A PERCUSSION PROBING TOOL FOR THE DIRECT SENSING OF SOIL CONDUCTIVITY

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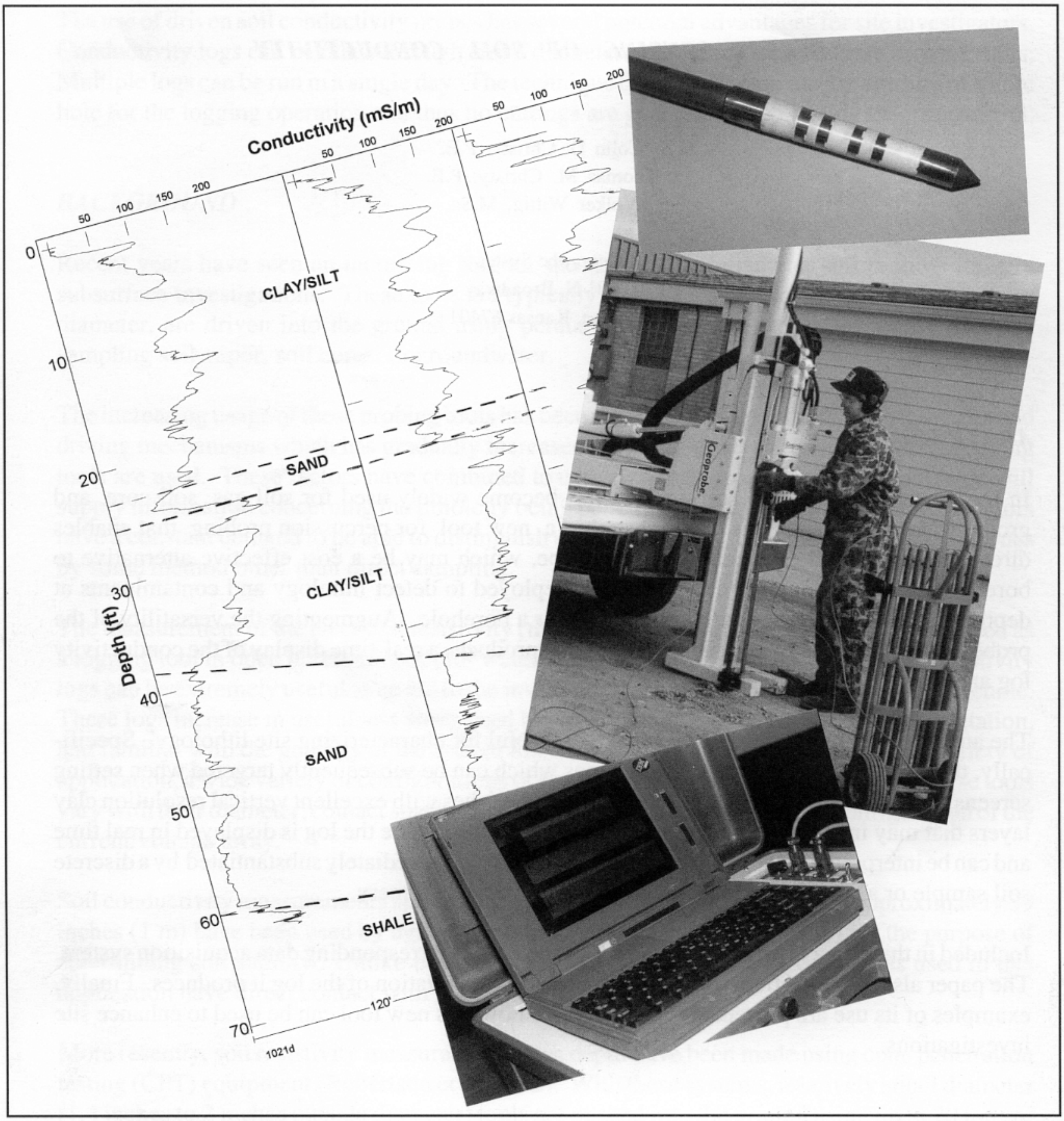

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A PERCUSSION PROBING TOOL FOR THE DIRECT SENSING OF SOIL CONDUCTIVITY

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ABSTRACT

In recent years, percussion soil probing has become widely used for soil gas, soil core, and groundwater sampling. This paper describes a new tool for percussion probing that enables direct sensing of soil conductivity. The probe, which may be a cost effective alternative to borehole resistivity logging, can be readily deployed to detect lithology and contaminants at depths of 60 feet and more without the need for a borehole. Augmenting the versatility of the probe is a PC-based data acquisition system that produces a real-time display of the conductivity log and stores the data for further analysis.

The authors have found the system especially useful for characterizing site lithology. Specifically, the conductivity log reveals sand zones which can be subsequently targeted when setting screens for water sampling. Additionally, it distinguishes with excellent vertical resolution clay layers that may influence plume migration. Furthermore, since the log is displayed in real time and can be interpreted in the field, key information can be immediately substantiated by a discrete soil sample or a water sample using the same probing machinery.

Included in this paper is a description of the probe and its corresponding data acquisition system. The paper also explains field use of the probe and interpretation of the log it produces. Finally, examples of its use are presented to demonstrate how this new tool can be used to enhance site investigations.

INTRODUCTION

The purpose of this paper is to present techniques used and data gathered with soil conductivity probes driven into the ground using percussion soil probing equipment. This probe has been used to depths of up to 70 feet (21.3 m) and yields useful information for distinguishing various lithologic features. This paper presents a description of this soil conductivity probe, its construction, the related data acquisition system, sample soil conductivity logs, and an example of log interpretation.

The use of driven soil conductivity probes has several potential advantages for site investigators. Conductivity logs can be made through small diameter holes using light, mobile probing units. Multiple logs can be run in a single day. The technique does not require the pre-drilling of a bore hole for the logging operation and thus no cuttings are generated in collecting the information.

BACKGROUND

Recent years have seen an increasing role for the use of small diameter soil probing tools in subsurface investigations. These tools are typically 1 inch (2.5 cm) to 1.5 inches (3.8 cm) in diameter, are driven into the ground using percussion hammers, and are primarily used for sampling soil vapor, soil cores, or groundwater.

The increasing usage of these probing tools has been accompanied by improvements in tools and driving mechanisms which has gradually increased the depth of investigation at which probing tools are used. These factors have combined to create an increased demand for tools that will supply information concerning the lithology being penetrated by driven probes. Field operators have a constant demand to be able to distinguish sand zones from finer grained silt or clay zones by some method other than direct sampling.

The measurement of the electrical resistivity (the inverse of conductivity) has long been used as a logging tool in open boreholes both for water well and oil well applications. These resistivity logs can be extremely useful as an aid to the investigator in logging the lithology of the borehole. These logs increase in usefulness when used by investigators experienced in log interpretation, and familiar with the geology of the area of interest. Owing to their long history and variety of application, a wide variety of configurations of borehole logging tools has emerged. These tools vary with their diameter, contact spacing, number of contacts employed, and configuration of the current/voltage array.

Soil conductivity measurements and logs of soil conductivity profiles down to approximately 39 inches (1 m) have been used by agricultural scientists (Rhoades et al.,1976) for the purpose of determining soil salinity. Unlike borehole geophysical logging tools, the probes used in this application have direct contact with the soil.

More recently, soil resistivity measurements with depth have been made using cone penetration testing (CPT) equipment (Robertson et al.,1992). With these systems, relatively small diameter (1.4 inches to 2 inches outside diameter) tools are pushed into the ground using up to 20 tons of static weight at ground surface. Again, these tools employ resistivity measurement techniques similar to traditional borehole logging tools, but with the added advantage of direct contact between the soil and the probe and without the need for drilling of an open borehole as a conduit for the logging tool.

Unlike cone penetrometers which rely on static weight to advance tools into the ground, percussion probe units operate by applying an oscillating force or percussion to the top of the tool string being advanced into the ground. The effect of this percussion on soil conductivity measurements and tool life has heretofore been unknown.

The authors have undertaken to develop a probe for the measurements of soil conductivity with depth using a tool which is driven into the ground using a hydraulic hammer. The primary hurdles in the development of this tool concern the aggressive vibrations that a driven tool is subjected to. Prototype models of this probe experienced failures from vibration in contact rings, electrical conductors, and isolating materials. Each of these failure areas was analyzed and changes made in the design of the probe and materials of construction in order to extend probe life.

PROBE CONSTRUCTION

The sensing portion of the probe (Figure 1) consists of a steel shaft running through the center of four stainless steel contact rings. An engineering grade plastic electrically isolates the rings and the shaft from each other. This part of the probe is about eight inches (203.2 mm) long with a 1-inch (25.4 mm) diameter at the drive point and a 1-1/8-inch (28.6 mm) diameter just above the top ring. This geometry results in a one degree taper angle to assure soil contact with the rings as the probe is being pushed to depth. Above the sensing part of the probe is a two-foot (0.61 m) long steel shaft with a 1-inch

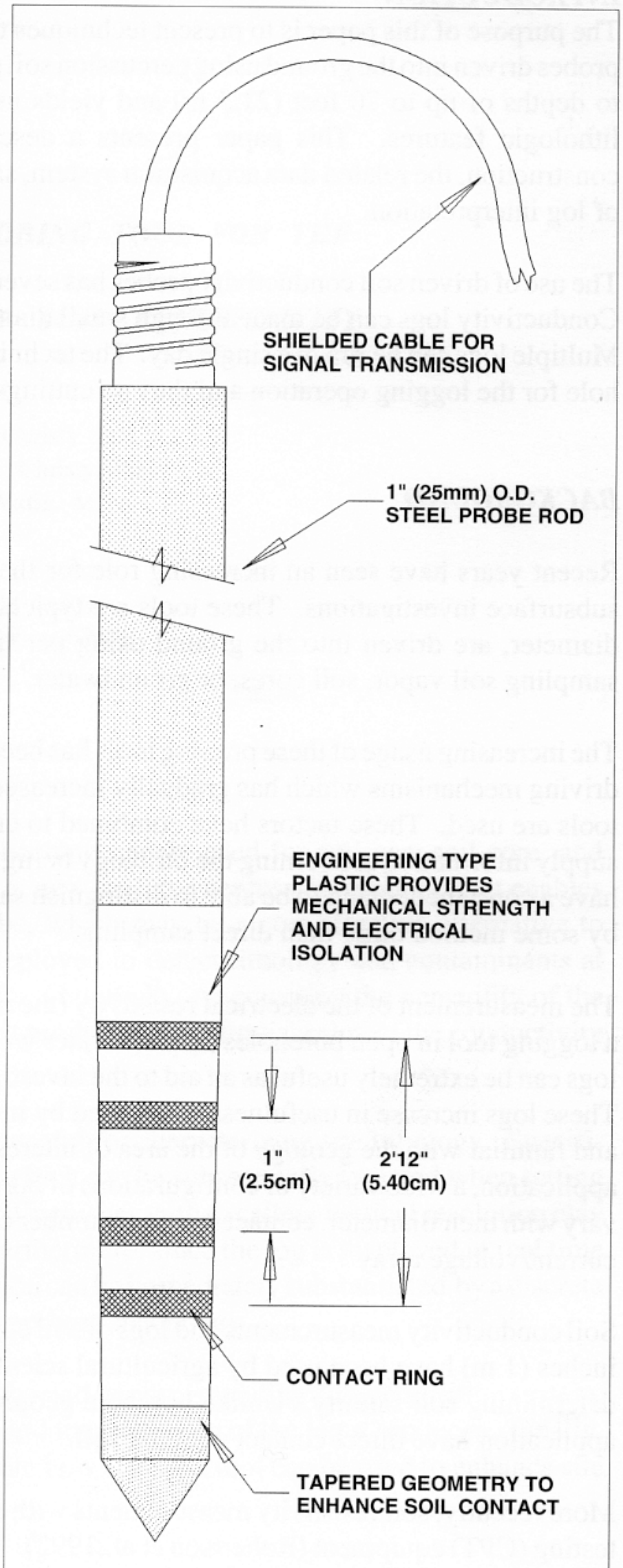


Figure 1. Conductivity Probe Construction

(25.4 mm) outside diameter and a 1/2 inch (12.3 mm) inside diameter. The shaft houses a shielded signal cable which is integrally connected to the probe via a watertight rubber seal.

Due to the high shock environment that the probe is subjected to, none of the electronics required for the system are built into the probe itself. Instead, the source for alternating current excitation of the probe and all signal conditioning circuitry (for voltage and current measurement) is housed in a separate ruggedized case. This construction philosophy also makes the probe less expensive to replace in case of failure in the field.

SYSTEM DESCRIPTION

A pictorial view of the conductivity system used in this work is shown in Figure 2. A probe approximately 1-1/8 inches (28.6 mm) in diameter with isolated contacts is advanced through the ground using a hydraulically driven percussion probing machine. Percussion is applied to the top of the probe rod at a rate of approximately 30 Hz and may result in instantaneous forces greater than 12,000 pounds being transmitted through the probe rods. Percussion also results in resonant vibrations which move along the probe rod between each blow. The probe is advanced to depth at a variable rate which depends on the strength of the soils being encountered and the cumulative friction on the probe rods. This rate typically varies from 2 to 25 feet per minute (0.6 to 7.6 meters per minute). Sections of probe rod are added as necessary to reach greater depth.
A signal cable attached to the probe is run through the inside diameter of the rod and then into

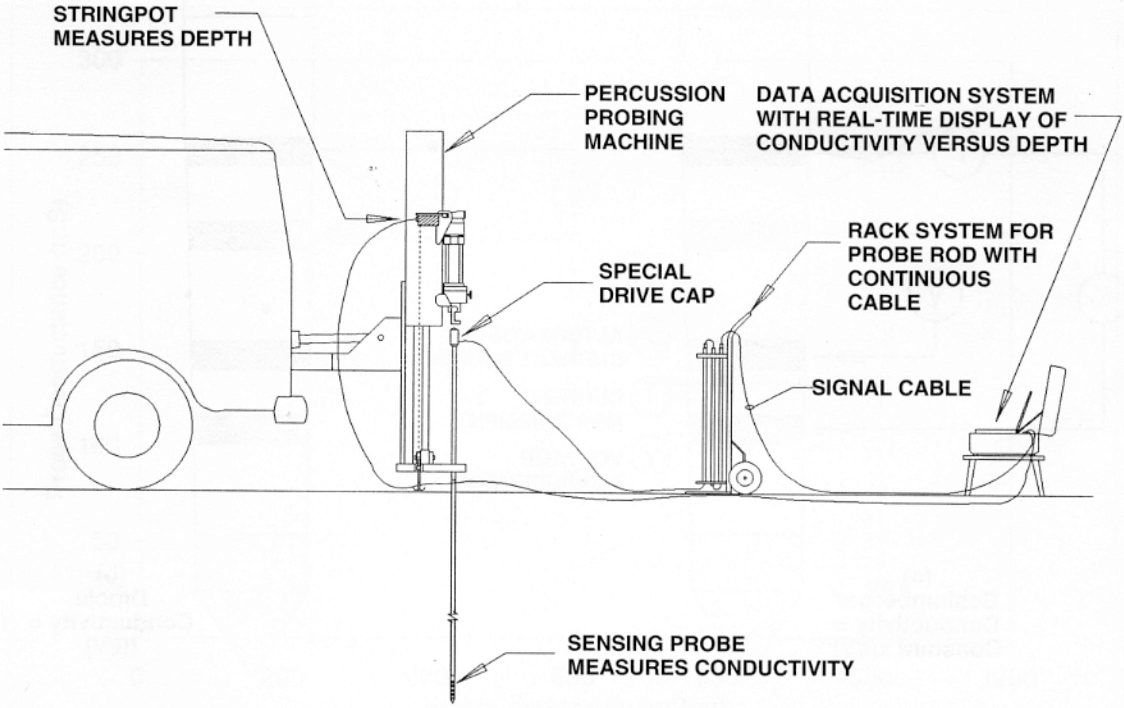


Figure 2. Major Components of the Conductivity Probe System

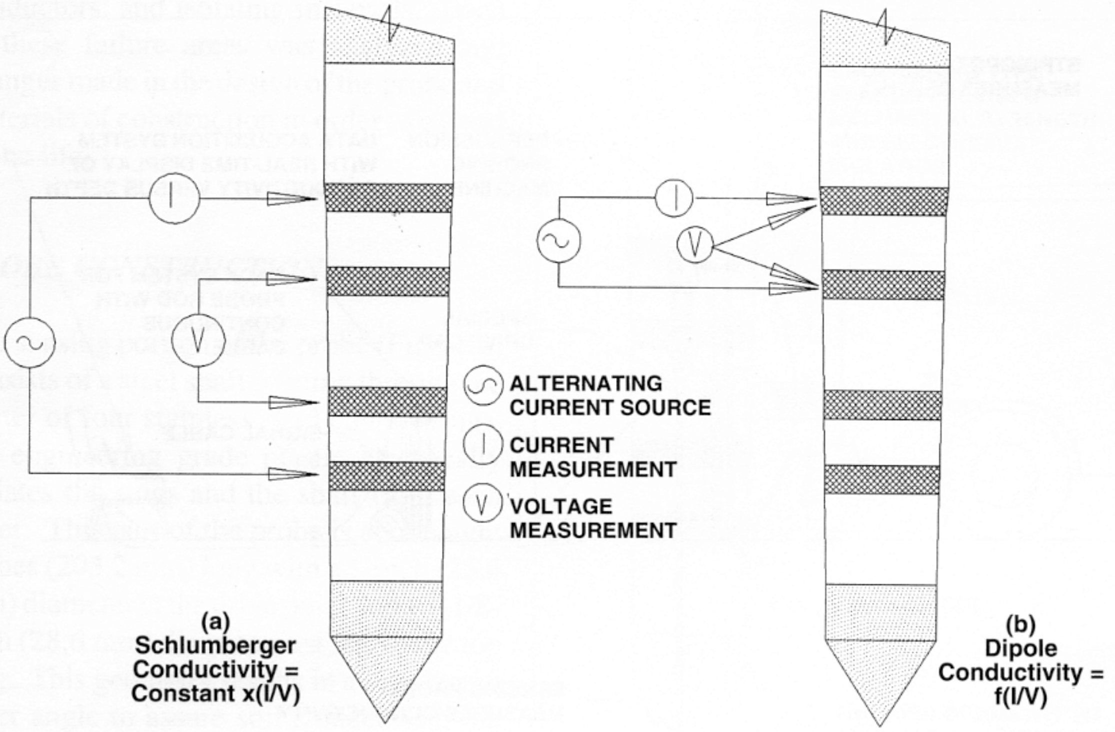
a PC-based data acquisition system housed in a ruggedized case. A specially designed probe rod cart allows the rods to be stored and handled with the cable strung through them.

Depth measurement is obtained from the stringpot system configured to measure the distance from the driving mechanism to ground surface. When driving the rod, a change in string length is indicative of the probes progression through the soil. The stringpot signal, which is proportional to the length of the string, is connected by a cable into the data acquisition system. The stringpot signal is used both to determine probe position and the speed at which the probe is moving.

A notebook PC, mounted in the case, provides a real-time display of conductivity versus depth during probing. In addition to the display, the data is stored in spreadsheet format for later analysis.

CONDUCTIVITY ARRAYS AND CALIBRATION

Two different conductivity arrays are presently being used (Figure 3), although more may be possible . The first is the Schlumberger array, which employs all four probe contacts, and the second is the dipole array, which uses just two.



(a)
Schlumberger
Conductivity =
Constant x(I/V)

(b)
Dipole
Conductivity =
f(I/V)

Figure 3. Electrode Arrays for Conductivity Measurements

In the Schlumberger array (Figure 3a), current is sent through the formation between the top and bottom contacts of the probe. This current is measured along with the voltage that results across the middle two contacts. The conductivity is merely a constant times the ratio of current to voltage. This array is effective even when soil contact with the probe is not ideal. Specifically, if poor contact causes less current to flow between the top and bottom contacts, the voltage drop across the inside contacts would also decrease. The Schlumberger array is identical to the widely used Wenner array except that the Wenner array has all four contacts evenly spaced.

Figure 4 shows the response of the Schlumberger array to being immersed in liquids of known conductivity. In accordance with theory, the response is basically linear, especially up to 400 mS/m, which is higher than the soil conductivities encountered in this work. Linear regression was applied to the data shown to determine the calibration constant for this probe.

Although the Schlumberger array yields good vertical resolution, it may be desirable to increase resolution for some applications. This could be done by constructing a probe with less spacing between the four contacts. Alternatively, it may be more practical to use the same probe connected in a dipole array. The dipole, shown in Figure 3b, uses just two contacts of the probe by passing current from one contact to the other through the formation and measuring the voltage across the same two contacts. Such an array would not be considered feasible for surface resistivity measurements (Milsom, 1987) because poor contact with the soil would produce an artificially high resistivity. However, much better contact is obtained during soil probing, making the dipole a viable option. The dipole has the added benefit of allowing alternate uses of the remaining contacts on the probe.

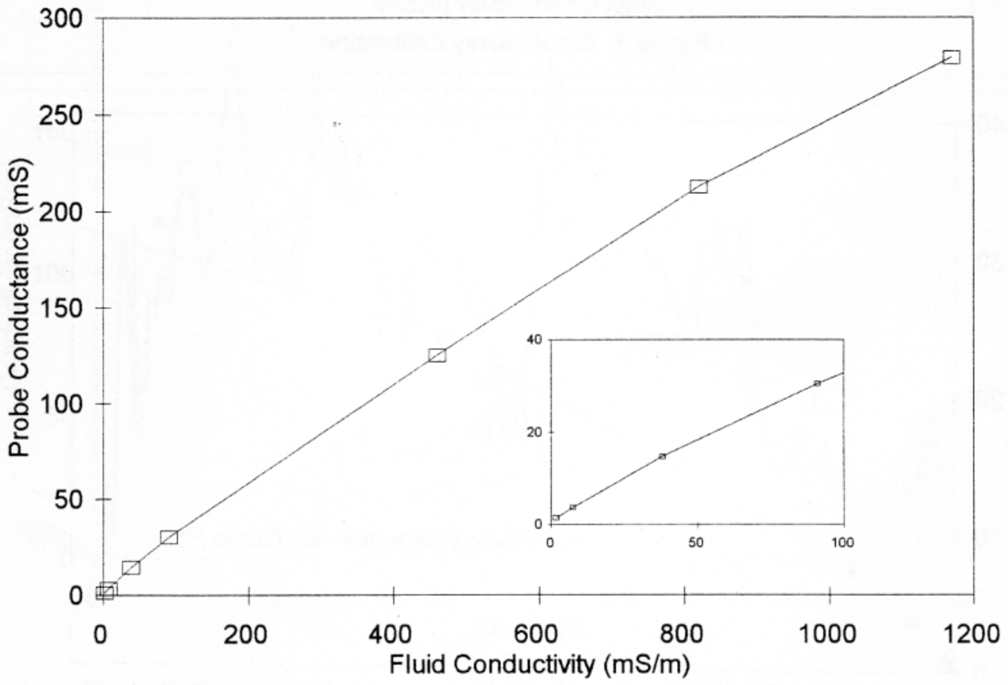


Figure 4. Schlumberger Array Calibration

Unlike the Schlumberger array, the dipole does not react linearly to variations in formation conductivity. Figure 5 shows the conductance sensed by three different dipole spacings for a variety of liquid conductivities. The nonlinear response can be accommodated by using a second order equation to calibrate the probe instead of the linear calibration used for the Schlumberger array. Figure 6 shows the curve fit used for the short dipole, which was formed using the top two rings of the probe. The fit is almost exact up to 400 mS/m, making it adequate for the range of conductivities encountered at the test location.

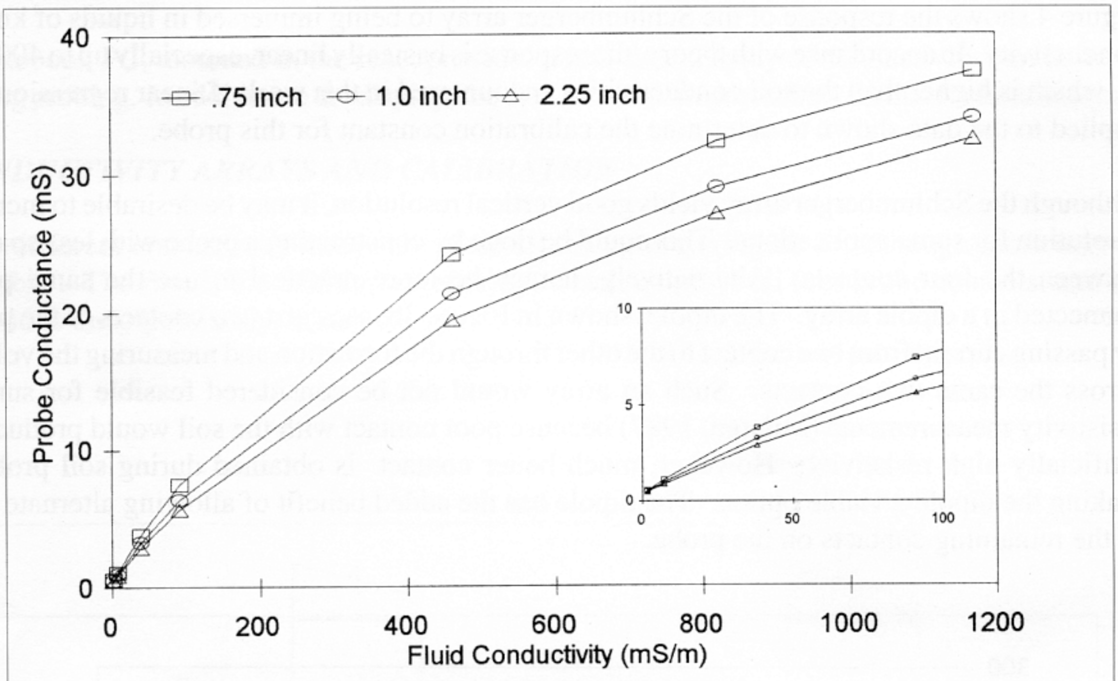


Figure 5. Dipole Array Calibration

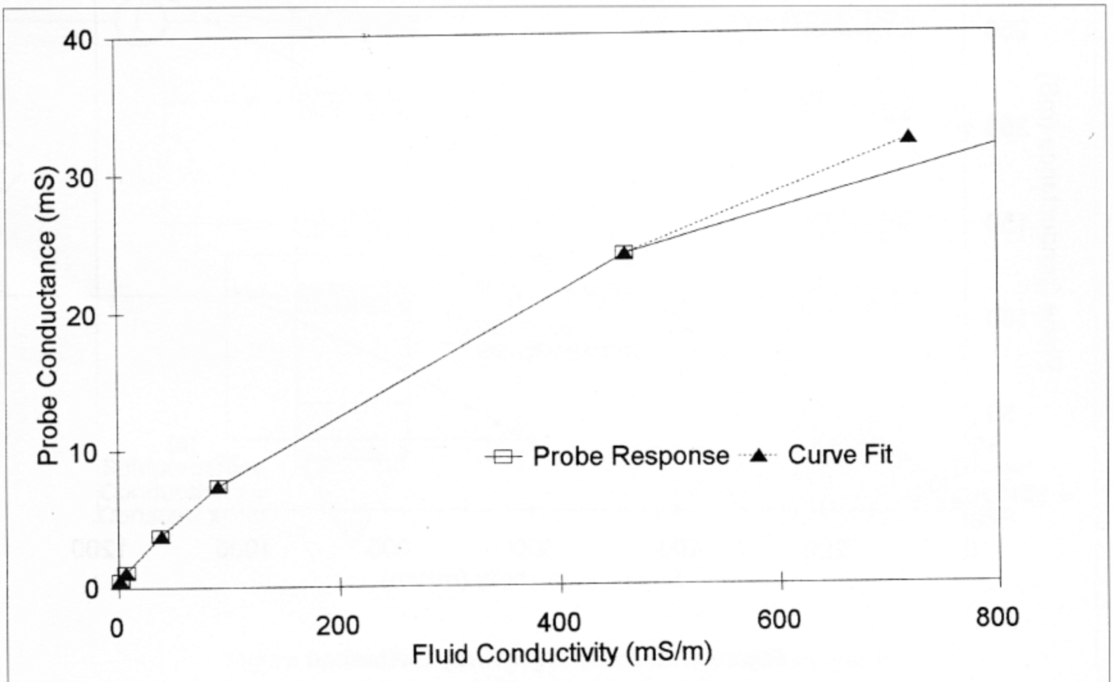


Figure 6. Curve Fit for Dipole Array Calibration

FIELD REPEATABILITY

Besides being able to calibrate a conductivity probe, the field investigator is also interested in the repeatability of the tool when applied in the field. This question goes beyond the ability of the probe to maintain its calibration when repeatedly placed in a claibration tank of known conductivity fluid. The field investigator must have assurance of the consistency of the soil in its electrical response to the probe and the ability of the probe to make repeatable measurement while undergoing percussion at 30 Hz (which results in thousands of G's of acceleration at the probe tip). The conductivity probe technique must be repeatable to be of value for site investigation.

Unfortunately, no test is possible to measure the repeatability of a probe in a natural soil; the probe being a tool which causes disturbance as it makes measurements. Duplicate measurements through the exact same path through the same undisturbed soil are impossible. However, a useful concept of the working repeatability of the probe can be attained by making successive probings at locations offset by short increments. Figure 7 shows the results from three successive probings, each probe being placed approximately 1 foot (0.3 m) from the other two. These logs were made using the probe in the previously described Schlumberger configuration. It should be noted that due to soil heterogeneity, there is no certainty that the three probes were sampling the same material, despite their close proximity. The figure does indicate that the major features of the soil profile which determine electrical conductivity are consistent at this location and can be repeatably measured with the probe.

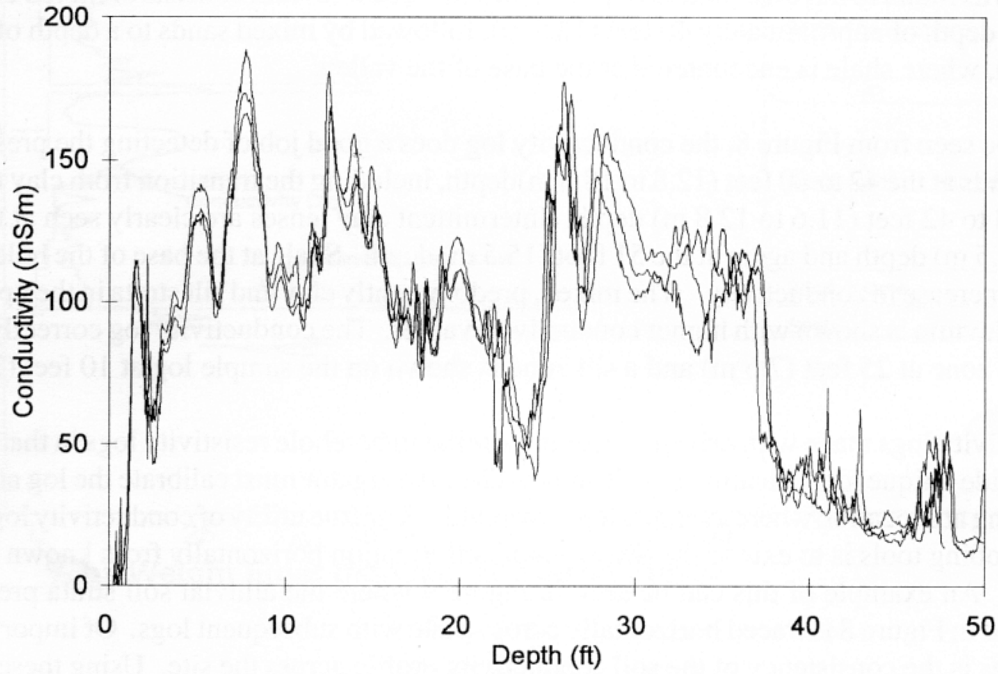


Figure 7. Repeatability Demonstrated by Three Logs at the Same Location

CONDUCTIVITY LOG INTERPRETATION

One of the first points to state concerning interpretation of electrical logs generated with driven probes is that it is not critical whether the soil electrical property is expressed as a conductivity or as the inverse, resistivity. All of the data is stored in digitized spreadsheet format and the field investigator can invert the output to yield the desired unit of expression. As referenced earlier, agricultural soil scientists have traditionally worked with units of soil conductivity, while geologists and geophysicists have used units of resistivity. All of the logs discussed here will be shown in units of conductivity.

There are many factors which will affect the measurement of soil conductivity. Most investigators cite first and foremost the degree of saturation and the conductivity of the saturating fluid. Other factors are also important, such as the clay content of the soil, soil structure, the ability of the soil to make mechanical contact with the probe, and the presence of contaminants in the soil.

Figure 8 shows a log of soil conductivity made to a depth of 62 feet (18.9 m) in an alluvial valley area in central Kansas. This log was made using the probe in the Schlumberger electrode configuration. At a close offset to this probing hole, approximately 3 feet (1 m) away, a continuous core sampling was made of the soil strata. Twenty-nine samples from this core hole were recovered, logged in the field, and then submitted for grain size analysis. A log of the percent finer than a No. 200 mesh U.S. standard sieve (0.074 mm opening) from each soil sample is presented in Figure 8 along with the soil conductivity profile and the sample description log. The water table was measured in the open core hole at a depth of approximately 22 feet (7.7 m) below ground surface. Groundwater was sampled at this location from a depth of 45 feet (15.7 m) and was found to have a conductivity of 83 mS/m. The alluvium consists of mixed clays and silts to a depth of approximately 40 feet (12.2 m), followed by mixed sands to a depth of 60 feet (18.3 m), where shale is encountered at the base of the valley.

As can be seen from Figure 8, the conductivity log does a good job of detecting the presence of clean sands at the 42 to 60 feet (12.8 to 18.3 m)depth, including the transition from clay to sands in the 38 to 42 feet (11.6 to 12.8 m) depth. Intermittent clay lenses are clearly seen at the 47.5 foot (14.5 m) depth and again at the 51 foot (15.5 m) depth. Shale at the base of the hole is seen with an increase in conductivity. The mixed, predominantly clay and silt strata in the upper part of the alluvium is shown with higher conductivity values. The conductivity log correctly shows the sand zone at 25 feet (7.6 m) and a silt zone is shown on the sample log at 10 feet (3.0 m).

Conductivity logs made with driven probes are similar to borehole resistivity logs in that they do not provide unique identification of soil strata. The investigator must calibrate the log at the site by logging at a location where a sample log is available. The true utility of conductivity logs made using probing tools is to extend the investigators information horizontally from known vertical profiles. An example of this can be seen in Figure 9 where the alluvial soil strata previously described in Figure 8 is traced horizontally across a site with subsequent logs. Of importance in these logs is the consistency of the soil conductivity profile across the site. Using these logs, it is a simple task to correlate the upper silts and clays in the cross section. The shale increases

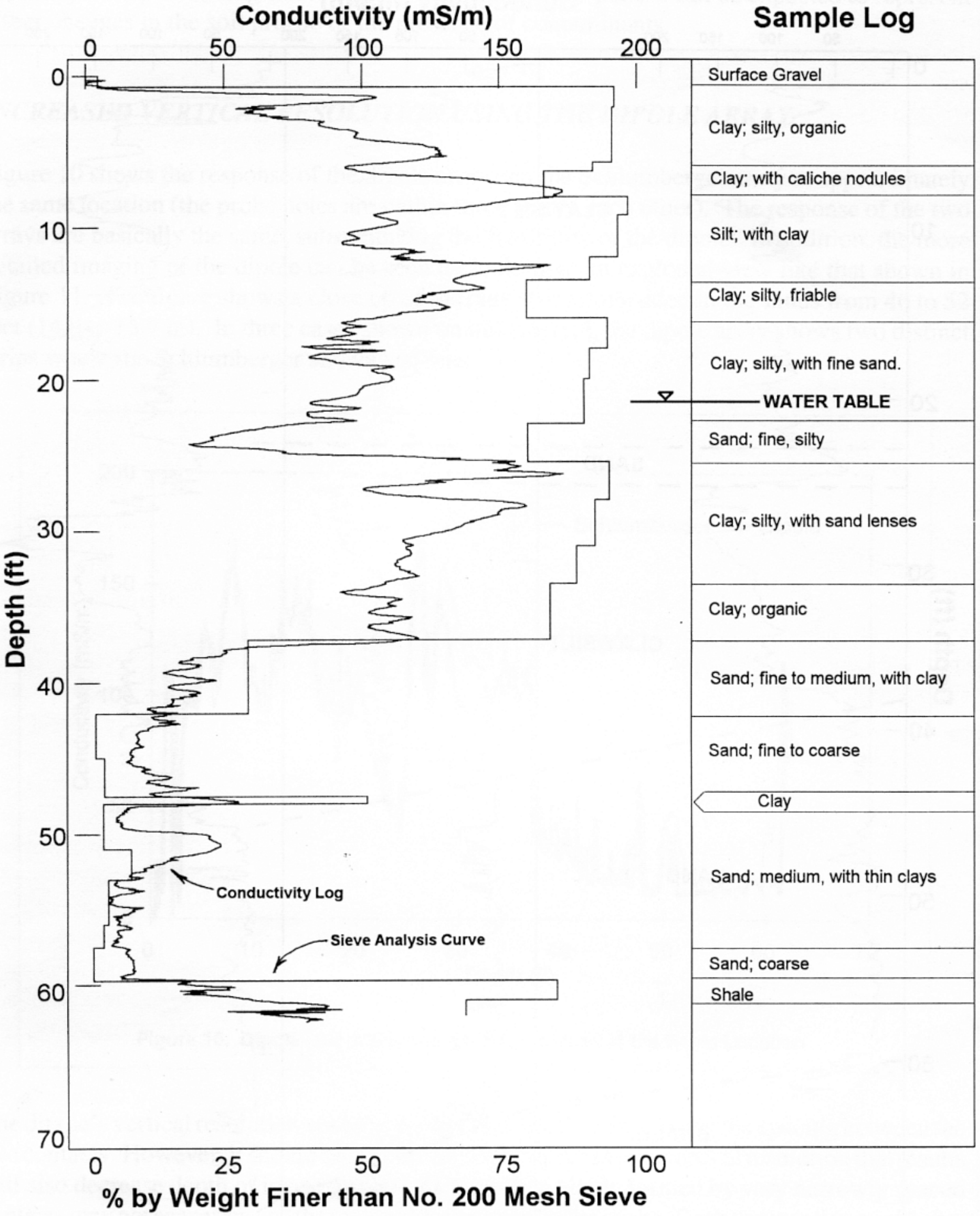


Figure 8. Compilation of Soil Conductivity, Minus 200 Mesh Fraction. and Sample Log Location: KEI - B

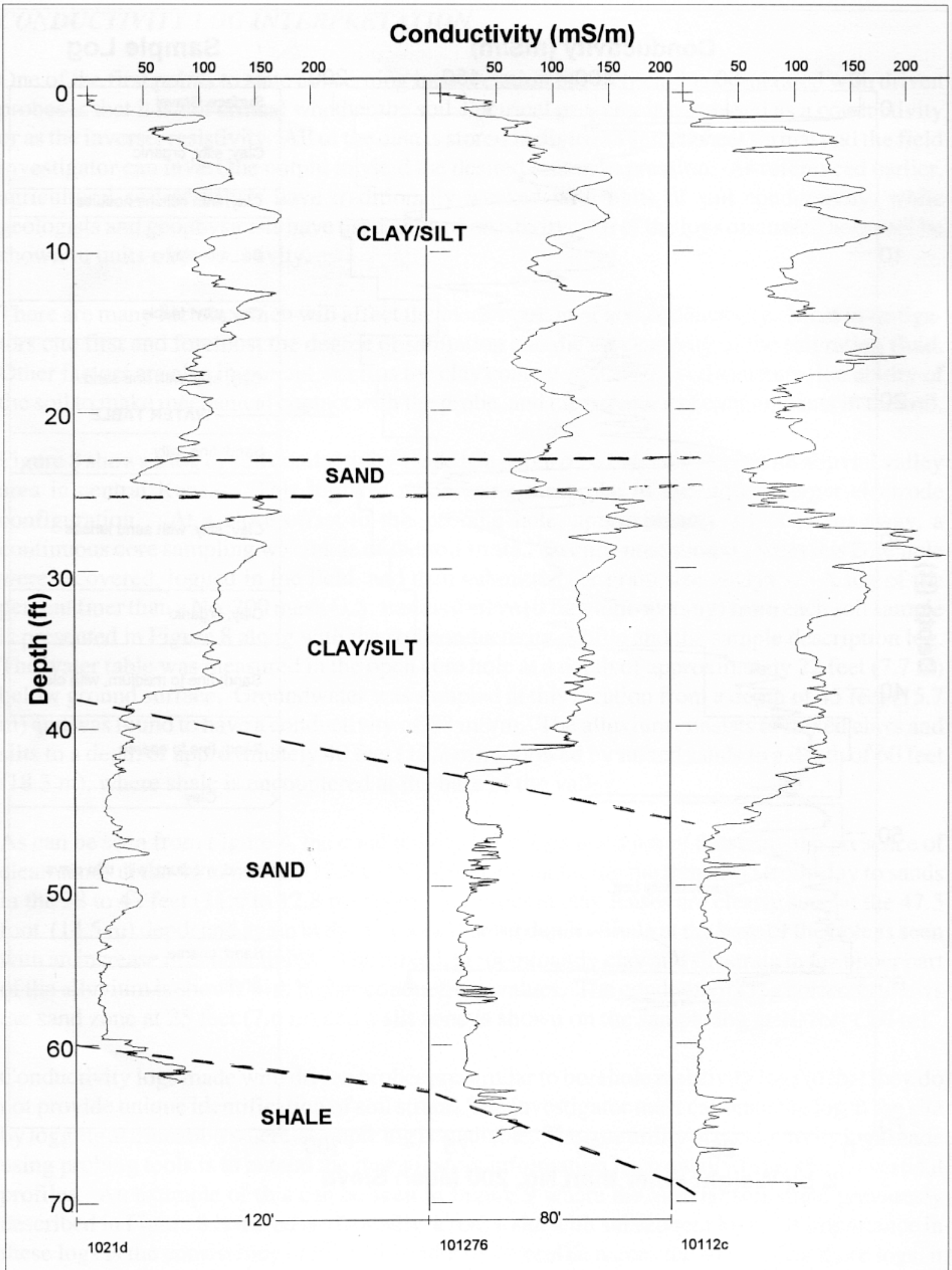


Figure 9. Conductivity Logs Spaced Horizontally Across the Site

gradually in depth moving left to right. Anomalies to this pattern can be expected to represent either changes in the soil profile or the presence of contaminants.

INCREASED VERTICAL RESOLUTION USING THE DIPOLE ARRAY

Figure 10 shows the response of the dipole array and the Schlumberger array at approximately the same location (the probe holes are within three feet of each other). The response of the two arrays are basically the same, substantiating the feasibility of the dipole. In addition, the more detailed imaging of the dipole can be seen by looking at an exploded view like that shown in Figure 11. The figure shows a close up of the clay strips embedded in the sands from 46 to 52 feet (14.0 to 15.9 m). In three cases shown on this interval, the dipole array shows two distinct strips where the Schlumberger shows just one.

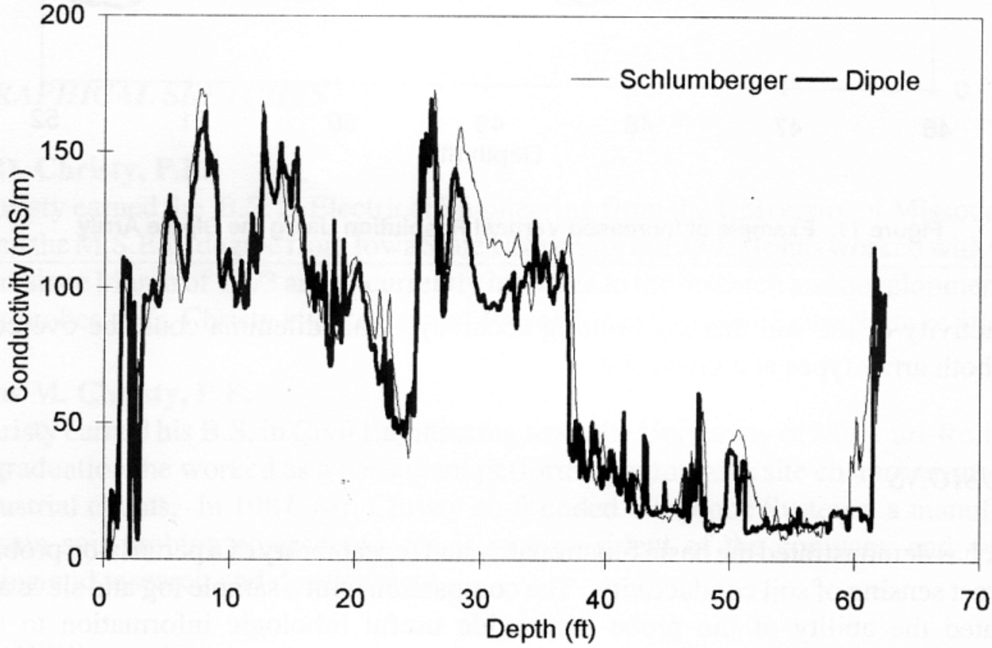


Figure 10. Dipole and Schlumberger Arrays Used at the Same Location

The dipole's vertical resolution could be further increased by decreasing the spacing between the two contacts. However, it should be pointed out that the increase in vertical resolution that results will also decrease depth of investigation. As a result, a dipole formed by very narrowly spaced contacts may not sense beyond the material compacted by the probe. Such compaction could alter

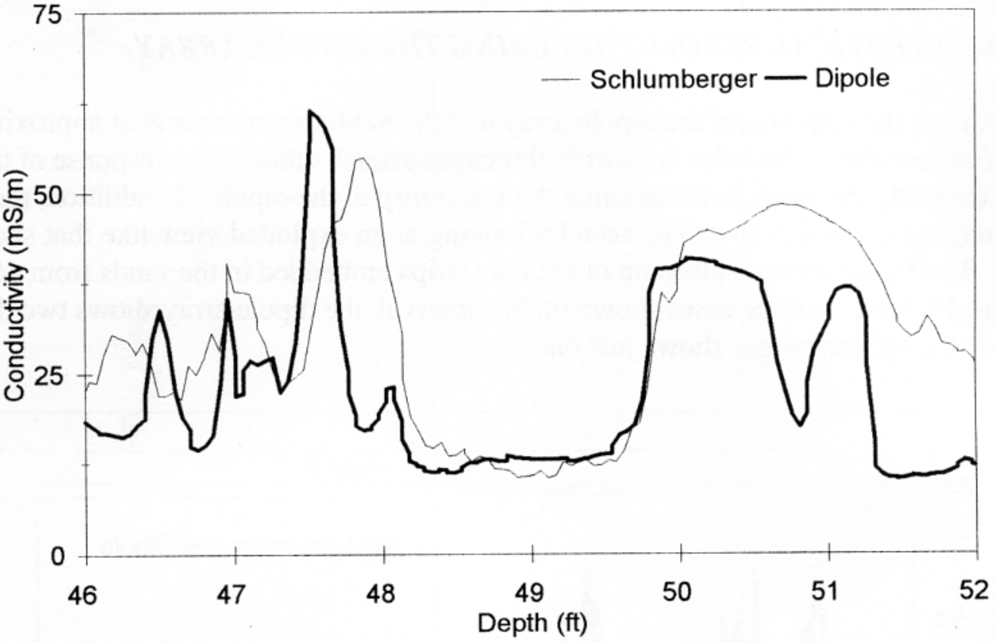


Figure 11. Example of Increased Vertical Resolution Using the Dipole Array

the conductivity of the soil thereby limiting accuracy. This dilemma could be overcome by applying both array types at a given site.

CONCLUSIONS

This work has demonstrated the basic functionality and repeatability of a percussion probing tool for the direct sensing of soil conductivity. The comparison with a sample log and sieve analysis substantiated the ability of the probe to provide useful lithologic information to the site investigator. Furthermore, logs across the test site were presented to show how the probe can be used to determine variations in strata over a broad area. Comparisons between the Schlumberger and the dipole array showed a general agreement in response with the dipole providing more resolution. Due to the trade-off between vertical resolution and depth of investigation, both arrays would probably be used in a given investigation.

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BIOGRAPHICAL SKETCHES

Colin D. Christy, P.E.
Mr. Christy earned the B.S. in Electrical Engineering from the University of Missouri-Rolla in 1987 and the M.S.E.E. degree from Iowa State University in 1990. He has worked with Geoprobe Systems since March of 1993 and is currently involved in the research and development of direct sensing probes. Mr. Christy is a Registered Professional Engineer in the State of Illinois.

Thomas M. Christy, P.E.
Mr. Christy earned his B.S. in Civil Engineering from the University of Missouri-Rolla in 1980. Upon graduation, he worked as a consultant performing numerous site characterization studies for industrial clients. In 1987, Mr. Christy co-founded Geoprobe Systems, a manufacturer of percussion soil probing equipment. He is vice-president of the company and works with marketing and research and development.

Volker Wittig
Mr. Wittig earned his Diploma in Mechanical Engineering at the University of Carolo Wilhelmina in Braunschweig, West Germany. He received his M.S. in Agricultural Engineering at South Dakota State University in 1990. He has worked with Geoprobe Systems since 1992 on the development of soil probing tools. Mr. Wittig is a member of the ASTM Committee for Vadose Zone Monitoring and Ground Water Sample Collection and Handling.

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