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REMOTE SENSING OF SOIL TRAFFICABILITY FACTORS

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I. ABSTRACT

The ability of a soil to support military vehicular traffic is usually determined by using the US Army cone penetrometer. The cone index obtained from this method may be used in the AMC-74 mobility model. Moisture is an important factor in the cone index of all types of soil. Experiments indicate that the electrical resistivity of a soil is related to its moisture content. This paper describes some of these experiments and introduces a technique for aerially obtaining and machine processing soil resistivity data for the mobility model.

II. BACKGROUND

The desirability to obtain data relative to the ability of the terrain to sustain both troop and vehicular traffic was recognized centuries ago. One of the recent approaches to characterize "soil trafficability" numerically was developed by the US Army Corps of Engineers, Waterways Experiment Station (WES), Vicksburg, Mississippi. The device (Figure 1) is the "Army Cone Penetrometer," which is normally used to measure the force required to penetrate a soil incrementally to depths up to 18 inches. Undisturbed soil yielded a "cone index." A device was used to remold soil samples so that a cone index of the remolded soil could be taken. The ratio of the remolded cone index to the original cone index is termed the "rating cone index" and is used as a single-figure trafficability rating.

Specific vehicles are assigned a "vehicle cone index." If a given vehicle has a "vehicle cone index" less than the "rating cone index," 50 traverses are assured. If the rating cone index is less than the vehicle cone index, 50 traverses cannot be made. If the rating cone index is less than 75 percent of the vehicle cone index, the vehicle cannot make even a single traverse.[1]

This technique for determining soil trafficability has become Army doctrine and has been incorporated into the Army mobility models AMC-71 and AMC-74. These models were generated by WES and the US Army Tank Automotive Command.

The AMC-74 computer model is used for predicting the performance of tracked or wheeled vehicles across most types of terrain, and requires a variety of terrain data to make mobility calculations. Twenty-one terrain factors are

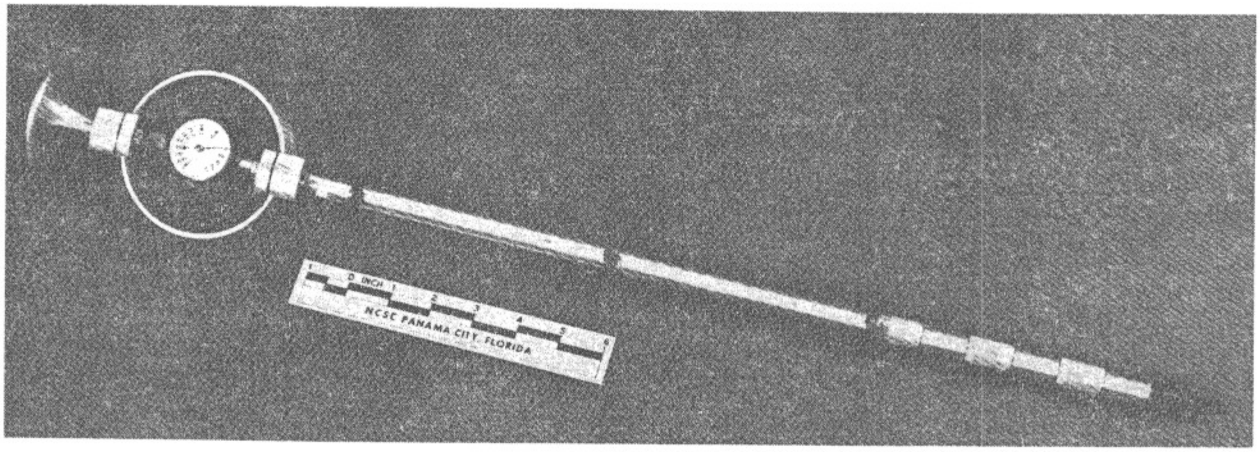


FIGURE 1. ARMY CONE PENETROMETER

required among which are primary terrain descriptors, surface type, and surface strength in dry, wet, and average conditions. The outputs of the AMC-74 model are:

- Maximum Vehicle Speed
- Vehicle Up-Slope Speed
- Vehicle Down-Slope Speed
- Vehicle Speed on Level Ground
- Limiting Factor for Vehicle Up-Slope Speed
- Limiting Factor for Vehicle Down-Slope Speed
- Limiting Factor for Vehicle Speed on Level Ground

These limiting factors refer generally to vegetation, marshy soils, slope, and combinations thereof.

The current opinion is that the major factors affecting mobility are marshy soils, the presence of vegetation having stem diameters that can affect the speed of a vehicle, and the presence of certain soil types. Since moisture affects the strength of all soils, hence their trafficability, the desirability of knowing soil moisture is unquestioned, particularly methods for measuring soil moisture remotely.[1] This paper will describe some of the work conducted at the Naval Coastal Systems Center leading to a method to measure soil moisture remotely.

Some early work (1957 to 1970) was performed by the Waterways Experiment Station (WES). Data were collected in a variety of soils by aerial penetrometers impacting vertically at a velocity of around 100 feet per second and penetrating usually to around 3 feet. From these data a relationship between cone index and rating cone index versus penetration depth was demonstrated (Figure 2). WES concluded that remolding due to penetration was not a detriment at an impact velocity of 100 feet per second. Their experiments continued and an experimental aerial soil penetrometer was tested which was capable of responding to preselected soil strengths based on compression of springs. Apparently, no other WES aerial hardware was studied further.[2]

III. THEORETICAL CONSIDERATIONS AND LABORATORY EXPERIMENTS

One of the most significant areas of study conducted by WES was the relationship between rating cone index and soil moisture content. Some of these results are shown in Figure 3.

Soil moisture is recognized as one of the most important factors in trafficability prediction yet its measurement is one of the most difficult to perform in the field in near real-time. A knowledge of soil moisture versus depth, taken simultaneously with the deceleration profile of the impacting aerial penetrometer, should go far toward characterizing soils for trafficability prediction. Under sponsorship of the Naval Ocean Systems Center (NOSC), work is being conducted at present to relate deceleration profiles to cone index in a variety of soils. The relationship between cone index and moisture content is also being studied at the Naval Coastal Systems Center (NCSC) with emphasis on methods to measure moisture versus depth in near real-time. This paper will treat these investigations.

The relationship between soil resistivity and soil moisture has been studied by a number of investigators, in the United States notably by Dr. Frank Wenner of the Bureau of Standards (1915), by McCollum and Logan of the same organization, and in Britain by P. J. Higgs (1930). Much of this study was directed toward methods of designing and measuring the characteristics of grounding systems for electrical purposes. This early work is very valuable and these works are still cited frequently.[3]

The possibility of relating soil resistivity, a simple and rapid measurement, to soil moisture is intriguing. If this could be done the practical applications are significant and of wide use. But, resistivity of soils is dependent on factors which vary widely from one geographical point to the other. These main factors are:

(a) Type of soil
(b) Chemistry of the dissolved salts (types)
(c) Concentration of dissolved salts
(d) Moisture content
(e) Temperature
(f) Grain size, and grain size distribution
(g) Closeness of packing and pressure[3]

At first, this wide array of factors appears to preclude the possibility of utilizing electrical resistivity of soil as a criterion for soil moisture content. However, a closer examination of these factors begins to reveal that resistivity tells much more about soil moisture than might have been formerly realized. From my own experience in designing and installing ground systems for radio transmitting installations and for telephone systems, I have found that, generally, where earth resistivity is low, the soil is usually marshy; that is, the shear strength is low. The converse is true; dry soils are often hard and have a high resistivity. This is not always true and several soil factors have been examined to try to determine under which circumstances the resistivity measurement characterizes soil moisture content, and the extent to which this simple measurement may be depended upon. Let us first examine how soils conduct electricity.

Most soils conduct electricity through the moisture between the grains. There are only limited cases where a soil will contain ore or carbon, etc., which alone can conduct on electric current.[3] Consequently, most soils, when completely dry, will exhibit an infinite resistivity. This is true regardless of soil type and is shown in Figure 4. These curves were obtained by measurements conducted in the laboratory on a variety of soils containing a variety of ground

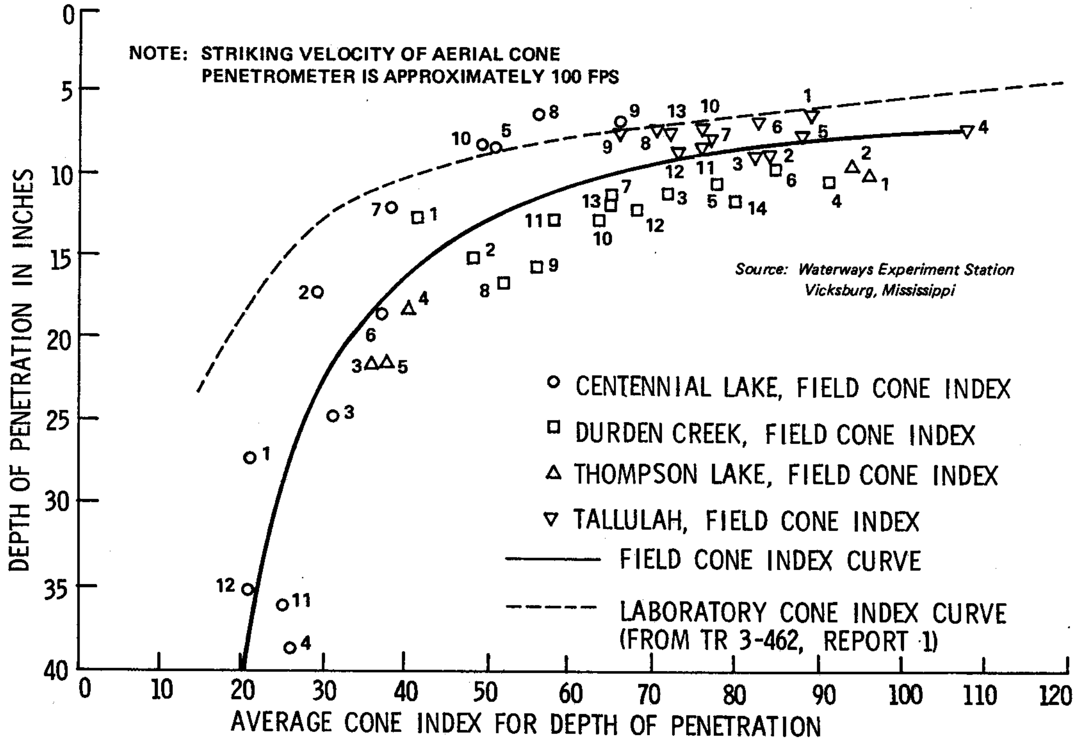


FIGURE 2. PENETRATION OF AERIAL CONE PENETROMETER VS. CONE INDEX

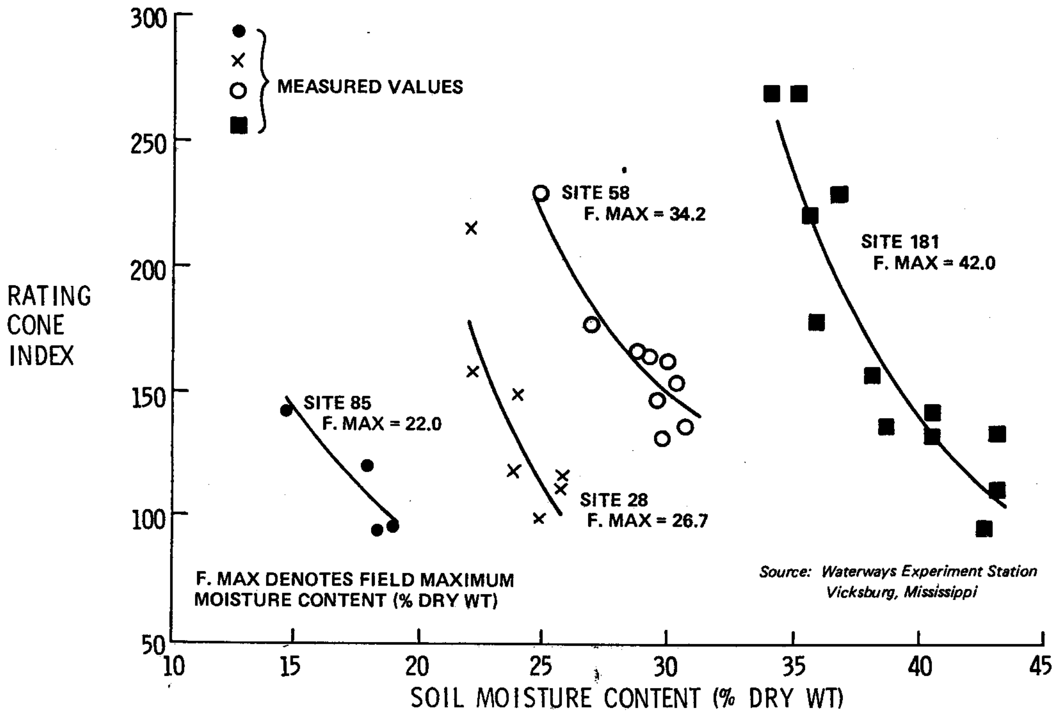


FIGURE 3. RATING CONE INDEX, SOIL MOISTURE CONTENT RELATIONS

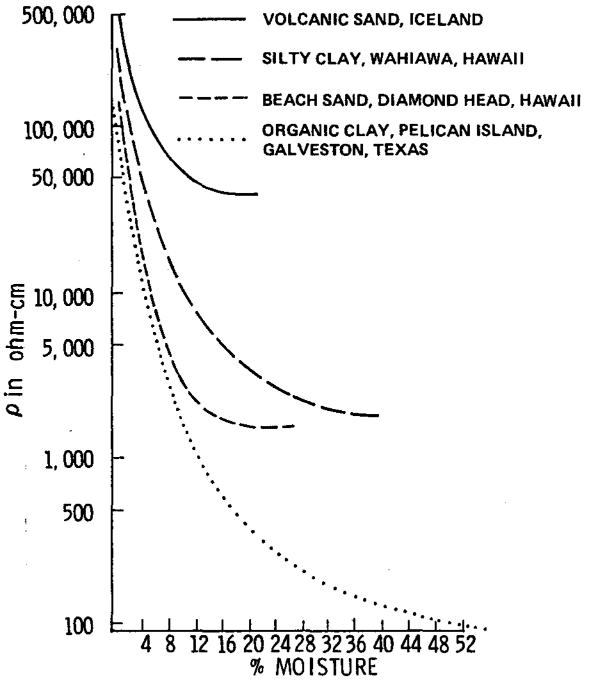


FIGURE 4. ELECTRICAL RESISTIVITY VS. MOISTURE IN SAND AND CLAY

waters each with its characteristic electrical resistivity. Note that when these soils are saturated, they have a resistivity that is apparently dependent upon several of the factors previously mentioned; but, when they are completely dry, they all have the same resistivity, approaching infinity. These end points in soil resistivity are extremely valuable in moisture content measurement as will become clear later.

It might be helpful at this point to review the effect that changing the configuration of an electrical conductor has upon its resistance. For example, a 1-centimetre cube of copper has a resistance across opposite faces of 1.724 microhms at 20 degrees Centigrade. This same cube of copper when drawn into a wire 10/1000 of an inch in diameter would produce a wire about 64 feet long with a resistance of 6.64 ohms or an increase by a factor of about 3.85×10^6 (Figure 5). This same physics applies to other conductors such as groundwater.

Ground water near the Gulf of Mexico, at Galveston, Texas, has a measured resistivity of 20 ohm-centimetres. If a cubic centimetre of this water is formed into a filament 10/1000 of an inch in diameter, its resistance would be about 81 megohms. Similarly, a cubic centimetre of ground water from Fargo, North Dakota, formed into a filament of this size would have a resistance of about 168 megohms.

These figures illustrate that a given volume of an electrical conductor may have a wide range of resistances due to its mechanical configuration.

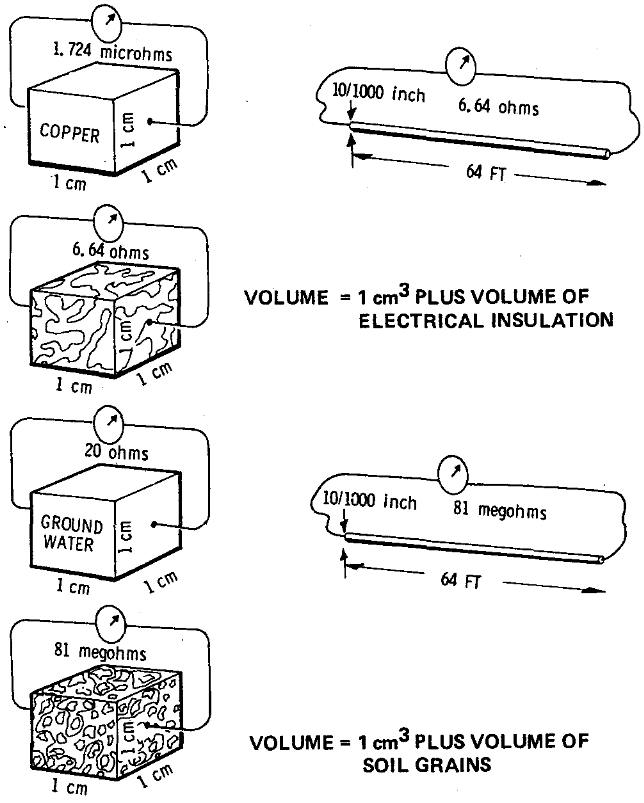


FIGURE 5. CONFIGURATION OF ELECTRICAL CONDUCTORS VS. RESISTANCE

These variations in resistance also occur between materials so that an infinite number of soil resistivities could be expected in various geographical areas due to the factors mentioned.

The conduction of electric currents in rock has been described in the literature and is typically represented as in Figure 6.[4] Conduction in soils appears to be similar. The upper view shows soil grains surrounded by moisture, the large spaces between the grains being designated "storage pores" and the smaller spaces, mostly where they touch, being designated the "connecting pores." The connecting pores account for most of the electrical resistivity of the soil. As pointed out previously, the soil grains themselves are usually of high-dielectric material and are rarely conductive.[3,4] The soil grains are embedded in a fluid electrolyte, in this case the ground water, which is the medium of electrical conduction. When a soil is saturated, its resistivity is represented by the point of lowest resistivity on the curves in Figure 4 regardless of the soil type and matrix electrolyte.

As a soil begins to dry, the first moisture to exit is that in the storage pores.[4] If drying continues these pores become voids as shown in the bottom view in Figure 6 in which the principal current paths are now the connecting pores. At this point the electrical resistance turns sharply upward for sands, less sharply for clays. If drying continues, all soils exhibit increasing resistivities converging at infinity when the soils are theoretically completely dry.

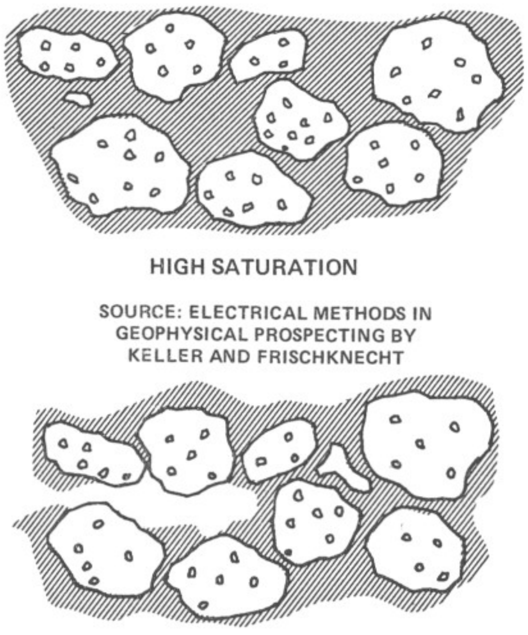


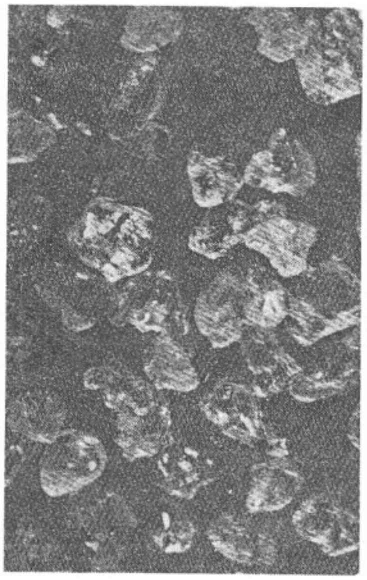
FIGURE 6. ELECTRICALLY CONDUCTIVE PATHS IN STORAGE PORES AND CONNECTING PORES

Note the difference in shape between sand curves and clay curves (Figure 4). This may be partially explained as follows. Wet sand grains may be thought of as impermeable electrical insulators surrounded by electrolyte (Figure 7). Disappearance of electrolyte from the storage pores leaves very little conductive material, hence the sharp upward turn in resistivity. The moisture remaining is located in the connecting pores where the disappearance of a small amount of moisture can effect a large change in resistivity, yielding a curve with a steep slope.

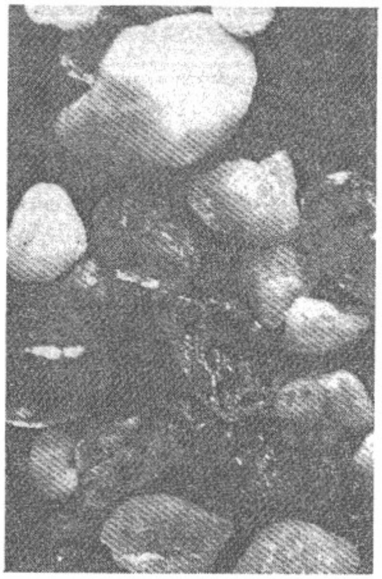
Some clays respond differently due to their platelet structure.[5] Therefore, clays may be thought of as permeable soil grains each of which has an electrical resistance due to the adsorbed water. This water is hard to drive out.

In the drying process clays, like sands, first lose the water in the storage pores, the remaining electrical circuits now being the connecting pores and the clay grains themselves, remembering that moist clay grains are conductors instead of insulators. Continued drying of the clay results in a gradual upward trend in resistivity with less of the pronounced change noted in sand. If you examine the equivalent electrical circuit for sands and clays it becomes obvious why a matrix of "insulators and electrolyte" and a matrix of "conductors and electrolyte" behave differently. Sand and clay mixtures produce hybrid curves.

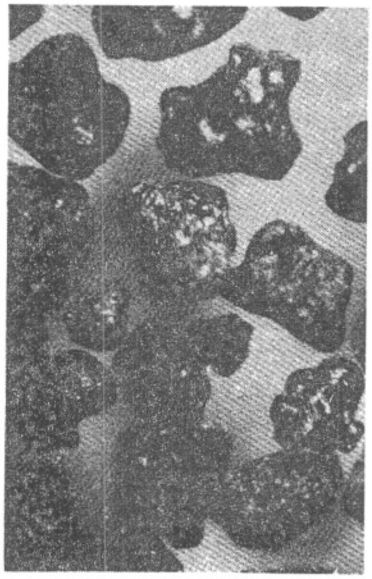
The curves of Figure 4 are of very little value in measuring soil moisture content unless one knows the soil type and the electrical characteristics of the electrolyte. The curves do lead



SAND - PANAMA CITY BEACH, FLORIDA



SAND - DIAMOND HEAD BEACH, HAWAII



VOLCANIC SAND, ICELAND

FIGURE 7. PHOTO MICROGRAPH OF SANDS

us to other concepts which are valuable in measuring soil moisture content.

If the curves of Figure 4 are examined, it is evident that sands saturate at about 16 percent to 20 percent moisture and that clays saturate at 45 percent to 70 percent moisture, or greater. Mixtures of sand and clay saturate at values somewhere in between. Depending upon the conductivity of the electrolyte, from a standpoint of resistivity of a soil, this saturation point may vary from such low values as 80 ohm-centimetres in saline soils, to 50,000 ohm-centimetres in fresh water soils. This disparity may be eliminated, for practical purposes, by generating curves for the first derivative of these curves with respect to moisture. Typical curves of this type are shown in Figure 8.

These curves are not used directly in measuring moisture content of a soil unless we know the exact soil type and its electrolyte, specifically, if we had a curve like Figure 4 for the soil and electrolyte in question. The curves of Figure 8 are useful, conceptually, to visualize the endpoints at saturation now occurring all at zero-slope, and the endpoints at "completely dry" now occurring all at infinite slope. This approach has essentially eliminated the effects of wide variation in ground water conductivity and permits practical application of the slope of a resistivity versus moisture curve rather than the absolute value of resistivity of the soil, which is of limited value directly for our purposes, as illustrated in Figure 4. This "moisture gradient" approach is described here.

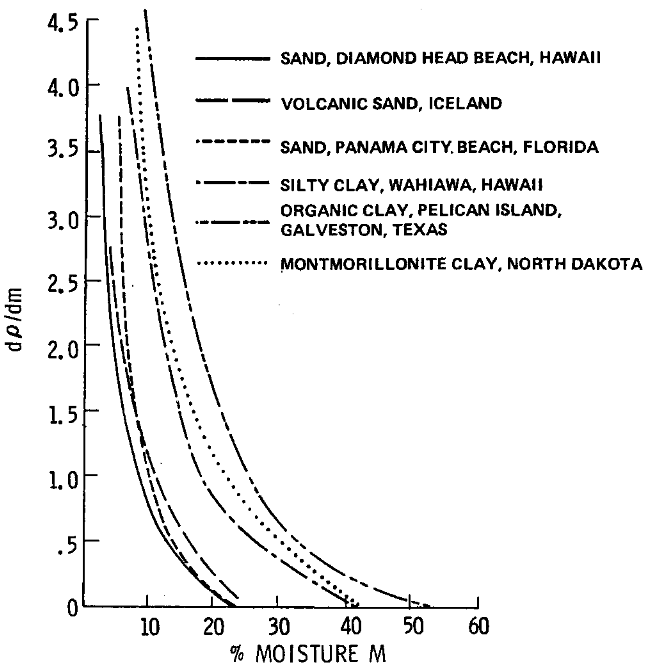


FIGURE 8. DERIVATIVE OF ELECTRICAL RESISTIVITY VS. MOISTURE

IV. FIELD TESTS

This "moisture gradient" for measuring soil moisture has been used by NCSC in field experiments in Florida, Texas, North Dakota, and Virginia. Some of the results are described.

Figure 9 shows a typical Florida pine-palmetto flatwood coastal plain of the Gulf Coast. The high moisture content at the surface was due to recent rains. The resistivity curve reflects the vertical moisture distribution well. This experiment illustrates the leveling-off of the resistivity to a constant value at saturation, that is, in the water table which occurred at a depth of about 36 inches. Continued penetration beyond this depth would produce a straight vertical line indicating saturation.

Figure 10 shows a typical resistivity versus moisture curve for organic clay in a highly saline environment at Galveston, Texas. Note the extremely low-resistivity readings of the soil, yet the feasibility of predicting the presence of dry soil and wet soil based on the slope of the resistivity curve.

Figure 11 shows North Dakota montmorillonite firm silty clay soil from the Glacial Lake Agassiz Plains. The percentage of clay was 25 to 35 percent.[6] This curve is representative of the variability in resistivity versus depth for a clay soil which has not been remolded. It is reasonable to expect that perhaps the top 6 inches of soil had been remolded because of the location in an agricultural field. Over the first 24 inches the moisture content and resistivity correlate well. Note the low resistivity near the surface due to rain in the early morning. Below 24 inches the resistivity curve indicates a substantially constant moisture content to a depth of about 5 feet which correlates fairly well with measured moisture content.

Below 5 feet the correlation ends, apparently due to anomalies in the soil structure which mechanically constrain the electrolyte and the electric current, to follow a more complex path than is demonstrated by a remolded soil. Evidence to support this is demonstrated in Figure 12 in which the data were obtained in the laboratory from North Dakota clay that had unmistakably been remolded. The curve is smooth and demonstrates moisture loss from a remolded grain structure within the sample in contrast with a variety of grain structures in the field which may be encountered in different strata as the soil is penetrated. The three grain structures accounting for different electrical responses are shown in Figure 13. These electrical responses will occur only in clays or soils having a substantial percentage of clay. Remolding destroys this structure and its characteristic electrical resistivity response.

A single attempt has been made by NCSC to correlate electrical resistivity of the soil with cone index. Figure 14 shows the results of a test in

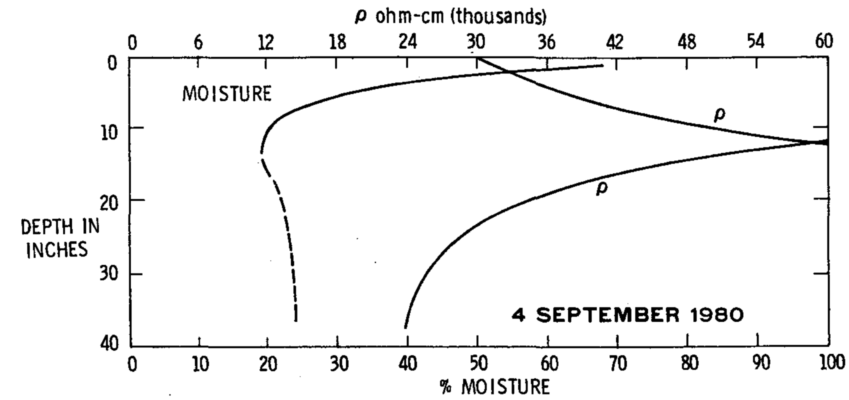


FIGURE 9. SAND AND PALMETTO, SITE P-1, LONG POINT, PANAMA CITY, FLORIDA (4 SEPTEMBER 1980)

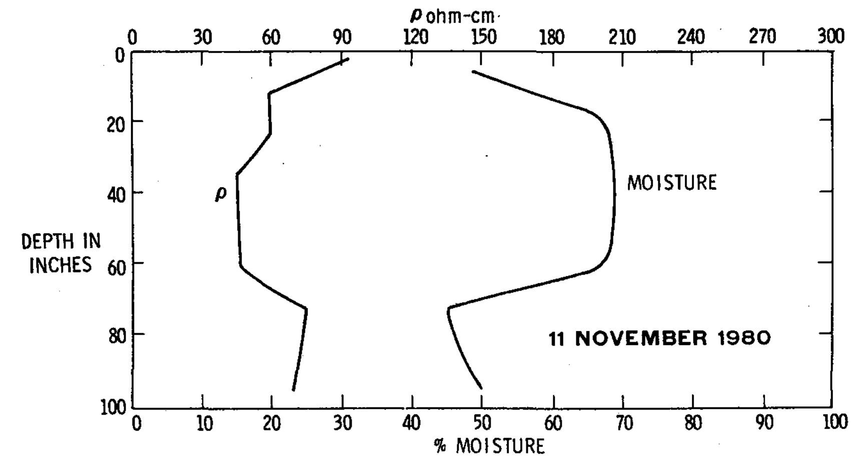


FIGURE 10. ORGANIC CLAY, PELICAN ISLAND, GALVESTON, TEXAS (11 NOVEMBER 1980)

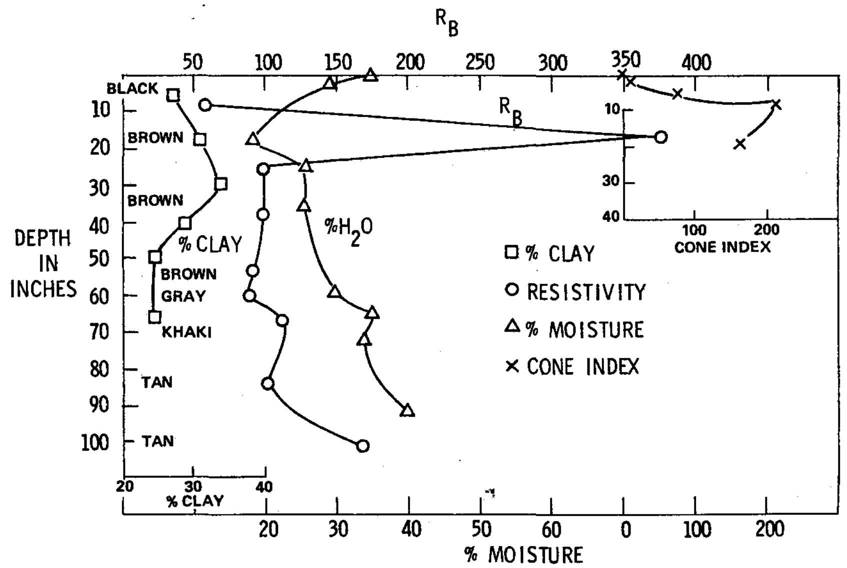


FIGURE 11. STUBBLE FIELD TEST AT FARGO, NORTH DAKOTA

sandy soil containing a small percentage of clay with an electrolyte having a resistivity of approximately 42 ohm-centimetres. Note that the curves are tending to converge in the drier soil at the surface with a corresponding increase in cone index and electrical resistivity. Resistivity measurements taken in the field corresponded well with those taken in the laboratory on remolded samples, supporting the diminished influence of remolding on soils that are predominantly sandy. No structural anomalies in the soil were evident in the resistivity curve taken in the field. Note that this curve is tending toward zero slope at the water table which was at about 6 feet. It is from such a resistivity versus depth curve, which may be generated in real-time, that we hope to predict cone index. This possibility is enhanced greatly by obtaining the two valuable end points on the resistivity curve corresponding to the surface and in or near the water table where the curve has essentially zero slope. It is recognized that in many circumstances the water table is too deep to probe and a moisture gradient curve may be useful in predicting its depth.

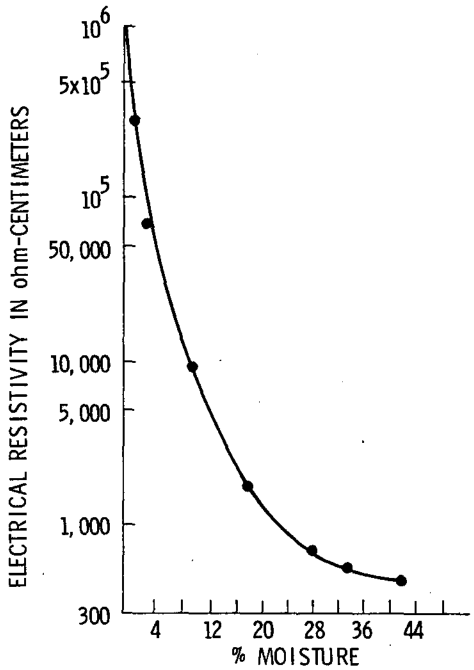


FIGURE 12. LABORATORY TEST ON MONTMORILLONITE CLAY, SITE L-1, FARGO, NORTH DAKOTA

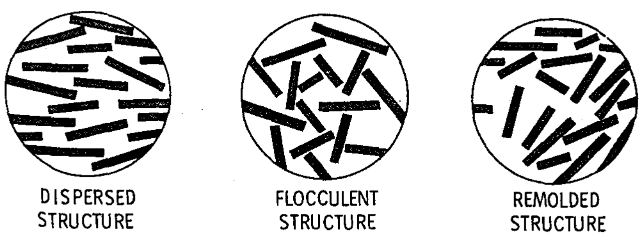


FIGURE 13. CLAY STRUCTURE

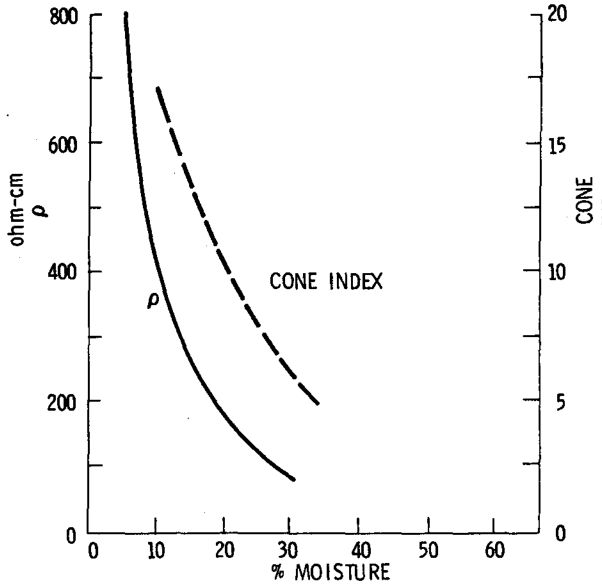


FIGURE 14. BUSHY SITE, CORPUS CHRISTIE, TEXAS

V. PROPOSED SYSTEM

Figure 15 shows a block diagram of the envisioned trafficability prediction system.

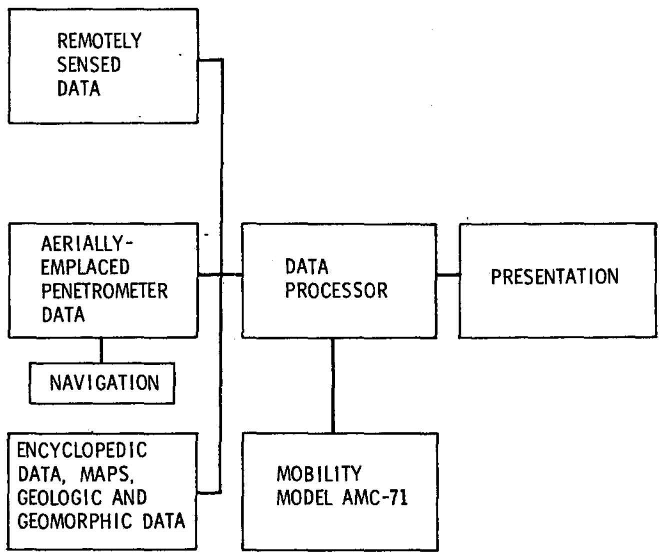


FIGURE 15. PROPOSED TRAFFICABILITY PREDICTION SYSTEM

Remotely-sensed data of opportunity will be placed in a data-bank along with other data from maps, etc. A near real-time update of these data will be obtained by aerially implanting soil penetrometers which will provide soil moisture and cone index inputs. The data processor will utilize the Army Mobility model AMC-71 or AMC-74 to compute vehicle trafficability from these various inputs.

A color hard-copy, such as that shown in Figure 16 is envisioned as portraying trafficability information in map form. Several series of these maps may be generated to represent the real-time trafficability condition and projected trafficability conditions due to rain, continued drought, etc. Figure 16 was produced, in part, from multi-spectral scanner information obtained by the Environmental Research Institute of Michigan under contract with NCSC.

VI. CONCLUSIONS

1. Predominantly sandy soils, unable to possess a dispersed or flocculent structure, will have a resistivity response that may be related to moisture content hence to cone index.

2. Predominantly clayey soils will possess a dispersed, flocculent or remolded structure which shows promise of differentiation by resistivity measurements, which in turn, may be related to moisture content hence to cone index.

3. The simultaneous collection of penetrometer deceleration data with electrical resistivity data appears worthwhile. The deceleration data will define zones of different shear strength and the resistivity data will provide information on moisture content versus depth and the structure of the soil.

4. A knowledge of soil structure and moisture content is of considerable value in predicting vehicle trafficability.

5. Some degree of soil classification is possible by electrical resistivity methods due to the non-ability of sands to electrically exhibit a flocculent or dispersed structure in the presence of an electrolyte of uniform resistivity. Hence, a smooth curve of resistivity versus depth from ground surface toward the water table would very likely indicate a substantially sandy soil containing moisture distributed by capillary action. Rainfall would cause a corresponding resistivity anomaly as I have demonstrated.

6. In many geographical locations the soil type is known to depths which could be of concern to trafficability, generally 3 to 5 feet. This knowledge supports the resistivity/deceleration trafficability prediction approach.

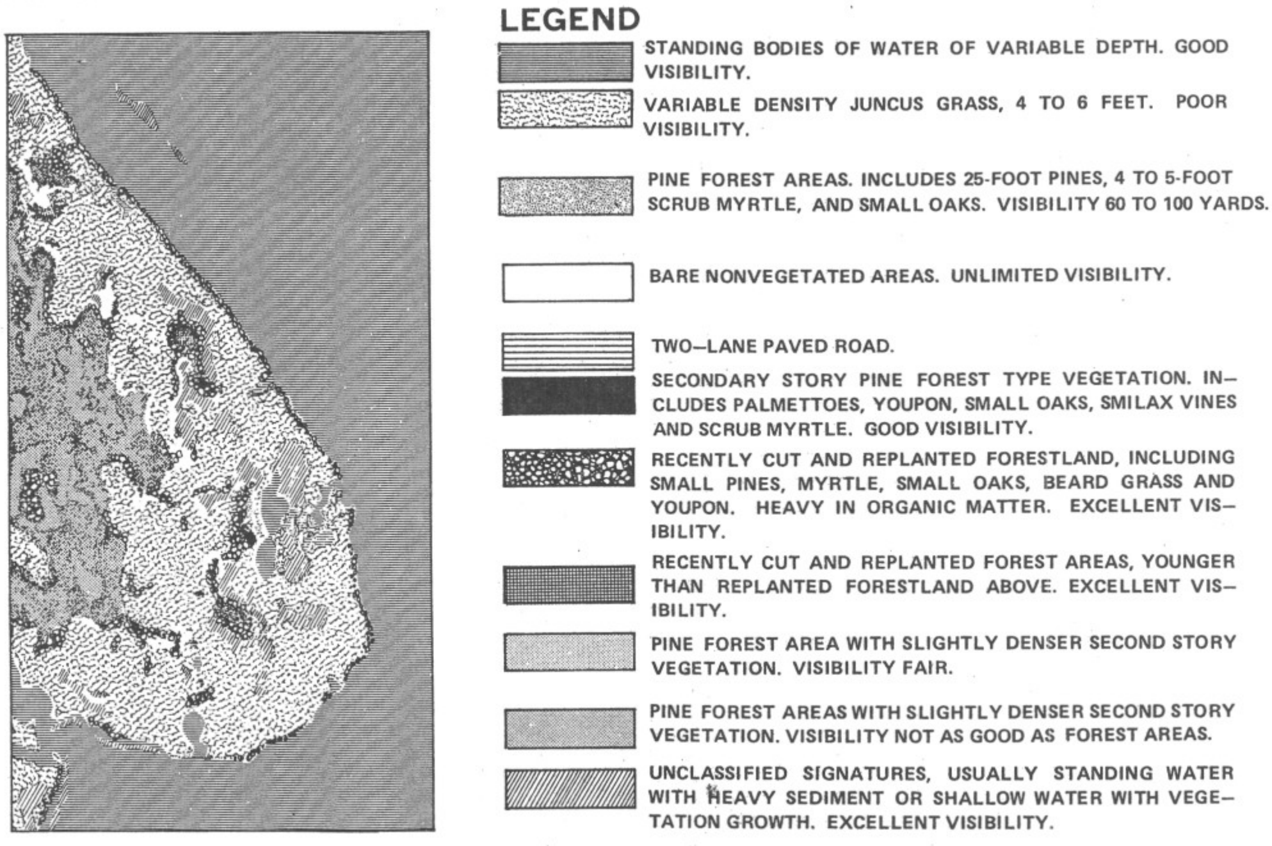


FIGURE 16. LAND COVER CLASSIFICATION MAP

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AUTHOR BIOGRAPHICAL DATA

James L. Kirkland. Mr. Kirkland gained his early experience in commercial broadcasting and shipboard radio and participated in the early development of aircraft RADAR at the Naval Research Laboratory, Washington, DC. His recent experience, gained as a Physicist at the Naval Coastal Systems Center, Panama City, Florida, is in magnetic detection and radio wave propagation in which he holds several patents for instrumentation. His current assignment is the development of ground-truth instrumentation subsystems in support of remote-sensing systems. Mr. Kirkland holds a BS degree in physics from Florida State University.