MAPPING SOILS WITH A MULTIPLE-SENSOR PENETROMETER

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Introduction

The mapping of the Earth's subsurface is a scientific and technical challenge. The creation of such maps can result in a greater understanding of our capabilities and limitations with regard to agriculture, construction, transportation, environmental assessment, and resource management. Additionally, water, nutrients, pesticides, and herbicides must flow through or be contained by the soil environment. Subtle changes in soil properties can have large impacts on land usability, solute transport calculations, soil fertility, carbon sequestration, bioremediation, and vegetative health. Intensive land use applications and management practices require more detailed subsurface information than is currently available in most instances. Information regarding the depth, thickness, and properties of subsurface strata are currently obtained through soil core sampling, well logs, or the excavation of pits to enable detailed analysis of the characteristics of the ground on which we all live.

Brief History of Penetrometer Use

The probing of soil with rods to locate soil strata has been conducted since approximately 1917. It wasn't until about 1934 in The Netherlands that penetrometers were utilized in a form that is recognizable today. It was during this time that various configurations of the first systems were used for some agricultural and environmental studies. The earliest comprehensive studies describing penetrometer systems and their applicability to determining various soil properties appear in the late 1930's and early 1940's. In a study in the 1942 Soil Science Society Proceedings (Shaw et. al., 1942), a cart-mounted penetrometer was used to investigate tillage effects. The system could be wheeled around a field and resembled a modern day dolly. It used a hand crank to insert a 1.6 cm diameter shaft with a 45-degree tip into the soil and measured force at four increments to a total depth of 30 cm. Richards (1942) described a similar push system and concluded that a penetrometer could be used to demonstrate quickly and easily whether or not a compacted layer existed at or below the soil surface. He also determined that the information obtained with a penetrometer could be useful in connection with plant-root development or infiltration studies.

Penetrometer use in agricultural research and investigations has traditionally involved the measurement of penetrometer resistance to assess soil compaction for correlation with observed root growth, crop yields, and other soil physical properties

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related to agricultural production. Today, penetrometers are used to delineate soil properties not once considered important to agriculture. These properties are relevant to managing agricultural landscapes rather than crops alone. The future of penetration testing will grow to include systems capable of measuring soil physical, chemical, and hydrological properties important to the assessment of soil as a resource.

Current Penetrometer Standards

Two primary standards for penetrometers exist in the United States today: One by the American Society of Agricultural Engineers (ASAE, 1999a) and the other by the American Society of Testing and Materials (ASTM). It is the ASAE system that is used to delineate soil properties for agricultural applications. Though minor deviations occur, the primary design specifications have traditionally been followed; namely, cone diameter (20.27 or 12.83 mm), push rod diameter (15.88 and 9.53 mm), and cone angle (30-degrees). The ASAE penetrometer standard specifically identifies the intended uses for their design: 1) To provide a common method of constructing a device capable of measuring general soil mechanical conditions that facilitates the reporting and interpretation of soil data by different research workers; 2) To assist those who work with different soils and soil conditions and those who need a measure of soil mechanical properties for comparative purposes; and 3) To provide a common system, of characterizing soil properties from which it may be possible to develop performance and predictive relationships. The standard defines cone index (CI) as the amount of force generated for a given surface area on the front of the cone as it is inserted to the soil. CI is the only measurement made with the ASAE system and is reported as a measure of the penetration resistance of a given soil in kilopascals. The measurement is made above ground either with a load cell or a proving ring. It is from this one measurement that all assessments of soil properties are determined with the ASAE design.

The ASAE procedures for “Using and Reporting Data Obtained with the Soil Penetrometer” (ASAE, 1999b) are the guidelines used for planning, using, and reporting data obtained with a penetrometer. There are only a few specific guidelines outlined by the procedures. They state that there are three applications for which the ASAE design is intended. They are: 1) mobility/trafficability; 2) depth of root-impeding layers; and 3) root growth. The procedures also note that the cone should be pushed into the soil at a uniform rate of approximately 30 mm/sec.

The ASTM specification calls for a cone tip with an angle of 60-degrees and a push rate of 20 mm/sec. Another type of measurement, sleeve stress, is included on the ASTM cone specification and is a measure of the friction that is exerted over a given surface area on the side of the cone. This measurement is taken independent of the CI and can be used to assess the behavioral properties of deep soil environments. Both CI and sleeve friction are measured at the base of the cone and not above the soil surface as with the ASAE design. The sensitivity of such systems to delineate near surface soil properties is impaired because they must be able to measure forces equivalent to that required to push them into the soil up to 100 m (300 ft) (up to 30,000 kg or 60,000 lbs). They must be built to withstand such forces and are thus constructed with a larger diameter (44.45

mm or 1.75 in. and 36.58 mm or 1.44 in.). In a standard 8 bit digital system with 256 bytes this means that a cone with a 30,000 kg load cell has a sensitivity of 117 kg per byte. Though many designs are more sensitive, the ASTM cones rarely have a sensing capability higher than 10 kg even with gains in the sensor output. This is not adequate for distinguishing soil properties in the top few meters.

The majority of penetration testing through the 1990's for agricultural applications involved determining compaction and its influence on root penetrability. Most applications used 30-degree cone angle to study root penetrability as the configuration more closely emulates the resistance experienced by a root on its tortuous path in the search for water and nutrients. Though not intended for such applications, scientists and practitioners have attempted to use the ASAE penetrometer to measure multiple soil properties with only CI. This design paradigm still exists today.

Applied Penetrometer Technology

Recent advancements in computer and digital technology have dramatically improved the scientist's and practitioner's ability to collect, process, and analyze penetrometer data. Digital data loggers and depth measurement devices have enabled the real-time association of raw data output with depth of penetration and calibration factors. The result is that soil properties can be assessed given a known error and plotted in the field. It is now possible to assess bulk density, texture, moisture, and color in the field without taking a sample. Of course, penetrometer data are not meant to replace sampling, but rather to optimize the placement and depth of analysis of the samples that are taken. In fact, all penetrometer data can be made more accurate during post processing if samples from a few key location are analyzed and used to perform a site-specific post-calibration for the data. This may or may not be necessary depending on the application. Plots similar to Figure 1 can be generated within minutes of measuring. In this example a decrease in sleeve friction between 75 and 95cm (30-37 in.) indicates the presence of a sandy soil with less cohesion on the sleeve element. If only the force on the tip were measured, it would be impossible to delineate this soil horizon.

Hundreds of profiles can be generated in a single day dramatically improving the amount of soil data available for mapping soil layers. Additionally, statistical analysis is made easier and more significant because of the digital format and high data volume. A global positioning system (GPS) can be used in conjunction with a digital penetrometer to aid in the conversion of penetrometer data to a format recognizable by most mapping software.

A penetrometer can be used to rapidly measure the depth to soil layers and help to determine the locations on the field where root penetrability and/or drainage may be impacted. This information can in turn be used to guide the location and depth of drainage tile or help to determine whether simply breaking up a thin compacted layer might serve the same purpose of increasing drainage or root penetrability. If a yield map

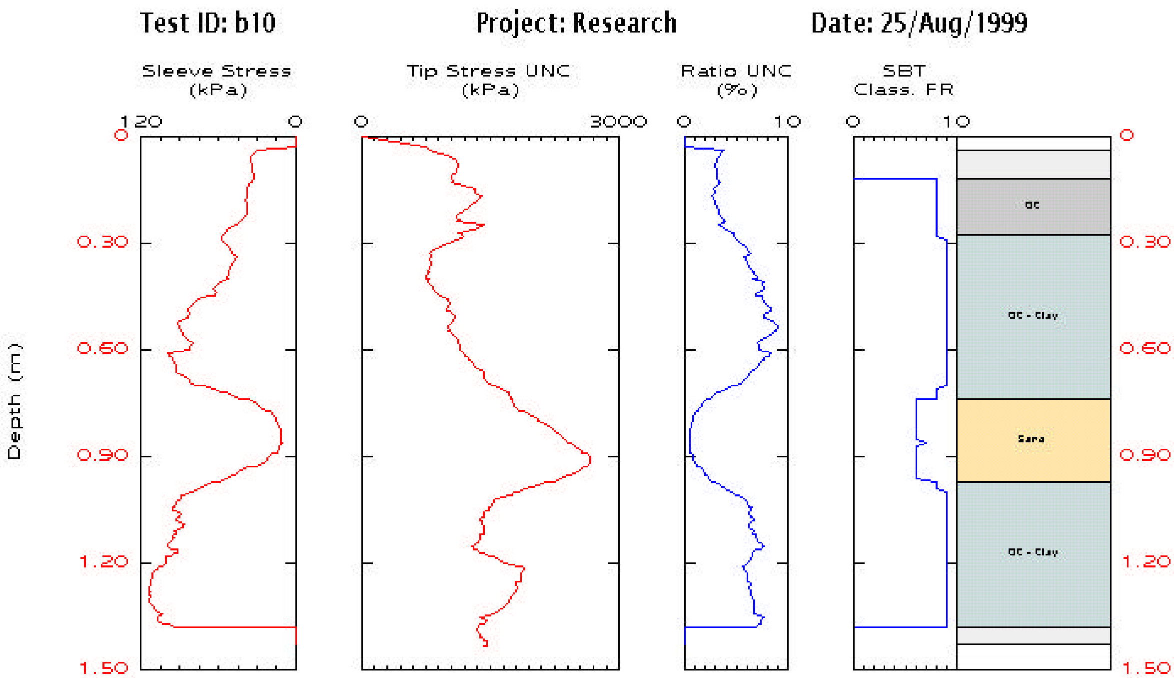

Figure 1. Field output from the physical property penetrometer generated in 60 seconds to a depth of about 4.5 feet.

is created for the same site, then a correlation can be developed between the penetration resistance distribution (position, depth, thickness) and crop yield.

Soil Mapping with a Penetrometer

A more efficient and cost effective method is needed to determine the variation of soil physical-property data with depth at a landscape scale. This method must create a stronger link between the field measurement and the desired soil property; thus diminishing the need for a laboratory testing during landscape scale site investigations. There are several advantages of using penetrometer technology over conventional methods for determining depth profiles of soil properties. First, the data are collected almost continuously for the entire depth of penetration and real-time information is obtained relatively quickly. This, in turn, enables the user to make decisions in the field to determine future testing locations, and helps to eliminate unnecessary laboratory time and costs associated with samples taken in the wrong locations. Data from a penetrometer are converted to a digital format in an acquisition system as the data is collected, minimizing possible sources of error that might occur during the sample handling and laboratory testing processes. The digitized information can be easily transferred to existing databases and used in models or statistical analyses.

The digital data obtained with a penetrometer system can be integrated with a GPS to associate soil physical property information with landscape position and elevation. The penetrometer and GPS data can be integrated into a geographic information system (GIS) as well as statistically driven sampling routines to facilitate efficient and interactive "on the fly" mapping of soil attributes. This facilitates a “smart” sampling and mapping approach as the optimal location for sample collection can be determined in the field.

When combined with landscape position, the penetrometer output can be associated with other spatially significant information such as crop yield and watershed maps. This ability to immediately visualize the penetrometer output and associate it with existing soil and landscape data increases the functionality and usefulness of the tool. As advancements continue to be made in both sensor design and data acquisition and analysis, the penetrometer will become more than just a great tool for measuring compaction.

Physical Property Penetrometer

A Physical Property Penetrometer (PPP) has been developed to characterize and map soil texture and compaction in the soil environment. The PPP (Fig. 2) has a diameter of 20 mm (0.79 in) and a 70 mm (2.76 in) sleeve device. The sleeve is located

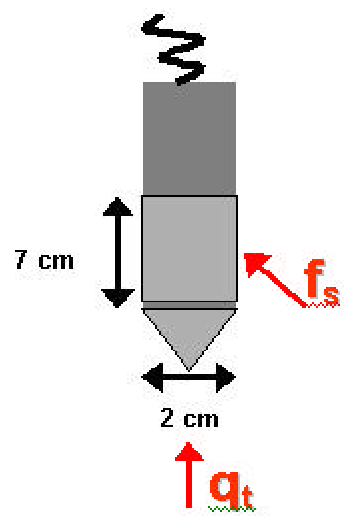

Figure 2**.** Schematic of the Physical Property Penetrometer where q_t (tip force) increases with an increasing density and f_s (sleeve friction) increases with increasing cohesion.

directly behind the 60-degree tip that has a surface area of 3.14 cm^2 (0.49 in^2). An internal strain gauge calculates both the tip force and sleeve friction as the device is inserted into soil. The advantages of this system are that two physical variables are measured as opposed to tip force only, and that it has a high level of sensitivity for measuring soil properties.

The PPP system has the ability to predict texture as well as compaction. For example, the tip force can increase due to the presence of sand and/or compaction. However, sand grains are less cohesive so that the friction exerted on the sleeve device is less for coarse-grained soils. Cohesive soils (fine textures) create greater sleeve friction; therefore soil horizons with varying textures can be distinguished. The ratio of sleeve friction over tip force can be used to rapidly estimate the particle sizes of the soil. The PPP system can be mounted on a light duty truck and is inserted into the soil using a hydraulic ram. Other designs would enable the user to mount a system on an all-terrain vehicle or a hand-held device.

Field Application

Data were collected with the PPP on October 11 and 12, 1999 at the University of Wisconsin-Madison Arlington Research Station. The field had recently been harvested (corn) and contained a great deal of crop residue. The field was about 5 acres is size and had about 1% slope.

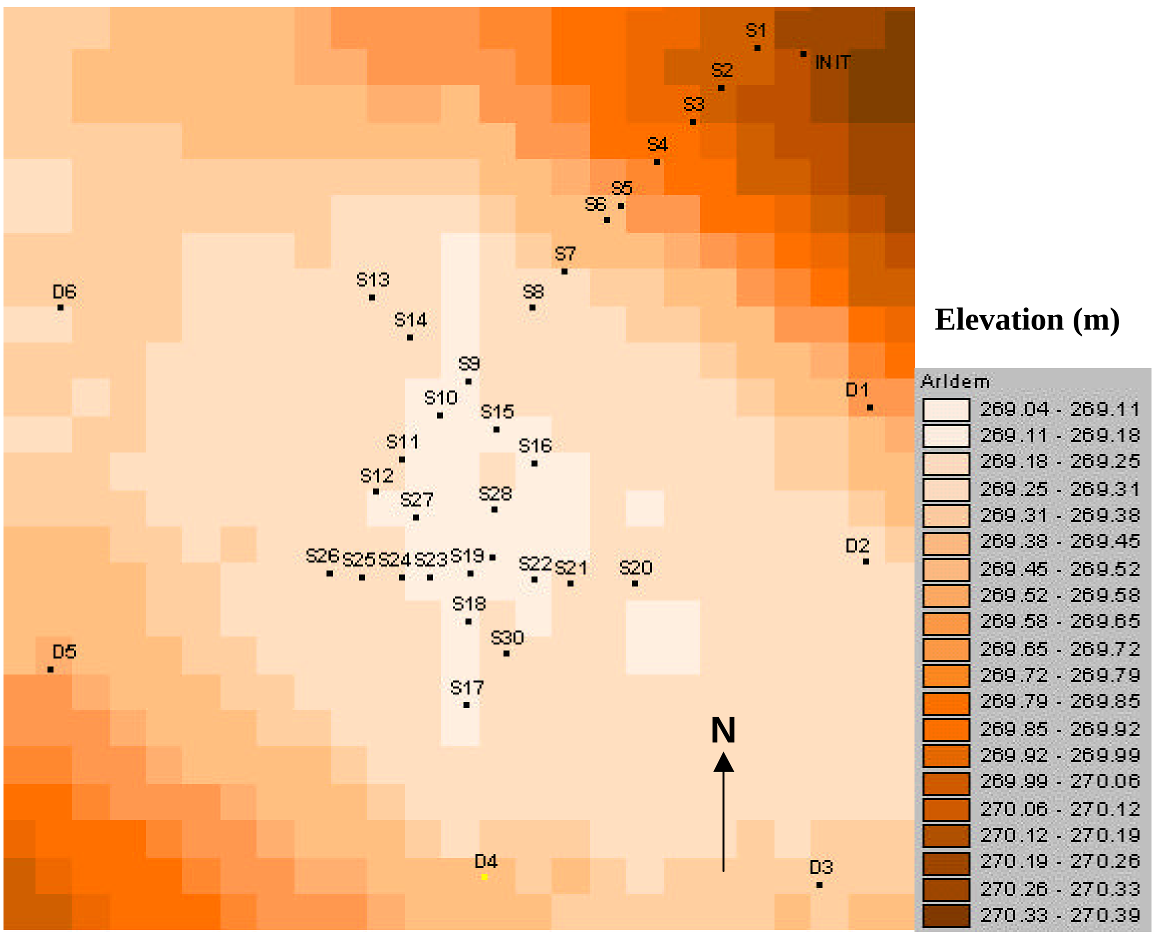

Figure 3. A digital elevation model (DEM) of site in Arlington, WI with the enumeration of 36 test locations. The field is about 5 acres and the elevation variation is about 4.5 feet.

Previous investigators of the site revealed a compacted layer at a depth “somewhat less than a meter” in the middle of the field. It was also noticed that given sufficient rain, ponding would occur in this location. This situation seemed ideal for integrating the PPP and GPS for the purposes of mapping a 3-dimensional feature located in the subsurface. Additionally, the glacial till that underlies the entire field is a significant natural feature as it determines to a great extent the flow pattern of water moving through the subsurface. The till was estimated to be between 2 and 3 m in the test field and acts as a barrier to the downward movement of water.

The penetrometer system was first adapted to push the PPP to a depth of 3 meters (10 ft), equivalent to two hydraulic strokes on the soil-coring unit. This type of test takes a great

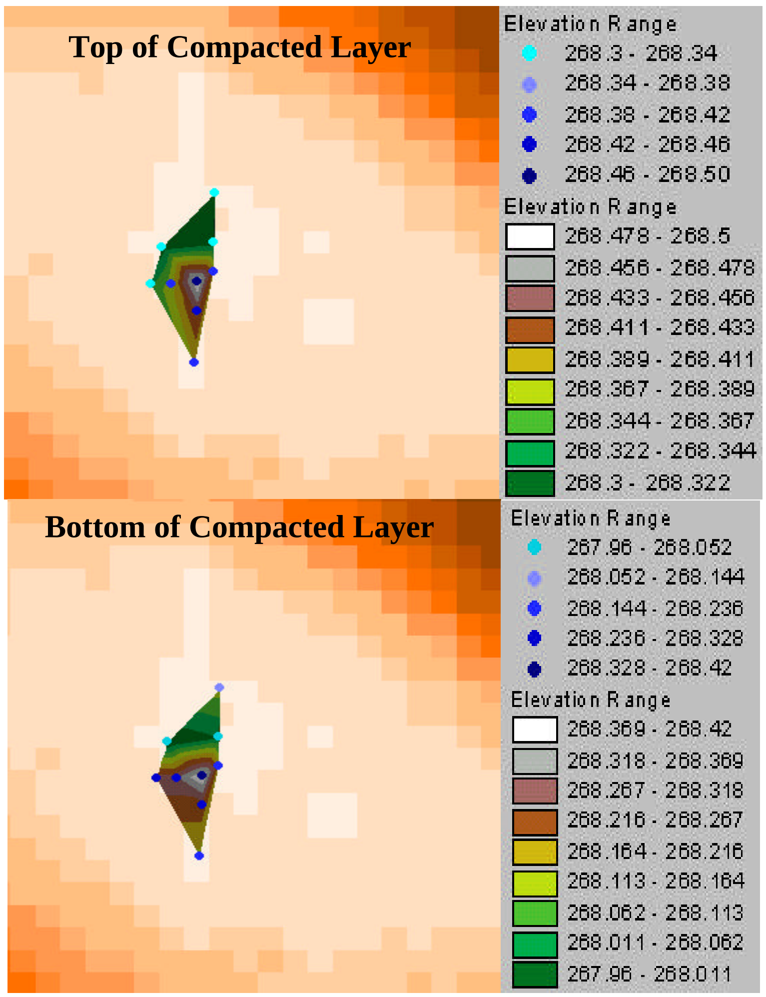

Figure 4. The compacted layer is less than 10 cm thick in the middle and has a convex shape. The steepest slope is to the N.

deal more time, but was necessary to conduct to determine the depth of till. A total of six of these "deep" tests were conducted and are delineated as D1-D6 in Figure 3. These tests were conducted around the periphery of the suspected location of the compacted layer. The following day, 30 penetration tests were conducted to a maximum depth of 1.5 meters (60 in) and were referred to as "shallow" and are delineated in Figure 3 as S1-S30. Since the exact subsurface placement of the dense layer was not known, an initial transect was conducted starting at the northeast portion of the field and progressed towards the southwest. This was done in an attempt to initially locate a portion of the compacted layer. Once located, several smaller transects were conducted in a crossing pattern followed by random testing to obtain multiple detections with the instrumentation. Each of the 36 test locations was flagged for future surveying with the GPS unit. Three subsurface features were identified and the response of the instrument to each (sand layer, compacted layer, and glacial till) was mapped. Maps of the depth and thickness of the compacted layer are shown in Figure 4.

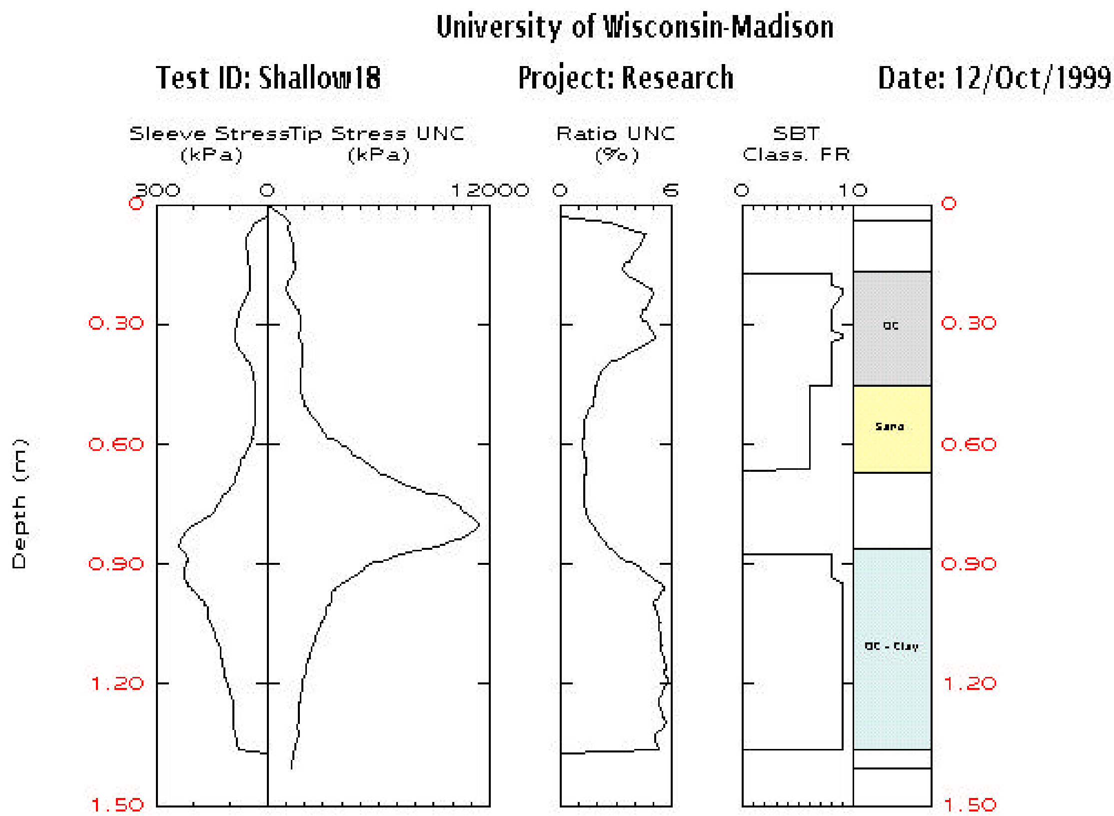

Figure 5. Data collected at location S18. Included is the ratio % calculation between sleeve stress and tip stress as well the horizon delineation.

The identification of the glacial till is the most obvious of the three features as the tip force increases rapidly independent of the sleeve measurement. The depth at which the till layer was encountered varied across the field from about 90 cm (35 in) at the top of the slope in the NE portion of the field (S1) to about 2 meters (6.5 ft) in the other three quadrants. The thickness of the glacial till was not determined as the layer was too difficult to penetrate. Only the top of this layer was determined in the area of the field surveyed. An example of a PPP penetration through both the sand and compacted layer is shown in Figure 5. At a depth of approximately 60 cm (24 in) the tip force began to increase while the sleeve measurement remained low relative to the tip. At a depth of approximately 70 cm (28 in), the sleeve measurement increases in conjunction with tip force indicating the presence of a compacted soil with a cohesive (fine grained) texture.

Conclusion

The utilization of a penetrometer that measures both tip force and sleeve friction is superior to one that measures tip force alone. The PPP can delineate both the compaction and textural characteristics of the soil environment. Data collected with the system can be integrated with landscape position to create 3-D maps of soil properties. The technique is more efficient than soil sampling to assess the distribution of soil properties at a landscape scale.

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