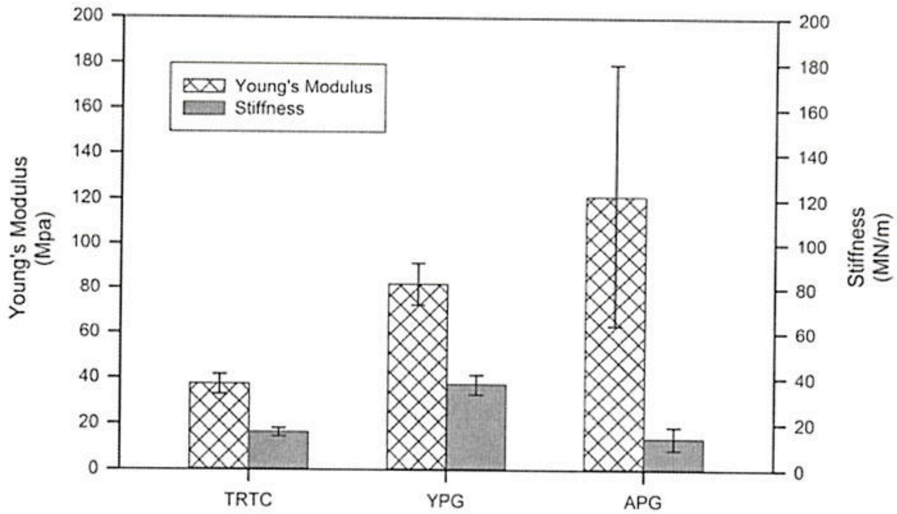


Fig. 9 Bar chart showing mean values (*top* of bar) for Young's modulus and soil stiffness as measured using a Geogauge. Vertical error bars for 1 σ standard deviation

values for Young's modulus and stiffness soils at YPG lie between the values for TRTC and APG largely due to the typical character of desert soils formed in weakly consolidated alluvium that consist mostly of gravel and sand mixtures with high pore (void) space. In addition, the dry and coarse-grained nature of the desert soils with subrounded particle shapes at YPG also inhibits soil compaction, even when subjected to similar vehicle traffic impacts to what occurs at APG.

4.3 Cone Penetrometer

Results from cone penetrometer measurements reflect large variations in soil strength similar to the trends in the GeoGauge data (Fig. 10). Penetration resistance was highest at APG with all road surface measurements exceeding the penetrometer resistance maximum of 5600 kPa (100 % refusal). Mean penetration resistance was considerably lower for TRTC (0 % refusal) and YPG (51 % refusal). Differences in resistance reflect the compaction of the road surface (highest at APG), variation in relative amounts of gravel (greatest at YPG), and soil moisture and fine-textured soil (highest at TRTC).

s.fleming@usc.edu

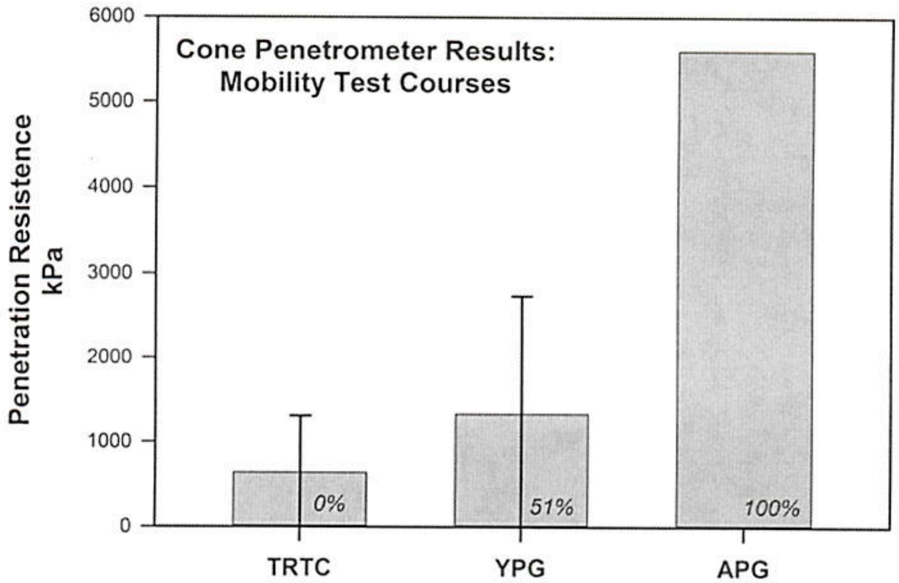


Fig. 10 Bar chart showing mean values (*top* of bar) for penetration resistance measured using a cone penetrometer. Vertical error bars for 1 σ standard deviation (no value for *APG*). Percent values show proportion of measurements where refusal (i.e. no penetration) occurred

4.4 Moisture Content and Bulk Density

Soil moisture and bulk density was measured with a nuclear density gauge at the TRTC and YPG (Figs. 11, 12). Not surprisingly, moisture contents of soils at TRTC are considerably higher than the moisture contents at YPG reflecting the large difference in precipitation between the tropic and desert test sites. Mean bulk density is higher at YPG than at TRTC and is primarily due to the abundance of gravel within the soil at YPG relative to the fine-grained and weathered soils at TRTC.

5 Summary and Conclusions

U.S. military equipment will become more sensitive to environmental conditions because of technological advancements and will require more comprehensive information about the testing environment (test sites) compared to test site information that was required half century ago. A long history of testing military equipment under extreme tropical conditions has demonstrated that extreme tropical conditions will have a considerably different impact on the operation and durability of military equipment relative to other military operating environments. Moreover, continued research, development, and testing of current and new designs of tracked and wheeled military vehicles will continue depend on an extensive network of ve-

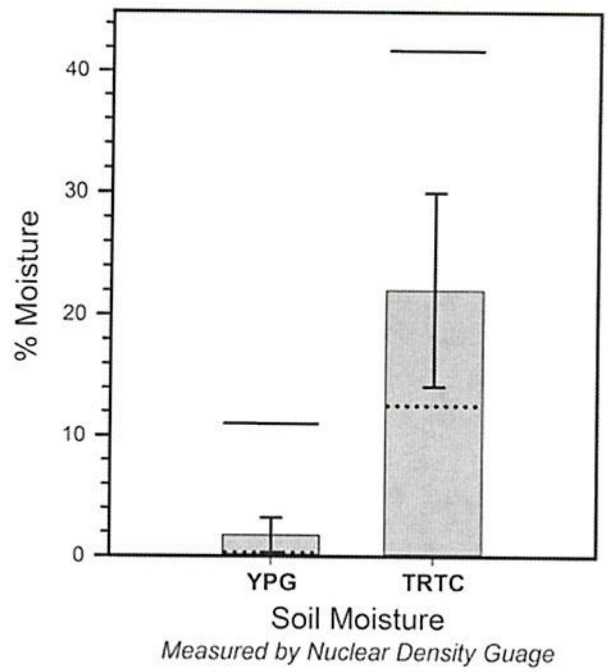


Fig. 11 Bar chart showing mean values (*top* of bar) for % volumetric soil moisture measured using a nuclear density gauge for soils at *YPG* and *TRTC* (no data for *APG*). Vertical error bars for 1 σ standard deviation. *Upper horizontal line* is maximum measured soil moisture and *lower dotted line* is minimum measured soil moisture

hicle mobility and durability test courses located in a variety of temperate, tropical, desert, and cold region environments. Most of test courses currently used consist of unimproved, dirt or gravel roads primarily developed on the native soil and landscape. Although several of these test courses have been in use for nearly 50 years, many of their terrain and geotechnical attributes have not been characterized.

Since 2007, multiple Cadet teams from the USMA's GEnE department have worked with DRI SMEs to characterize soils in desert, arctic, temperate and tropical environments. This work provides direct support to ATEC in the development of data collection methodologies for test site evaluation and follow-on products about many of DoDs primary test sites. The importance of proper test site characterization is not a new idea; future use of equipment by personnel is often only as accurate as the knowledge of and proper correlation to the test site where it was fielded. The different test site biomes are distinctly different, requiring extensive characterization work before testing is initiated and/or completed. For this work, specific collection protocols included soil sample collection, soil characterization at depth, terrestrial (iPIX ®) image collection, and positional location. In all cases, preliminary learning, on-site preparation, followed by weeks of collection efforts have proven successful in characterizing numerous sites, representative of varied climates. Final field collections have resulted in over 500 soil samples with corresponding in situ

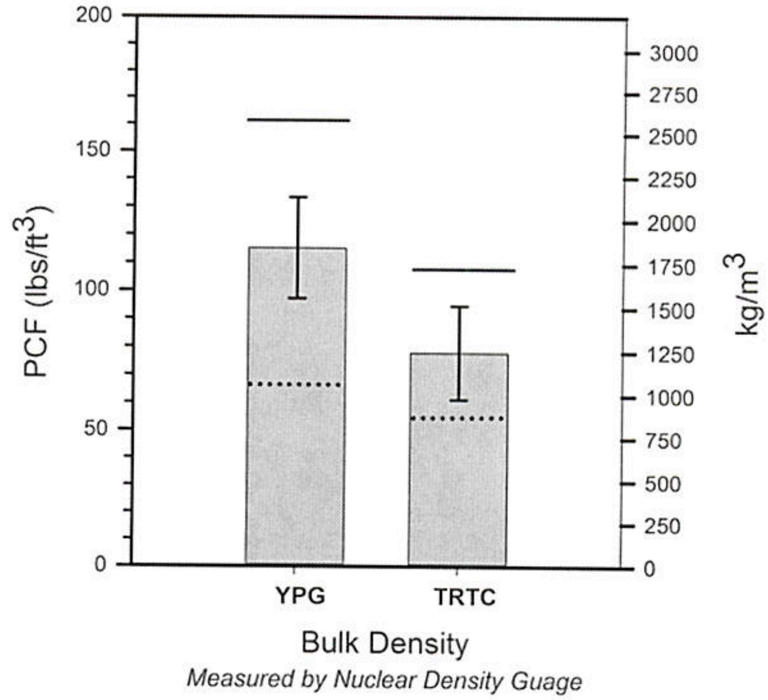


Fig. 12 Bar chart showing mean values (*top* of bar) for bulk density measured using a nuclear density gauge for soils at *YPG* and *TRTC* (no data for *APG*). Vertical error bars for 1 σ standard deviation. *Upper horizontal line* is maximum measured bulk density and *lower dotted line* is minimum measured bulk density

geotechnical properties and iPIX ® terrestrial imagery of each site. The sample data and images of each test site have since been linked in a geospatial database (ArcGIS data files) for each test course. USMA Cadets and faculty have been provided a hands-on, application-based learning experience to heighten their understanding of data collection. Further work by USMA with DRI and YPG is planned for future years, whereby needed characterization of ATEC test sites (and other DoD sites) are necessary. In addition to providing the DoD with new and updated data sets, this applied research serves as an ideal opportunity for USMA Cadets and faculty to apply their knowledge and skills of environmental science and geospatial information science in support of the Army's test community.

Acknowledgments This paper is a result of multiple discussions and working groups facilitated by the Yuma Proving Ground-Natural Environments Test Office (YPG-NETO), the US Military Academy (USMA), the Army Research Office (ARO), and the US Army Engineering Research and Development Center (ERDC). We especially thank Graham Stullenbarger, Wayne Lucas, Linda Spears (YPG-NETO), Russell Harmon (formerly of ARO), Chris King (formerly of USMA), Dan Gilewitch (formerly of USMA), William Doe (formerly of Colorado State University) and Chuck Ryerson (ERDC-CRREL) for many insights regarding test and evaluation in extreme environments. Partial funding for this project provided through YPG contract No. W9124R-07-C-0028/

CLIN 00001-ARCN-AA and ARO grants DAAD19-03-1-0159 and W911NF-09-1-0256. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the view of the U.S. Army, the U.S. Army Research Office or the Yuma Proving Ground.

References

Army Test and Evaluation Command (ATEC) (2014) Army Test and Evaluation Command ATEC, Alexandria, VA. http://www.atec.army.mil/. Accessed 2014

ASTM (American Society for Testing and Materials) (2000) Standard test method for determining the particle size distribution of alumina quartz by laser light scattering: C 1070-86 (reapproved 1992): 2000 Annual Book of ASTM Standards 15.02:375–376, ASTM. Philadelphia

Bacon SN, McDonald EV, Baker SE, Caldwell TG, Stullenbarger G (2008) Desert terrain characterization of landforms and surface materials within vehicle test courses at US Army Yuma Proving Ground, USA. J Terrramech 45(5):167–183. doi:10.1016/j.jterra.2008.09.005

Caldwell TG, McDonald EV, Bacon SN, Stullenbarger G (2008) The performance and sustainability of vehicle dust courses for military testing. J Terrramech 45(6):213–221. doi:10.1016/j.jterra.2008.10.002

Chan K (1999) DIGEST—a primer for the International GIS Standard. CRC Press LLC, Boca Raton

Cold Regions Test Center (CRTC) (2014) Cold Regions Test Center, YPG, Fort Greely, AK. http://www.crtc.army.mil. Accessed 2014

Department of the Army (1979) Army regulation 70—38—Research, development, test and evaluation of materiel for extreme climatic conditions. Department of the Army, Washington, DC

DigitalGlobe (2004) QuickBird_Datasheet_web.pdf: DigitalGlobe Inc., Longmont, CO. http://www.digitalglobe.com/index.php/. Accessed 2004

Emap International (2002) QuickBird—Aerial photography comparison report: Emap International, Reddick, FL

Environmental Systems Research Institute (ESRI) (2012) ArcGIS, ESRI, Redlands, CA. http://www.esri.com/products/index.html. Accessed 2012

Fleming S, Wright W, Gerschlutz J, Hokenson M, Pottorff C, Whitehouse D (2009a) CRTC test site characterization. Department of Geography and Environmental Engineering, West Point

Fleming S, Irmischer I, Roux D, Boxler B, Moomin A, Paulo A, Seese M, Summerlin L, Vaughn S (2009b) TRTC and YTC test site characterization, mapping and imaging. Department of Geography and Environmental Engineering, West Point

Garmin (2007a) Rino520HCx Owner's Manual, Garmin International, Olathe, KS

Garmin (2007b) GPSMap60Csx Owner's Manual, Garmin International, Olathe, KS

GeoEye IKONOS (2009) GeoEye Inc., Dulles, VA. http://www.geoeye.com/CorpSite/products/. Accessed 2009

Harmon RS, Palka EJ, Collins C, Doe W, McDonald EV, Redmond K, Ryerson C, Shoop S, Spears L, Sturm M (2008) A scientific characterization of cold region environments for army testing of materiel and systems and technical analysis of interior Alaska: U.S. Army Research Office, Research Triangle Park, NC

Humboldt Manufacturing Company (2009a) H-4140 GeoGauge Factsheet, Schiller Park, IL. http://www.humboldtmfg.com/datasheets/GeoGauge.pdf

Humboldt Manufacturing Company (2009b) HS-50001EZ Nuclear Density Gauge, Schiller Park, IL. http://www.humboldtmfg.com/datasheets/Nuclear_Density_Gauge.pdf

Humboldt Manufacturing Company (2009c) HS-4210 Digital Static Cone Penetrometer, Schiller Park, IL. http://www.humboldtmfg.com/manuals/HS-4210_DSCP.pdf

King C, Gilewitch D, Harmon R, McDonald EV, Redmond, K., Gillies J, Doe W, Warren S, Morrill V, Stullenbarger G, Havrilo L (2004) Scientific characterization of desert environments for military testing, training, and operations: Army Research Office Report to Yuma Proving Ground, p 111

King C, Palka EJ, Harmon R, Juvik J, Hendrickx J, Fleming SD, Doe W (2009) A technical analysis of locations for tropical testing of army materiel and opportunities for tropical training of personnel: US Army Research Office, Research Triangle Park, NC

Li R (1997) Mobile mapping: an emerging technology for spatial data acquisition. Photogramm Eng Remote Sens 63(9):1165–1169

McDonald EV, Caldwell TG (2005) Geochemical and physical characteristics of vehicle endurance and dust test courses at the US Army Proving Ground: Report prepared for US Army Yuma Proving Ground, Natural Environments Test Office by Desert Research Institute, p 51

McDonald EV, Bacon SN, Bassett SD (2006) Global physiographic and climatic maps to support army regulation (AR) 70-38: Final Draft Report prepared for U.S. Army Yuma Proving Ground, Natural Environments Test Office by Desert Research Institute, p 50

Minds-Eye-View Inc. (2009) iPIX Immersive Photography, Cohoes, NY. http://www.ipix.com/products_photography.html. Accessed 2009

Rimik (2009) CP4011 Cone Penetrometer, Toowoomba Qld, Australia. http://www.rimik.com/index.php?option=com_content&task=view&id=15&Itemid=39. Accessed 2009

Trimble Inc. (2009a) NOMAD Fact Sheet, Trimble, Sunnyvale, CA. http://www.trimble.com/nomadg.shtml. Accessed 2009

Trimble Inc. (2009b) GeoXT Fact Sheet, Trimble, Sunnyvale, CA. http://www.trimble.com/geoxt.shtml. Accessed 2009

Tropic Regions Test Center (TRTC) (2012) Tropic Regions Test Center, YPG, Yuma, AZ. http://www.yuma.army.mil/tc_trtc.shtml. Accessed 2012

Troxler (2009) Troxler Nuclear Surface Gauges, Research Triangle Park, NC. http://www.troxlerlabs.com/PRODUCTS/fieldequip.shtml. Accessed 2009

Yuma Proving Ground (YPG) (2012) Yuma Proving Ground, YPG, Yuma, AZ. http://www.yuma.army.mil/. Accessed 2012

Yuma Test Center (YTC) (2012) Yuma Test Center, YPG, Yuma, AZ. http://www.yuma.army.mil/tc_ytc.shtml. Accessed 2012