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THE NCSC AERIALLY-DEPLOYED SOIL PENETROMETER (ADSP)

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I. ABSTRACT

The Aerially Deployed Soil Penetrometer (ADSP) is designed to obtain vehicle mobility data remotely when implanted aerially.

Exploratory development of the Aerially Deployed Soil Penetrometer was begun in 1979. Two parameters have been studied: (1) deceleration of the soil penetrometer as it penetrates the soil, and (2) electrical resistivity of the soil. Correlations of these parameters with Army Cone Index, the current manually obtained mobility figure-of-merit, has been attempted with varying degrees of agreement. The current opinion of the Naval Coastal Systems Center (NCSC), and of several independent research organizations, is that the ADSP is capable of generating a Mobility Index from deceleration and electrical resistivity data which is obtained without the necessity of operators on the ground. The data may be either manually or machine processed.

Completion of the Exploratory Development Phase signals the beginning of the System Development Phase. Experimental field ADSP systems are expected to be available for testing in mid 1986.

The Exploratory Development was sponsored by the US Marine Corps Development and Educational Command, Quantico, VA.

II. BACKGROUND

Mobility of troops and materials has been a problem for the military for centuries. History has recorded numerous instances of the failure of military missions due to adverse mobility conditions frequently resulting almost instantaneously from rainfall. Two noteworthy instances of this change in mobility conditions caused by rainfall were the Battle of Agincourt (1415) and the Battle of Waterloo (1815), the former being confined principally to mobility problems encountered by foot soldiers and draft animals whereas the latter involved mobility problems for foot soldiers, draft animals and a new piece of military hardware: the wheeled cannon. This paper won't attempt to present a detailed account of these two events but the reader is encouraged to explore the accounts of these battles, and will, in so doing, be exposed to military mobility problems that have persisted for centuries and promise to be problems in the future.

It is evident that the trafficability of natural terrain is governed by many factors but, omitting foliage and slopes which are often obvious, visible limitations, the two principal factors are soil type and soil moisture content. Unfortunately, soil moisture content cannot be predicted, to the required temporal resolution, from weather patterns. But, since soil types are often known in many areas of the world, the problem of assessing an area for military mobility appears to be partially solved by measuring the moisture content of the soil.

Soil trafficability is now assessed with the Army Cone Penetrometer developed by the US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi. (Figure 1) Detailed descriptions of this technology are in the literature. It is sufficient to say here that the instrument is a manual version of the classical cone

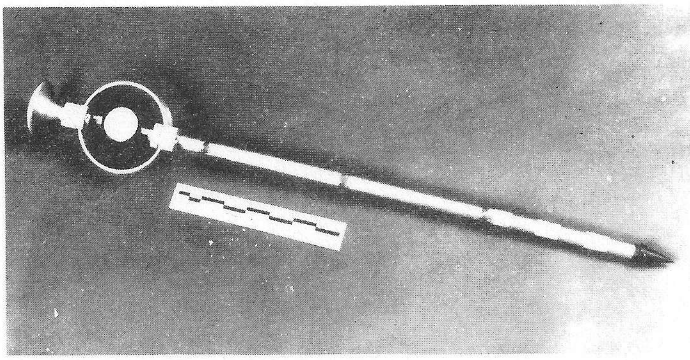

FIGURE 1

penetrometer and provides a static cone index measurement. The instrument is shown in use in Figure 2.

FIGURE 2

Readings of Army Cone Index are inputs to the Army Mobility Model, AMC-74 and the NATO Mobility Model. However, one of the principal drawbacks to obtaining Army Cone Index in an operational situation is the necessity of using ground personnel to perform the measurements. This process is time consuming and hazardous in some situations.

The ADSP is designed to obtain similar mobility information rapidly by deployment from aerial platforms, rockets, etc. It is planned to use the ADSP mobility data in conjunction with other near-real-time information from multispectral remote sensing systems, side-scan radars and conventional map data, to machine process all of these inputs and deliver a mobility map. The mobility map will embrace a wide variety of encyclopedic data, when available, such as soil type, foliage, slope, and expected soil moisture which will be updated and enhanced by ADSP real-time data to provide a remotely obtained machine-processed mobility map portraying GO-NO GO areas for specific vehicles and troops.

The ADSP approach has many advantages. First, it is a totally remote system requiring no operators on the ground. Second, it measures at least one parameter--electrical resistivity --which is an analog of soil moisture, such data being pertinent to soil strength, and moisture data are not bound up into other data like the force reading obtained by the cone penetrometer. Third, by integrating ADSP data with encyclopedic data, we are able to extend our mobility forecast by programming the computer to assess the changes that may occur in the trafficability of the penetrated soil resulting from changing weather conditions. And fourth, when no other data are available for use with the ADSP, the ADSP data alone can be invaluable for remotely sensing or manually assessing the trafficability of an area.

III. DESIGN FEATURES OF THE ADSP

An experimental ADSP is shown in Figure 3. This unit is built from commercial steel water pipe, equipped with

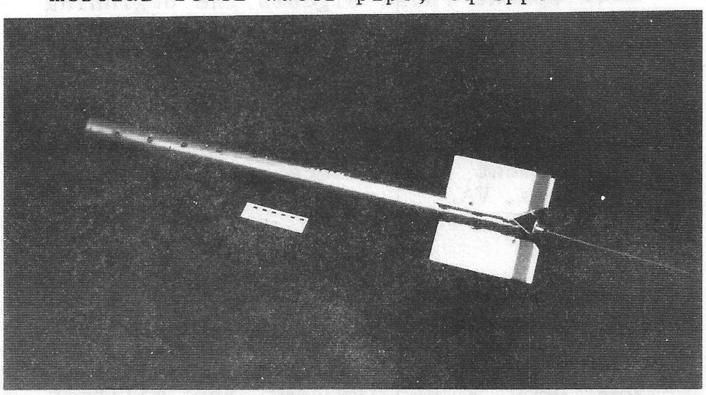

FIGURE 3

flight-stabilization fins, and a radio telemetry transmitter. The protruding electrodes perform the electrical resistivity measurement. An accelerometer and a battery for powering the entire unit are inside of the housing. The ADSP is intended to be disposable. The ADSP shown is designed for launching from a helicopter at altitudes of 400 to 1000 feet and, in most soils, will penetrate to about 4 feet. This particular unit has survived about 20 air drops without failure. Although inexpensive and disposable, the ADSPs used to date have been used repeatedly for reasons of economy as well as for collecting reliability data. Conventional off-the-shelf data-processing equipment has been used and is not shown.

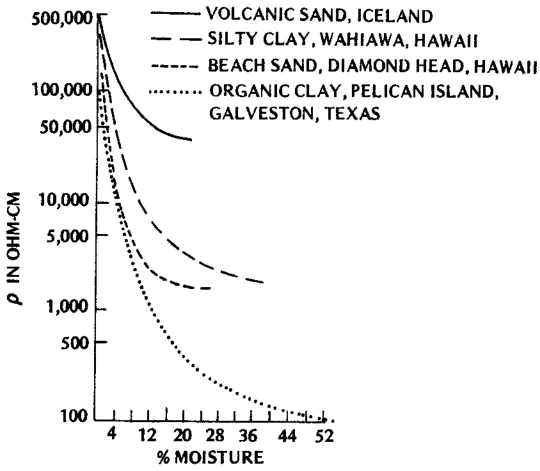

FIGURE 4

IV. THEORETICAL CONSIDERATIONS

The theoretical feasibility of assessing soil trafficability by the ADSP is presented in detail in a previous paper.[1] This paper outlined the relationship between electrical resistivity of the soil and the moisture contained in the soil pores, and demonstrated that in limited field tests, the Army Cone Index of a soil was related to the electrical resistivity of the soil. This relationship, which has been confirmed repeatedly since the original paper was presented in 1981, has been refined to provide for variations in soil type. It is recognized that ground water will vary in electrical resistivity with geographical location. This effect is shown in Figure 4. However, since the gradient of moisture content, from the ground surface downward, is the governing parameter, the varying electrical resistivity of the ground water is effectively eliminated by using the gradient of electrical resistivity data as shown in Figure 5.

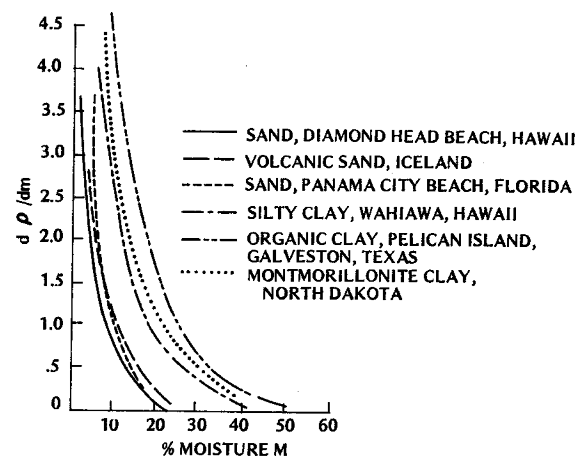

FIGURE 5

The approach should not discourage use of the absolute reading of electrical resistivity obtained by the ADSP. Research since 1981 has shown that the absolute values of electrical resistivity are of considerable value in defining the type of soil moisture present; for example, differentiating a saline or fresh water environment. Then the gradient would provide the soil moisture distribution versus depth. A good example of this approach is shown in Figure 6.

Figure 6 shows a relationship between the electrical resistivity of the soil, soil moisture, and Army Cone Index. The inverse relationship between Army Cone Index and soil moisture content, and the inverse relationship between electrical resistivity of the soil and its moisture content are obvious. The analogous behavior is used in the ADSP to relate the measured parameter, electrical resisitivity, to soil trafficability.

In one sense, the electrical resistivity data may also help define structural characterisitics. Figure 6 shows this. The anomaly around 20 to 24

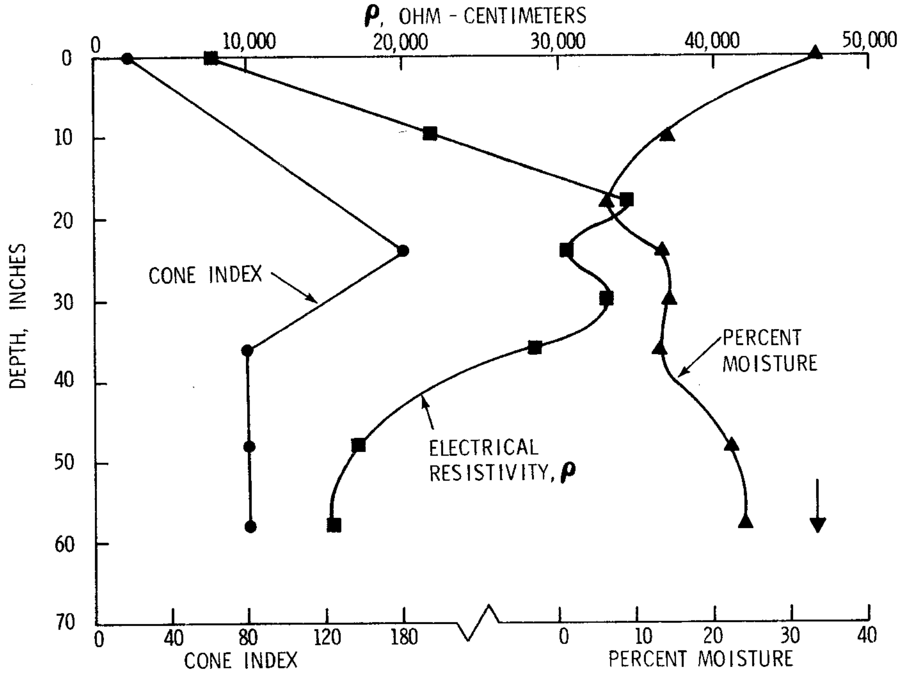

FIGURE 6

inches deep was due to a layer of pea gravel and clay in an otherwise uniformly graded soil above and below this stratum. This coarse stratum, having an Army Cone Index of at least 180, should be detectable in a deceleration profile. The relatively high electrical resistivity of the stratum, 33,000 ohm-centimeters, is characteristic of a dry soil in this freshwater environment. Dryness, in this instance, was caused by the incapacity of the pore spaces to accommodate over 7 percent water. The hard stratum correlated well with both Army Cone Index and electrical resistivity. From studies like this calibrations can be generated for nearly every field condition encountered.

The water table, detected electrically at about 60 inches, serves well as an index of soil saturation, and, so, is an excellent check-point of the electrical resistivity of the saturated soil.

Note also that Army Cone Index correlates with electrical resistivity. It is this type of correlation that was sought at the outset of the research in this technology. Such a correlation was not observed in predominantly sandy soils and, in the beginning, appeared to be a problem of such magnitude as to suspend further research. However, a fair understanding of the behavior of the electrical resistivity of a sandy soil under the influence of rainfall has been obtained experimentally. These experiments will be discussed next.

V. EXPERIMENTS WITH SANDY SOIL

Several experiments in sands at various geographical locations in Florida, Georgia, Texas, California, Alabama, and Hawaii have revealed a difficulty in measuring Army Cone Index reliably and repeatably and correlating the measurements with existing mobility conditions. This experience led to a series of experiments in the sandy soil at Panama City, Florida. The experiments were designed to observe the effects of rainfall on a predominantly sandy soil having very little vegetative cover. A given area would be studied over a period of time sufficient to demonstrate how cyclical rainfall affects the sandy soil in terms of electrical resistivity, moisture gradient, Army Cone Index, and observed mobility conditions. The chosen area had been studied occasionally for 2 years and its characteristics were known well.

The procedure for this experiment was to take data on some arbitrary date (in this case 17 February 1983) and to observe this same area at intervals, correlated with rainfall, to observe the changes in soil moisture gradient, and to observe at some date in the future the same reference conditions. When the reference conditions were met an assessment of the soil moisture gradient would be made from measured soil resistivity gradient alone, then correlated with the cone index. The objective was to see if a reading of the gradient of resistivity could be interpreted in terms of soil moisture gradient (percent) and to what accuracy. Assuming a correlation existed between cone index and moisture gradient, this correlation would be sought.

The soil tested was sand, grain size 0.001 to 0.005 inch diameter, with a little organic matter at about 24 inches deep. Sand of this type cannot be remolded. The results of the experiments are shown graphically in Figure 7.

One salient feature of the experiment was the generation of an electrical resistivity curve which could be compared with a reference curve to predict soil moisture gradient (Figure 7, 17 February 1983 compared with the curve of Figure 7, 17 March 1983). Note that by using electrical resistivity data alone, soil moisture is simultaneously measured within about 3 percent of the actual value. This experiment illustrated the feasibility of the ADSP technical approach for sands.

Note that Army Cone Index apparently does not correlate with either electrical resistivity or moisture content. Army Cone Index in this area usually measures 10 to 20 at the surface regardless of moisture content over the range 8 to 14 percent. A wider variation in Cone Index would have been expected. Likewise note the wide disparity in Cone Index versus depth between the reference curve 17 February 1983 and the curve 17 March 1983. Both experiments revealed about the same moisture gradient and should have yielded comparable Cone Indexes. The tests were conducted within 5 feet of each other and not separated by structural or other anomalies, which might account for this variation in Cone Index. Soil anomalies have never been observed in this area.

Several conclusions about sand were reached: 1) An Army Cone Index of 10 to 20 is usually obtained in the relatively dry surface sand (up to 1 inch deep),

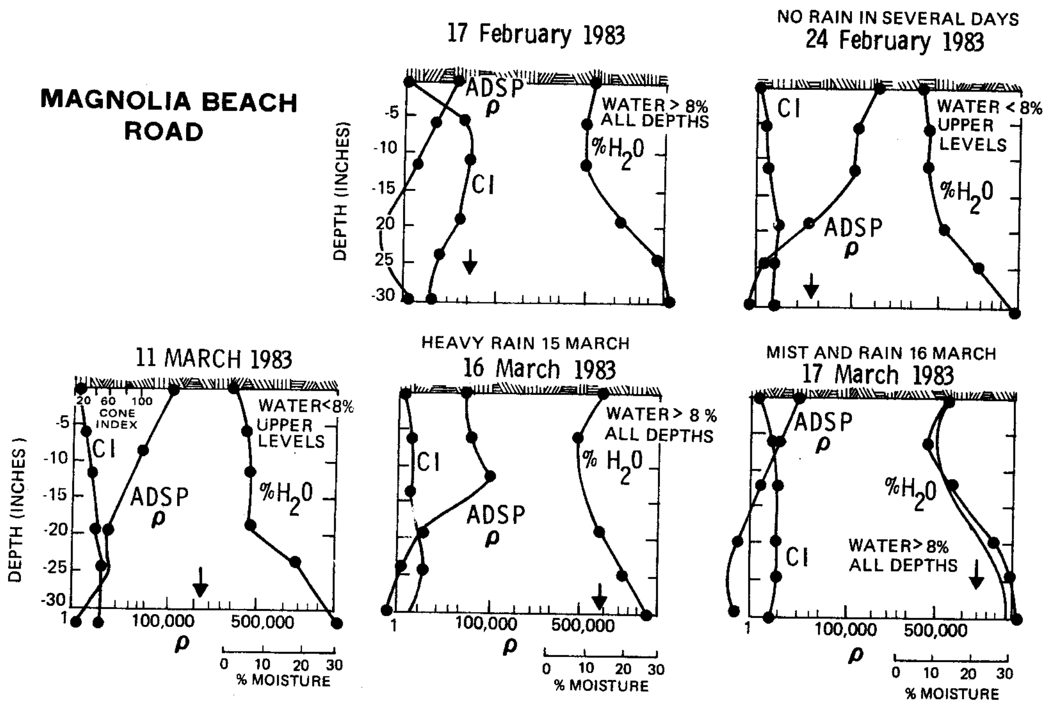

FIGURE 7

corresponding to moisture contents of near zero to about 7 percent. Sand this dry poses a mobility problem. An electrical resistivity measurement indicates this dry condition; 2) When the moisture content is increased beyond 7 percent an apparent cohesion occurs which develops a soil strength capable of supporting many types of vehicles. The measured increase in Army Cone Index is surprisingly small (from 20 to 30); 3) At moisture contents near saturation (usually 20 to 30 percent) the strength of the sand decreases and again presents a mobility problem; and 4) For mobility assessment, clays and clay-sand mixtures (clay at least 10 percent) behave conversely to sands when the mixtures contain less than about 20 percent moisture.

The conditions described are all measurable remotely or manually with the ADSP.

VI. FIELD EXPERIMENTS WITH SAND AND CLAY

Experiments were conducted using the ADSP impacting from about 500 feet altitude in predominantly sandy and clayey soils. Two of these experiments are described. The impact velocity for both penetrations was about 130 feet per second.

1. Beach Sand, Camp Pendleton, CA., grain size about 0.6mm. The results of this air drop are shown in Figure 8. The correlative data are electrical resisitivity, moisture content, and deceleration, all of which exhibit smooth responses to about 18 inches deep. Army Cone Index is usually high (60, about 2 inches deep) and was attributed to the large grain size compared to Panama City, Florida sands. Moisture content of less than 5 percent over the first 36 inches indicated that this was a NO GO mobility zone. Evidence of this mobility condition was clear in that no vehicles, such as pickup trucks, vans, etc., ventured onto these sands, unless landing mats were placed as a runway, and the only vehicle observed to travel in the bare sand was a US Marine Corps front-end loader commonly referred to as the "TEREX."

2. Dry Lake, Camp Pendleton, CA. Grain size 77 percent passed the No. 200 sieve. The results of this air drop are shown in Figure 9. The correlative data are electrical resisitivity, moisture content, Army Cone Index, and deceleration. The experiment was conducted in August when the lake bottom was dry and beginning to crack. The ADSP penetrated at an angle and only the fins remained visible which caused the surface electrical resistivity data to be lost. This will be avoided in future ADSPs which will be designed to obtain

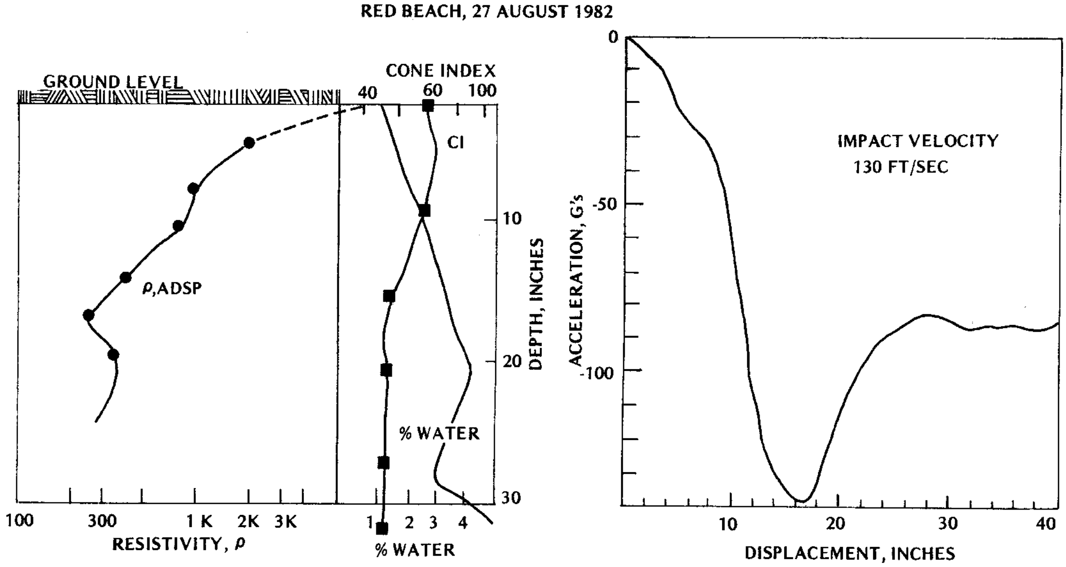

FIGURE 8

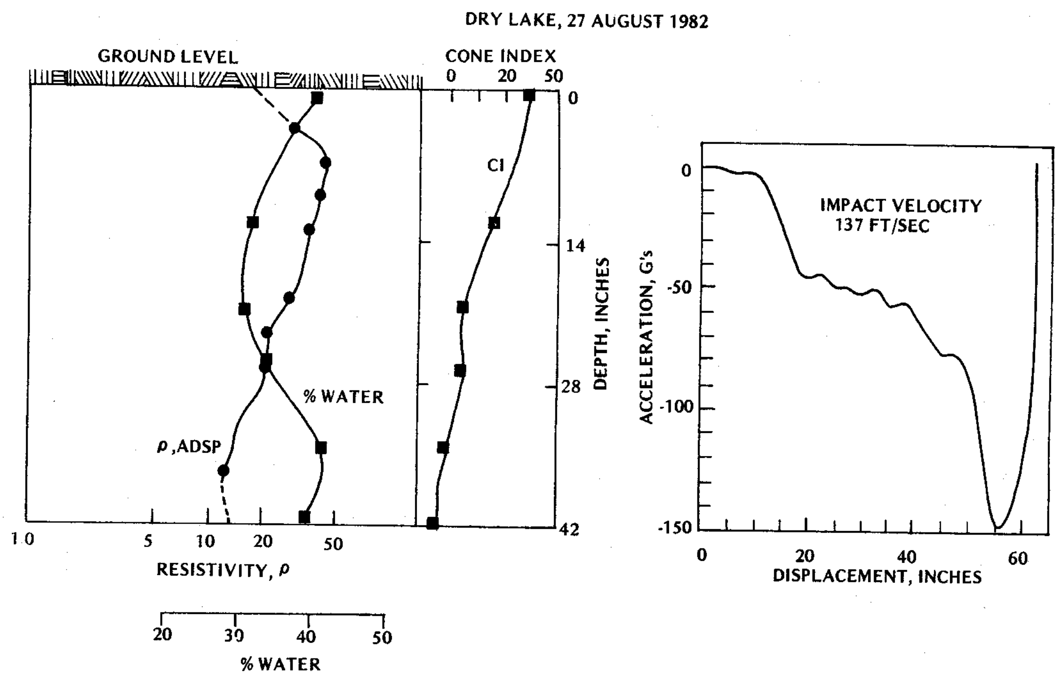

FIGURE 9

continuous resistivity data in real time over the complete penetration via the ADSP nose electrode. The tests in this section used radio-telemetered deceleration data; electrical resistivity data were obtained manually immediately after the ADSP had penetrated and stopped.

Note the close correlation between Army Cone Index and electrical resistivity beyond the relatively dry surface zone on the dry lake. This dry zone appears as the abrupt deceleration in the deceleration profile over the interval 10 to 20 inches.

The correlation between electrical resistivity and moisture content is excellent and the inverse relationship is shown. External calibration probes furnished the dotted-line portions of the resistivity curve at the surface and at 42 inches.

The Army Cone Index curve does not exhibit the soil structure as well as the resistivity - moisture curves and the deceleration profile. However, the Army Cone Index does show that a diminishing cone index is correct because this is a plastic soil and such a cone index response is expected.

This soil was rated as NO GO at the surface to about 4 inches, GO from 4 inches to about 10 inches, then NO GO beyond 10 inches based on the electrical resistivity alone. The average deceleration (30g's) was accepted over this depth because no information was available to define the effects of adherence of this plastic soil to the ADSP housing (an effect remaining to be studied) versus the nonadherence of sand to the ADSP housing.

The dry lake is an excellent example of a mobility problem and emphasizes the value of obtaining mobility data over a depth of several feet rather than being limited to the visual inspection of the surface afforded by the eye or by sensors operating in the visual portion of the spectrum. This condition is graphically demonstrated in Figure 10 and is discussed here.

In a previous experiment the surface of the lake bed visually appeared to be dry, hard, and very strong. Pickup trucks, automobiles, and multiton trucks traversed the surface readily, but rarely in the same ruts. The front-end loader, which could readily travel repeatedly in its ruts over the beach

FIGURE 10

sand, is shown bogged in the dry lake on its seventh pass in the same ruts. This NO GO mobility condition was predicted from electrical resistivity information and confirmed by an Army Cone Index of 10 below the hard crust of CI 50.

VII. PROPOSED ADSP SYSTEM

The proposed ADSP System is shown in Figure 11.

Feasibility of the system depicted has been demonstrated at NCSC for the parameters shown. The aim of the system is to deliver the deceleration profile, the electrical resistivity data and navigation data to the data processor, to relate this body of data to certain stored data pertaining to soils in general, and to the area specifically sampled, and to present a color map portraying the mobility conditions for vehicles and troops. Several iterations may be provided to inject changes in temperature, rainfall, drought, and other temporal factors affecting mobility, each iteration being essentially a mobility map valid for those conditions. And if one of these mobility forecasts is selected for use, ADSP's should be dropped in critical geographical locations to provide a near real-time update to confirm mobility conditions. Although navigation and other constraints may permit sampling only in general areas, repeated sampling in the chosen and critical areas should be given priority.

An example of a computer-generated color mobility map is shown in Figure 12.

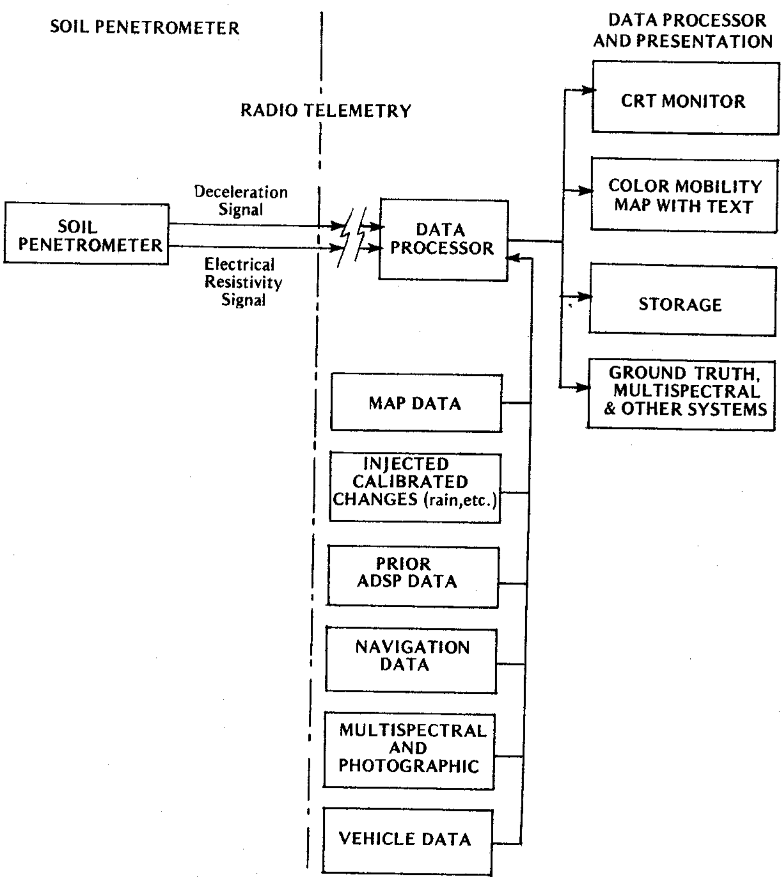

FIGURE 11

VII. CONCLUSIONS

The ADSP is capable of penetrating most soils to an adequate mobility assessment depth when dropped from operational altitudes. The deceleration profile, resulting from this penetration, appears to be interpretable in terms of soil strength and, to some degree, stratigraphy and soil type. Simultaneously, the electrical resistivity profile obtained is interpretable in terms of soil moisture gradient over the penetrated depth. All of this penetration data can be telemetered by state-of-the-art radio telemetry and data processing can be accomplished manually or by machine.

It appears possible to generate a mobility index based on the parameters measured by the ADSP, such an index also being correlated, where applicable, with Army Cone Index which relates certain soil factors to military vehicles. Typical mobility maps have been computer generated to demonstrate the applicability of ADSP data to a military scenario.

Rating Cone Index, a number derived from remolded soil, being the desired number, may be possible to obtain. The ADSP appears capable of delivering both statically (penetrometer left in place) and dynamically obtained data (during the penetration event) which may be interpreted and compared in both the undisturbed and remolded (drag-down deformation) soil states.

Off-vertical penetrations do not appear to detract from the ADSP's ability to obtain satisfactory electrical resistivity measurements, but do reduce the depth over which the moisture gradient is measured.

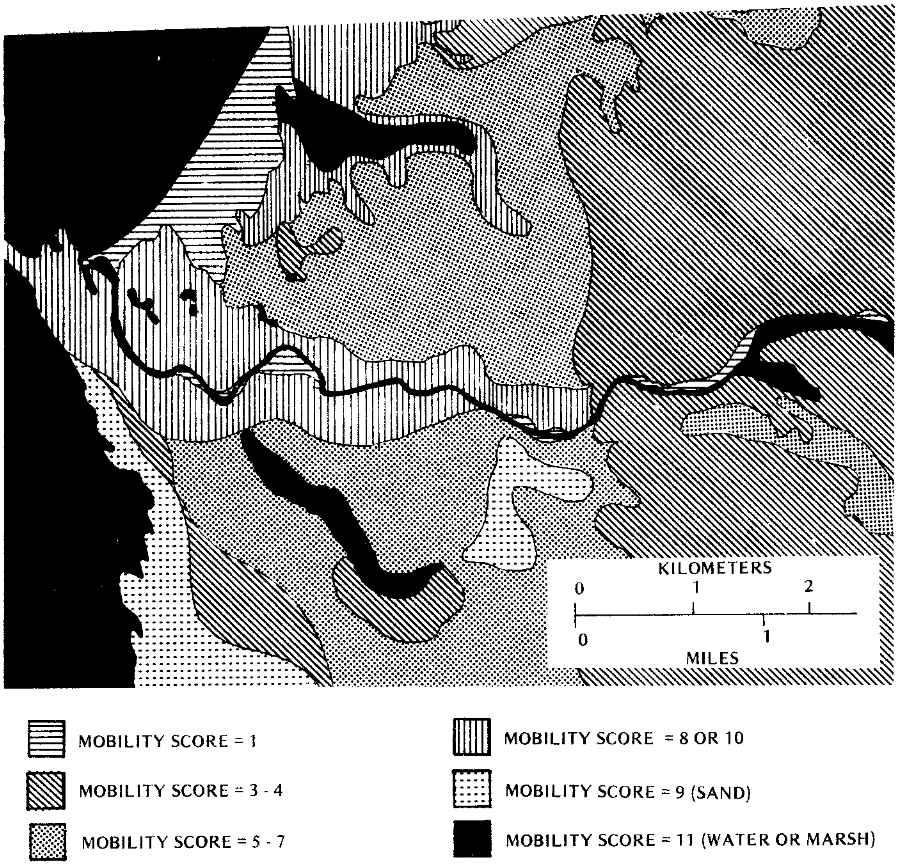

FIGURE 12

Sufficient Exploratory Development has been completed to support the Engineering Development of the ADSP.

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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.

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