CRACK DETECTION IN CLAY LANDFILL LINERS WITH NONINTRUSIVE MEASUREMENTS

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PREDICTIONS AND OBSERVATIONS OF LEAKAGE THROUGH CLAY-LINED LANDFILLS

PART II

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Project Report
To

State of Michigan
Toxic Substances Control Commission
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ACKNOWLEDGEMENTS

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During the course of the laboratory investigation, Nathan Conn from Saline High School was able to participate in the research through a program sponsored by the College of Engineering. His willing participation in the project contributed significantly to the completion of the project objectives. His effort is gratefully acknowledged.

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INTRODUCTION

There is a longstanding concern over the proper way to control the introduction of contaminants into the environment after their deposition into solid or hazardous waste landfills. According to recent information (support documentation for *Water Resources for the Future, Michigan's Action Plan,* by the Great Lakes and Water Resources Planning Commission, September, 1987), the sources of approximately 22 percent of groundwater contamination sites with known sources in the state of Michigan are associated with landfills. Most of these landfills were developed sufficiently long ago in time that there were no regulations or standards relating to the prevention or minimization of leachate. Current regulations for landfills, both hazardous (through Michigan state Public Act 64) and solid waste (through Public Act 641) contain specifications for incorporating liner systems into the design of the landfill. This stud concentrates only on those liner systems that involve the placement of compacted clay as a barrier to water migration. Figure 1 depicts the regulations pertaining to clay liners as they were originally formulated for the two different types of landfills.

Inherent in these specifications is the assumption that the permeability or hydraulic conductivity of the soil matrix is the variable that controls the migration of water through either the cover or the bottom liner. The maximum allowable permeability in the above regulations is 10^{-7} cm/sec. If it is assumed that this permeability is just attained, then the maximum leakage through a landfill liner could be approximately 3.2 cm/year if it is assumed that the liner is maintained in a saturated condition and the flow is due only to drainage by gravity with no significant standing water above the liner. This is less than the amount usually observed for annual rainfall recharge (approximately 25 - 30 cm. per year would be typical for many sites in Michigan), so most rainfall infiltrating through the ground surface would be expected to run off over the top of the liner in the cover soil. It would appear that the initial water content found in a landfilled waste would either drain through the bottom liner or be collected in the leachate collection system within a period of a few years. Thereafter, the main source of water which could exit the landfill as leachate is that leaking through the cover liner which is generated from rainfall infiltrating from above the landfill. If both liners have the same permeability, then

Clay Liner System Under P.A. 641 (Solid Waste) Regulations

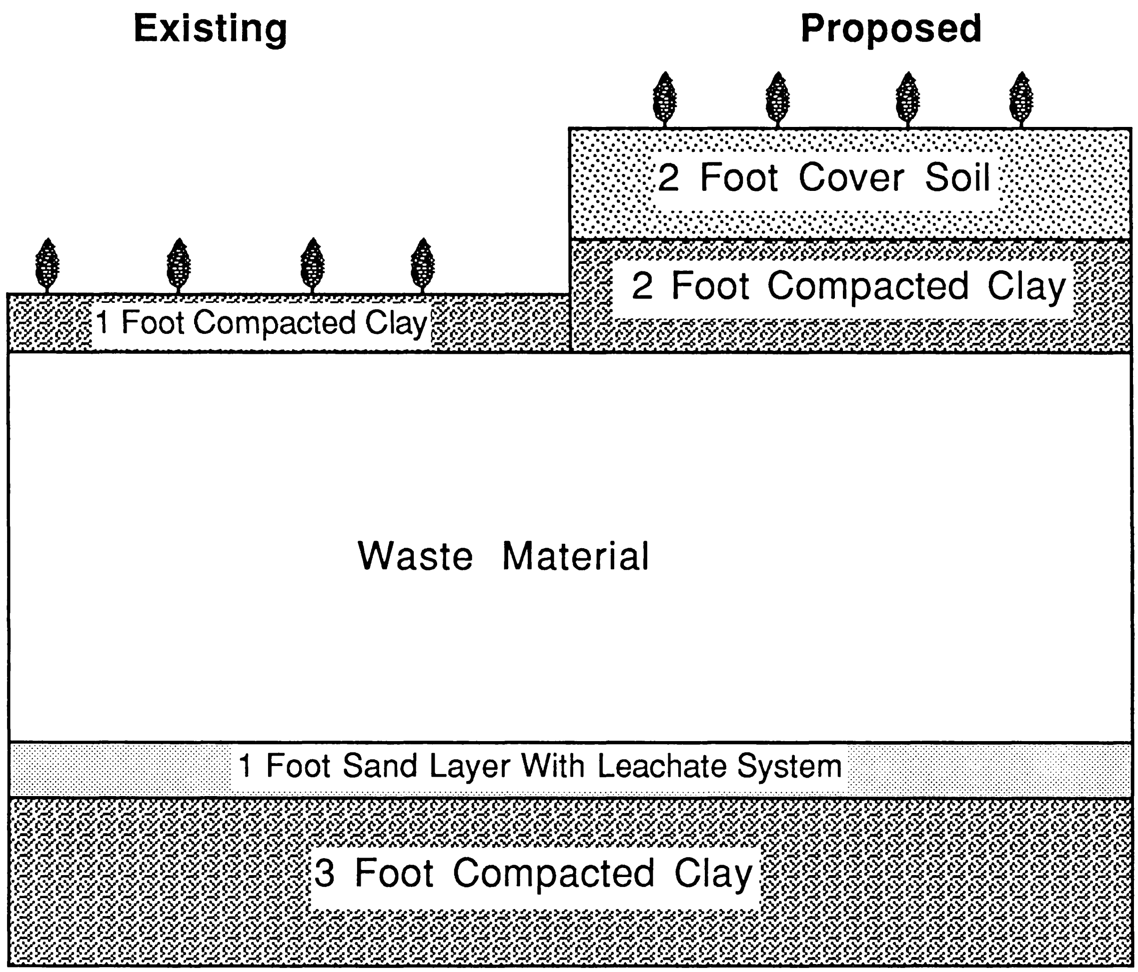


Figure 1b.) Schematic of Clay Liner System Under Act 641 Regulations.

the water should pass through both liners with equal ease and there should be no possibility for leachate collection above the top of the bottom liner in the leachate collection system. The recovery of large amounts of leachate after the initial startup of the landfill would therefore be indicative of a failure of the cover liner. In any case, this line of reasoning implies that the cover liner is equally critical to the determination of leachate production, yet current regulations apparently are based upon the assumption that the cover liner is less critical to the system performance. However, it can be seen by the proposed changes to P.A. 641 regulations that more attention is being paid to the cover liner conditions.

Early research (e.g. Anderson, et al, 1982) indicated that the presence of organic compounds in the leachate may significantly increase the matrix permeability of the clay and thus permit more rapid leachate migration. However, more recent studies (e.g. Foreman and Daniel, 1986) under conditions more representative of those in an actual landfill indicate that only very modest changes in permeability are likely with typical contaminant concentrations. Therefore, it would appear likely that the cover liner might well be the weak link in the liner system, since its proximity to the surface might subject it to seasonal freeze-thaw and wetting-drying cycles and thereby increase the probability that the clay liner would be subject to cracking. Also, the consolidation of the waste may result in failure of the cover liner.

There have been several documented cases which indicate leachate production considerably in excess of what might be expected on the basis of the matric permeability. Miller (1984) simulated the flow through a test cell in Boone County, Kentucky which had been established to examine the quality of leachate generated from ordinary solid landfill waste, but for which volumes of leachate collected were recorded. She found that far more leachate had passed through the test cell than could be explained on the basis of the permeability that she and others had measured; the discrepancy was tentatively explained on the basis of liner cracking. However, the test cell was only six inches thick and it is possible that this is not representative of relatively thickness landfill liners. Also, Daniel (1984) has documented several cases of field measurements in which the permeabilities measured in the field may are much greater than observed in laboratory measurements. One typical explanation is cracking in the clay liner, especially if it is not kept continuously saturated. If this is accepted as a valid explanation, then the

Clay Liner System Under P.A. 64 (Hazardous Waste) Regulations

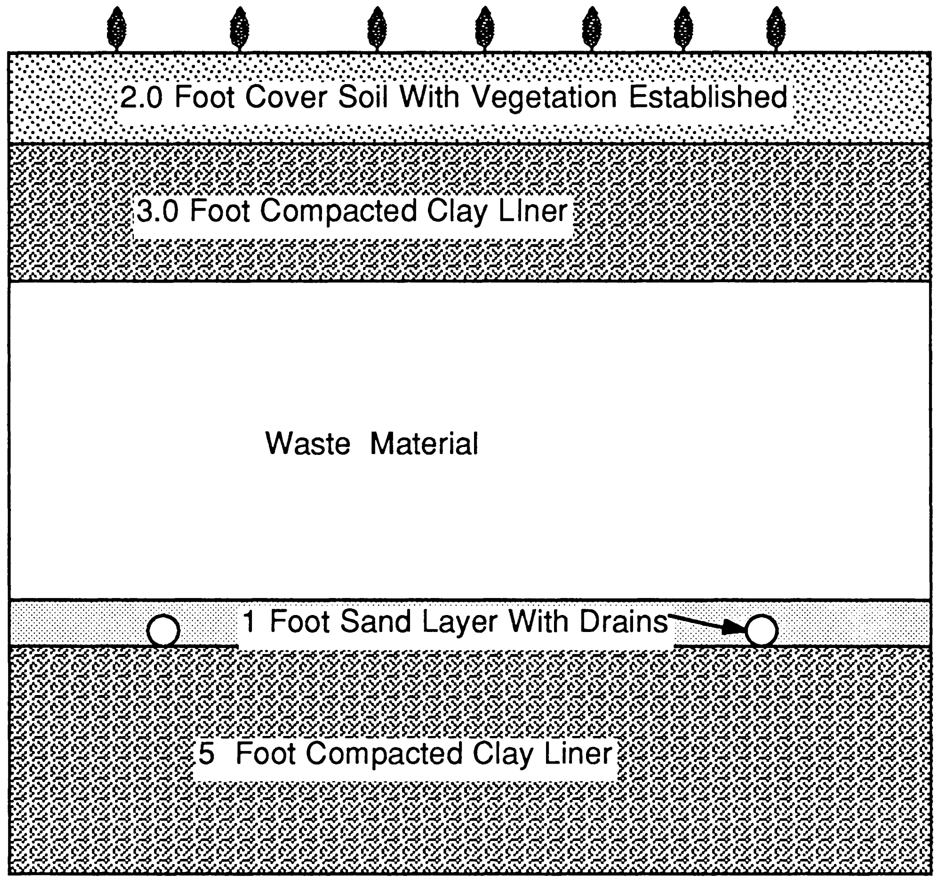


Figure 1a.) Schematic of Clay Liner System Under Act 64 Regulations.

cover liner may well be subjected to more phenomena (dessication, freeze-thaw, and consolidation) that promote cracking than the bottom liner, resulting in it becoming the weak link in the liner system.

A long term research project has recently been initiated to observe the migration of moisture through the cover liner on a prototype hazardous waste landfill. The site is the Michigan Disposal facility near Ypsilanti, Michigan. During the placement of the cover liner, vertical arrays of tensiometers, thermocouple psychrometers, and gypsum resistance blocks were installed at three different locations in the landfill liner. The installation is described in more detail in a companion report. The purpose of these arrays is to monitor the changes in moisture content in the clay liner over the life of the instruments in order to attempt to develop an understanding of the moisture migration through the cover liner. A vertical cross section of the liner - landfill is indicated in Fig. 2. By virtue of the presence of the synthetic liner beneath the clay cover liner, it is possible to capture all the moisture leaking through the cover liner in the drains in the sand layer, provided that the synthetic liner remains intact. By monitoring the bulk outflow through several of the sand drains, it will be possible to obtain an independent check on the flow through the cover liner. If there are significant differences between the moisture movement implied by the observed moisture profiles and that monitored in the drain tiles, it may imply that a significant amount of water is moving through cracks or other imperfections in the clay liner. It would be desireable to be able to supplement these investigations with a study of crack formation in the landfill liner. This report describes the portion of the present project involved with the investigation of possible methods for the detection and quantification of crack geometries by nonintrusive measurement methods.

POTENTIAL CRACK DETECTION TECHNIQUES

There are a variety of techniques commonly employed for the investigation of subsurface phenomena. In determining the potential applicability to the crack detection problem, there are two major constraints associated with the potential application at a hazardous waste landfill. First, the technique cannot generally be allowed to disrupt the integrity of the clay liner. This requires the use of a surface investigative technique, in which some sort of signal applied at or near the ground surface is also detected at the ground surface. Surface investigation techniques

WAYNE DISPOSAL MASTER CELL 5 COVER LINER DETAIL

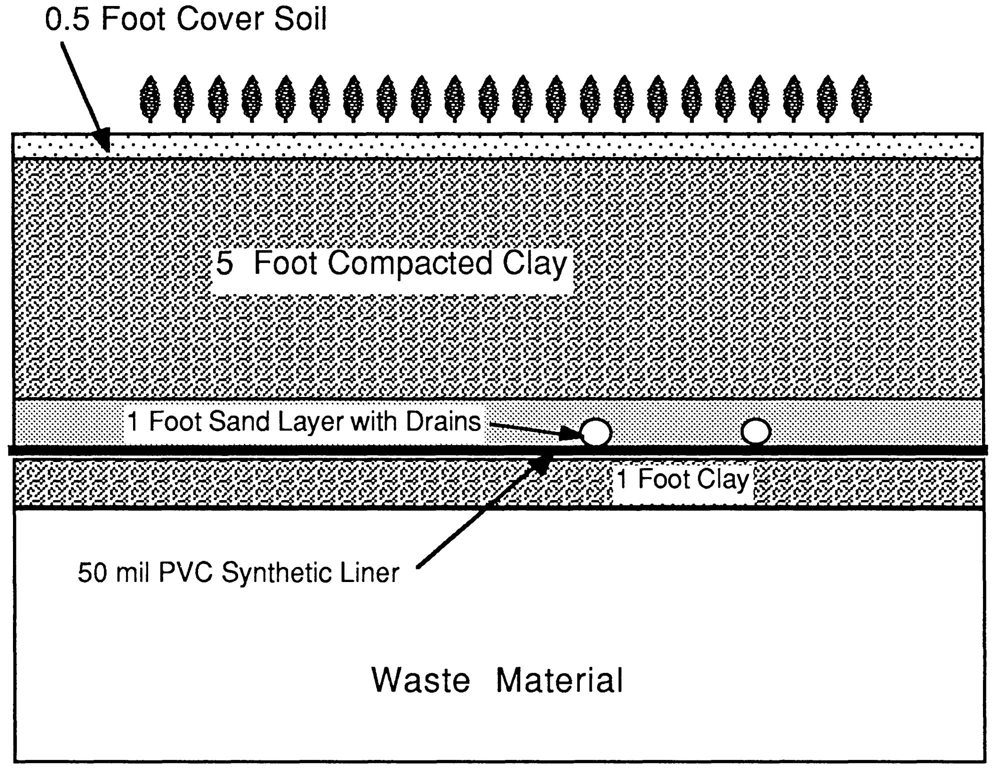


Figure 2. Cover Liner at Master Cell 5, Wayne Disposal Landfill.

include electrical resistivity, seismic wave analyses, shallow geothermic, magnetic and gravity field analyses, and ground penetrating radar (Simons and Mathews, 1982 and Gilkeson, 1981). Secondly, the spatial resolution must be adequate to resolve the characteristics of at least an assemblage of local cracks, and preferrably of an individual crack. Of the common methods for surface geophysical investigation, there appears to be only two candidates, electrical resistivity and general seismic methods, since the other methods cannot attain spatial resolutions remotely close to those required in this type of study.

Further requirements of a measurement method that could go beyond simple crack detection would include the ability to measure crack size and depth of penetration. These quantities would be required in any model that attempted to predict rates of leakage through a crack inasmuch as such a model attempted to directly model the flow in the crack.

Electrical resistivity is based upon the concept that different formations in the subsurface environment exhibit different resistance to the flow of an applied electrical current. Since the electrical current flows primarily through water within the pore spaces, the resistance depends both on the media porosity and the degree of water saturation. Resistance variations may also result as a consequence of the different conductivities of different water solutions and this is sometimes used to map contaminant plumes, particularly those that contain significant concentrations of electrolytes. In principle, it would be possible to use this technique to detect the location of cracks since it may be presumed that the crack may exhibit both a different porosity and a different degree of saturation.

This method has been used on a much larger scale problem to determine the primary orientation of joints in fractured rocks (e.g. Taylor, 1982) and porosities which is a very similar problem to the one in the present study. The essential difference is that the studies in fractured rocks are presumed to take place in a region where there are a large number of parallel fractures such that the system may be considered to consist of a series of elongated pores in a preferred direction. Since there is no indication that such an occurrence should be present in a cracked landfill liner, the application is quite different in that a single crack or, at most, crack system is to be detected. Therefore the theory developed for fracture systems is not likely to be applicable to the landfill crack detection problem. The previous studies involved azimuthal surveys (surveys profiling the resistivity variations as the electrodes are rotated about a common center in discrete angular rotations) and the variations of the resistivity with angular position to infer both orientation fracture planes and porosities. It may be possible to accomplish similar objectives in the crack detection problem.

Resistivity profiling takes a variety of forms that relate to the geometrical configuration of the electrodes. In general, the electrical current is passed between two current electrodes that are set at some distance apart. The voltage drop over some distance between two potential electrodes generally between the current electrodes is measured. The electrical resistance is thus the voltage drop divided by the imposed current. The exact geometry of the current and potential electrodes depends upon the intended objectives of the survey and determines the relation between the voltage drop and electrical resistance. *Apparent resistivities* are normally computed which are intended to remove the influence of the electrode arrangement. Because different electrode arrangements were used in this study, all formation resistances are reported as apparent resistivities. However, the standard apparent resistivity computations assume that the formation is homogeneous and semi-infinite and the landfill liner system is neither. In particular, the presence of the synthetic liner below the clay liner is presumed to be a complete barrier to the flow of electrical current, so the use of standard apparent resistivity calculations will not remove all geometrical effects. Although methods such as presented by Ghosh (1976) can be used to account for the stratification, this was not applied in the present study because vertical profiling was not performed.

A variety of seismic methods may be used for the determination of media variations in the subsurface environment. The most logical of these for the purposes of this study involves the study of Rayleigh waves which are essentially surface waves. Stokoe and Nazarian (1985) indicates a method that can determine the vertical variation of media properties. Park and Simmons, (1982) demonstrate that the method can be used to determine the anisotropy in fracture orientation. Presently, additional funding is being sought to further investigate this procedure as a method for the crack detection and quantification problem. However, since there is no presently available theory for interpreting Rayleigh wave propagation information to determine crack width, the electrical resistivity method was initially selected as the most likely method to provide the maximum information regarding crack geometries.

INVESTIGATION

The objectives of this study were to examine the use of the electrical resistivity method for purposes of a.) detecting cracks and b.) quantifying crack geometries. Towards this end, both laboratory and field studies were performed. The laboratory studies were performed in order to carefully control the crack geometry and observe the nature of the electrical resistivity response. The field study was performed to see if it is possible to make similar measurements at the field scale.

General Considerations

Since electrical resistivity essentially detects differences in the moisture content within the clay liner, there are two different situations in which the detection of a crack may be possible. One case would be if the crack is essentially void of water and also evaporation may tend to reduce the moisture content in the immediate vicinity of the crack. Then the crack would appear as an increased resistance to the flow of an electrical current. This methodology would favor the detection of cracks during relatively dry periods. After a rainfall event, infiltration into the crack may remove the resistance anomaly. The second case could be found if the liner could be expected to exhibit a relatively low saturation state. Then immediately after a rainfall event, the infiltration of water into the crack would cause a local region of low resistance and the crack could be detected in this fashion. The preferred time for crack detection would be immediately after a rainfall event during a relatively dry period. The report by Miller (1987) (companion project report to this one) indicates that the landfill cover liner for Master Cell 5 tends to remain at a relatively high degree of saturation, so it is expected that the first condition would be the most favorable for crack detection at the site.

In general, the depth of the resistivity measurement may be taken as approximately equal to the spacing between the current electrodes (). Vertical profiling can be obtained by repeated measurements with varying electrode spacing. However, the presence of the synthetic liner implies that little difference in results should be expected as the current electrode spacing is increased beyond the depth to the synthetic liner as the increase in spacing should not significantly influence the location of the electrical field lines within the clay liner. For the present investigation, electrode spacings that were a major fraction of the clay liner thickness were used in order to avoid initial problems with vertical variations in resistivity. However, this is an important part of the overall problem resolution and further studies are required in this regard.

The standard electrode configuration is referred to as the *Wenner* configuration. As indicated in Fig. 3, this consists of equal spacings between all of the electrodes. The apparent resistivity is given by Simons and Mathews (1982) as

$$\rho_a = 2\pi a \frac{\Delta V}{I}$$

where ρ_a is the apparent resistivity, a is the spacing between adjacent electrodes, ΔV is the voltage drop and I is the imposed current. An alternate electrode configuration used in this study because of the ability to perform rapid lateral profiling is the *central electrode method.* This configuration is also indicated in Fig. 3, in which the spacing between potential electrodes is held fixed and they are moved from near one current electrode to the other. The apparent resistivity for the central electrode method is given by

$$\rho_a = \frac{2\pi \Delta V / I}{b\left(\frac{1}{a(a+b)} + \frac{1}{d(d+b)}\right)}$$

The above formulae were used to compute apparent resistivities in the presentation of all results below.

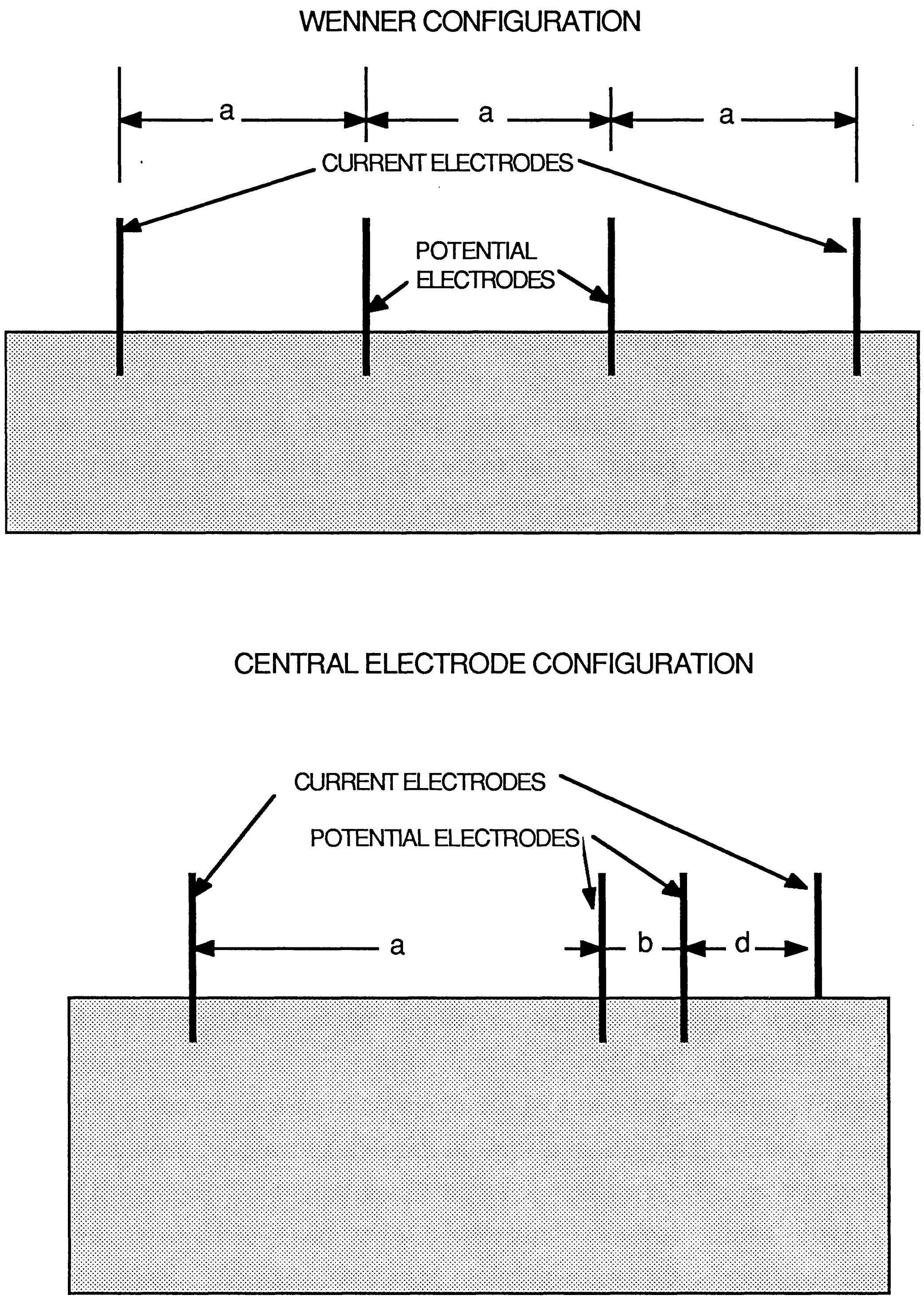


Figure 3. Different Resistivity Profiling Configurations.

Laboratory Investigation

The objective of the laboratory investigation was to establish, in a controlled environment, the response of the electrical resistivity measurements to basic variables which characterize the geometry of an individual crack. These included:

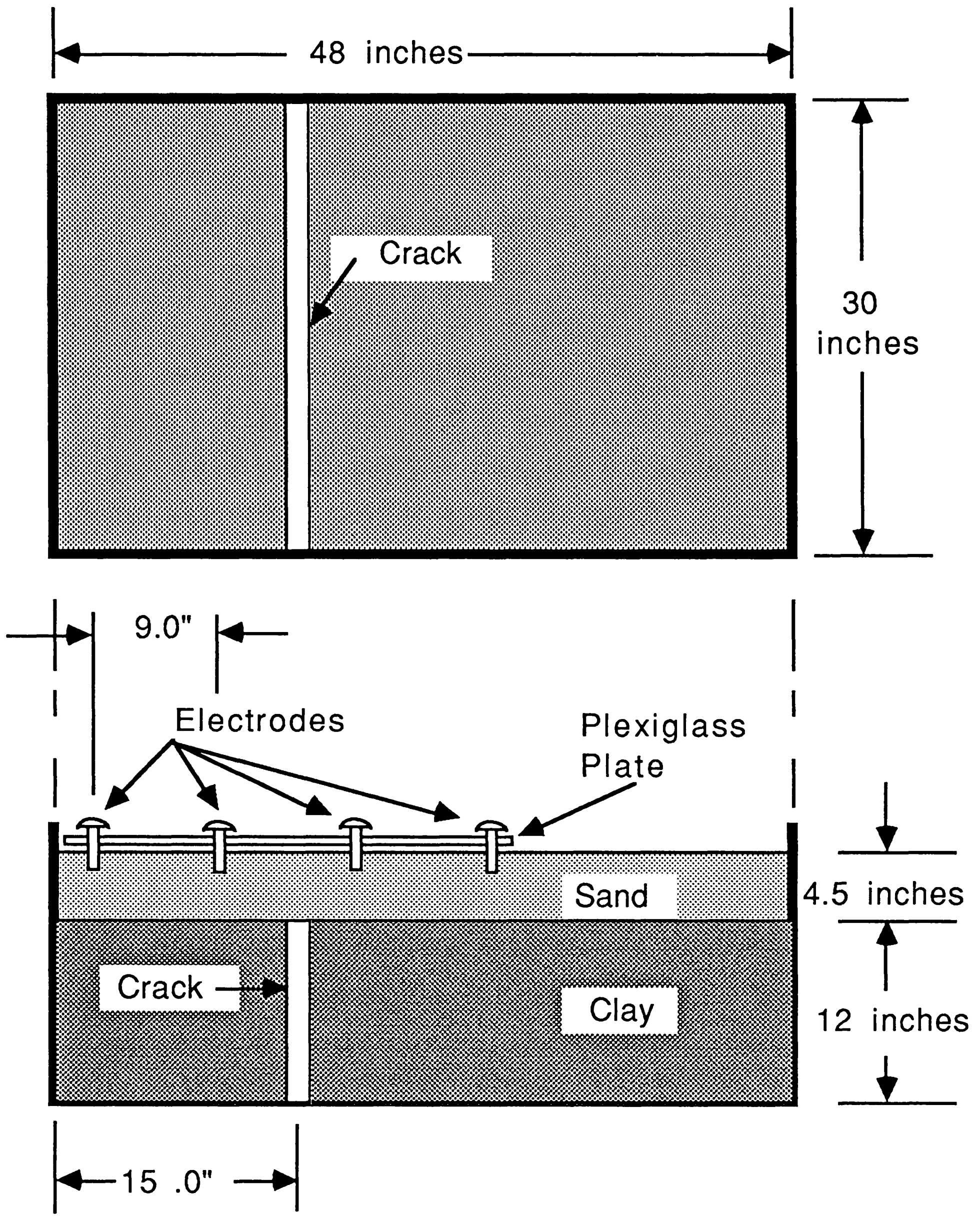
- Crack width
- Orientation of the crack with respect to the electrodes
- The effect of the cover soil over a typical clay liner

These effects would have been much more difficult to quantify in the field environment but could be systematically varied in the laboratory in order to determine the suitability of the electrical resistivity technique to the crack detection problem.

Experimental Techniques

The tests were performed in a sample of the same clay that had been used in the construction of the landfill liner for Master Cell 5. Approximately a half a cubic yard of the clay had been previously obtained and was stored until required for the laboratory investigation. The clay was compacted in a plexiglass container as indicated in the sketch of the laboratory setup in Fig. 4. The container was 40 inches long by 30 inches wide by 18 inches deep. Plexiglass was used since it is an electrical insulator and therefore simulates the expected effect of the synthetic liner under the cover liner. A total depth of approximately 12 inches of clay was compacted in the bottom of the plexiglass container; no sand underlayer was used to simulate the underdrain, since the crack was formed in-situ and interference in the results from disturbing the sand was to be avoided. In some experiments, the effect of a cover soil was simulated by placing a depth of approximately 4.5 inches of mortar sand over the top of the clay. This sand could be easily removed if a modification of the clay was desired, and this step was performed several times during the laboratory investigation. The sand was kept moist at about 50 percent saturation to provide for good electrode contact.

In order to compact the clay, water was added until it was fairly easy to work. A volume of clay sufficient to develop a lift of about 3 - 4 inches was placed into the container and compacted by dropping a hammer until most of the voids were

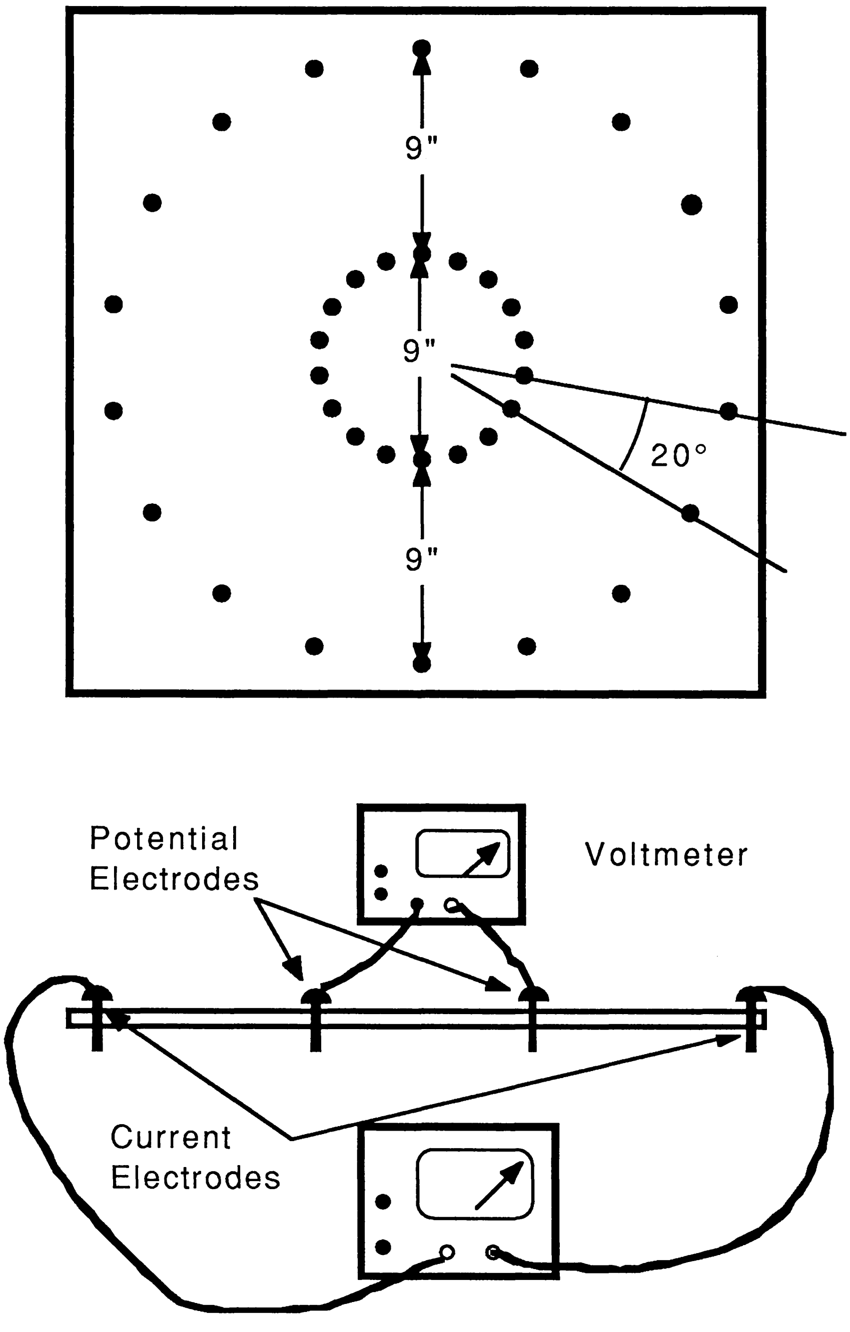


Laboratory Test Cell Configuration.

Figure 4. Laboratory Experimental Setup.

eliminated. In the initial filling effort, a one-fourth inch sheet of plexiglass was positioned vertically across the sample in the desired location of the crack, fifteen inches from one long end of the container. After completion of the clay filling procedure, the plexiglass sheet was extracted leaving a crack with the width of the sheet. After some time, the crack would tend to fill in as the clay settled; the crack would be reformed by driving the sheet of desired thickness back into the existing opening. Since the sides of the container was transparent, it could be verified that the reformed crack penetrated essentially the entire clay layer depth. In the experiments where a greater crack width was used, the initial crack geometry was formed by cutting the opening with a knife and extracting a sufficient amount of the clay to form a wider crack by a procedure as discussed above. In the cases where a sand layer was placed over the clay, the bridging action in the sand did not permit a significant amount of sand to enter the crack.

The electrical resistivity instrument was a Soiltest R50 Stratameter and was used in both the laboratory and field investigations. The instrument was used in a similar fashion in both experiments with a current flow of 100 milliamps in all cases. The only differences between the two cases were the electrodes used. During the field investigation, the standard electrodes provided with the instrument were used. However, it was decided to construct a template for the laboratory measurements so that the angular orientation and electrode spacing could be carefully controlled. This is similar to the setup described in Taylor (1982). The template was constructed from a plexiglass sheet with one-fourth inch holes drilled in the pattern indicated in Fig. 5. This allowed for the quick setup of a Wenner array at 20° segments around a circle. The electrode spacing of nine inches was held fixed for all laboratory experiments. Plated one-quarter inch bolts were inserted through the drilled holes and locked in place with nuts on either side of the plexiglass sheet. The bolts penetrated approximately one inch below the surface of the plexiglass. In order to perform a measurement, the template was placed on the surface of the clay (or sand as the particular experiment dictated) and pressed into the media until the plexiglass sheet touched the surface. The clips from the current source and voltage meter were then attached to the bolt heads and measurements taken in a standard fashion. In those experiments when the template was set directly on the clay and the center aligned with it, two electrodes would be set directly in the crack. In order to get a meaningful reading in those cases, the template was offset so that all electrodes



Plexiglass Template to Fix Electrode Spacing and Orientation.

Figure 5. Laboratory Electrode Template.

were in contact with the clay. In all experiments reported, the angular orientation of 0° or 180° implies that the electrodes are aligned parallel to the crack.

In order to get some sense of the accuracy of the measurements, circular profiles were made by placing the template over that end of the box with no crack so that there should be no difference in the resistivity with angular orientation. Experiments were performed both directly in the clay and with the sand layer placed over the clay. For these experiments, the voltmeter reading was 18 out of a full scale deflection of 100 with no sand and 16 with the sand layer present. The latter is presented in Fig. 6 as a polar plot of apparent resistivity versus angular position. Plotted are values of the apparent resistivity in ohm-feet. The readings were the respective value for about 14 of the 18 angular orientation and varied ± 1 for the other cases. Since the profiling over the entire 360° actually involves sampling the same electrodes twice (with the positive and negative electrodes reversed) any variations in resistance due to media properties should be seen as a symmetry in the deviations from the mean value (e.g. an anomaly at 60° should also been seen at 240°). These symmetries were not noted in the results, so the deviations are taken as representation of sampling error. Therefore the basic accuracy of the measurement is about 5-6%. If a higher voltmeter reading is obtained, the accuracy should probably increase somewhat, but it appear that an accuracy of about five percent should be considered as the limit of the instrument.

In a similar fashion, similar measurements were made over a 1/4 inch wide crack which had been completely filled with water. The profiling around the 360° circle indicated no significant variation in the resistance with angular orientation. In particular, no trend of resistivity variation at the 0° and 180° positions were present to indicate the presence of the crack. Therefore, the main influence of the results to be presented appears to be associated directly with the replacement of water in the pore spaces of the clay with air in the crack.

A series of measurements were made to determine the effect of various geometrical parameters on the electrical resistivity variations. The effects studied were:

- The effect of crack width was studied by performing measurements with both 1/4 and 1/2 inch wide cracks;

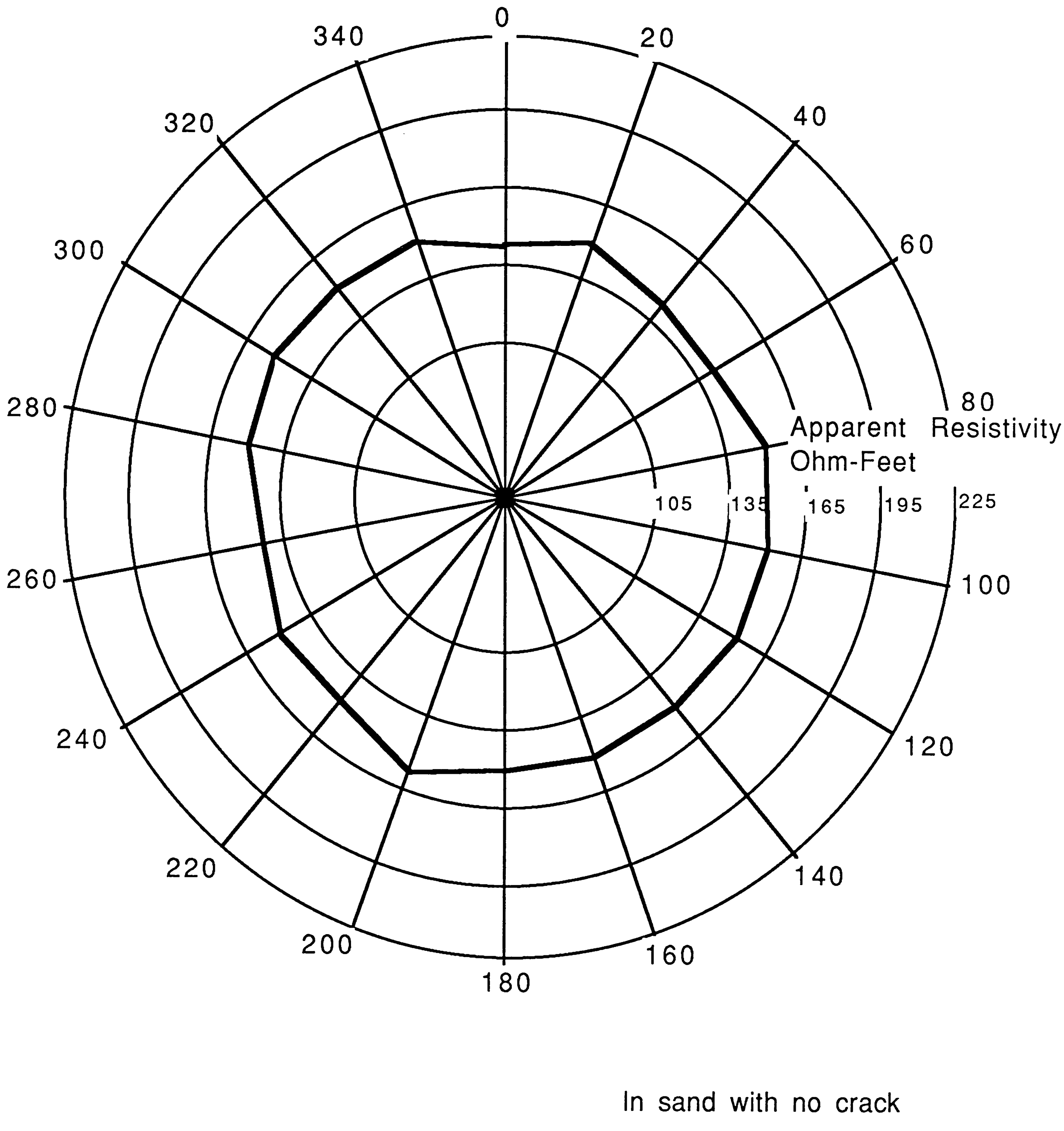


Figure 6. Azimuthal Resistivity Survey in Laboratory Cell with No Crack Present.

- The effect of the thickness of the layer over the crack was studied by making measurements both directly on top of the clay and through a sand layer placed over the clay. The thickness of the sand layer in a geometrically scaled sense is greater than that in the final cover soil for the Master Cell 5 at which the field study was performed and it was important to establish whether or not the cover soil would have a major effect;
- The effect of the crack location with respect to the electrode arrangement was studied by offsetting the template 4.5 and 9.0 inches from the centerline of the crack. Thus the crack was not located between the potential electrodes for any of the angular positions for the greatest offset and for six of the 18 positions for the smaller offset.

Results

All combinations of the various effects were studied and the results are presented in polar diagrams of the apparent resistivity variations are presented in Figs. 7 - 18. The results are discussed below in the following paragraphs.

When the electrodes were located directly over the crack with no cover layer, a distinct drop in resistance was observed when the electrodes were parallel to the crack. The results presented in both Fig. 7 and 13 indicate a gradual increase in resistance as the angular orientation turns towards the parallel alignment with a drop in resistance directly over the crack. However, when the cover layer is present, exactly the opposite result is observed with the maximum resistance values found when the electrode orientation is at right angles to the crack as observed in Figs. 10 and 16. This implies that similar studies in the future must consider the presence of any intermediate layers as they control not only the magnitude but the nature of the response.

When the template was offset from the crack centerline, the nature of the resistance ellipse is noticed to change, with the most clear indication in Figs. 16-18 with the sand cover layer present and a 1/2 inch crack. When the template was aligned with the crack, the major axis of the ellipse is at right angles to the crack orientation. However, with the 9 inch offset, the major axis is now aligned with the crack. At the intermediate offset, there are essentially four resistance peaks, one in each of the quadrants. This result implies that it may be difficult to define crack orientation with the resistivity method unless very detailed measurements are made.

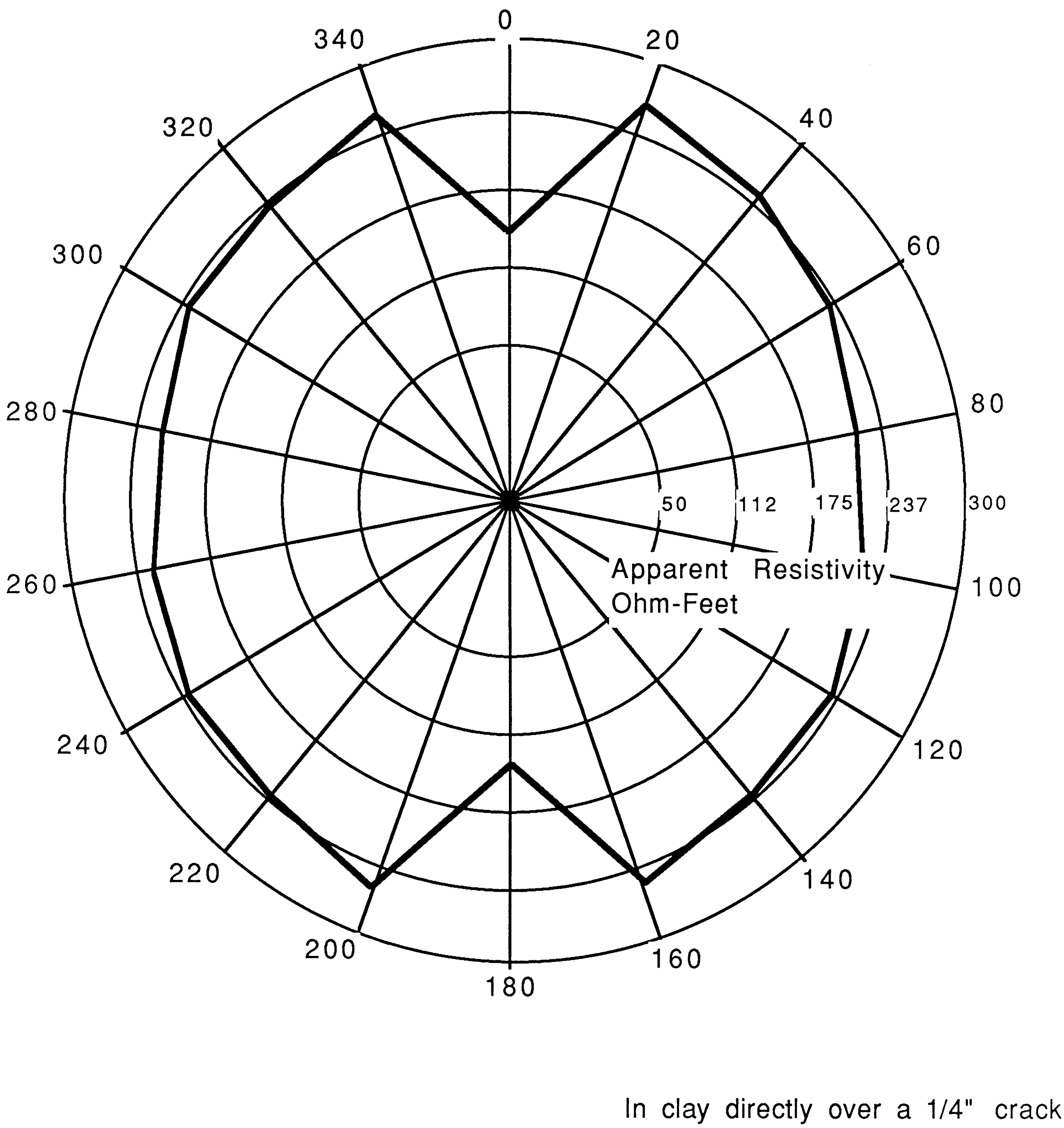


Figure 7. Azimuthal Resistivity Survey with No Cover Layer Present and with Template Aligned Over 1/4 inch Crack.

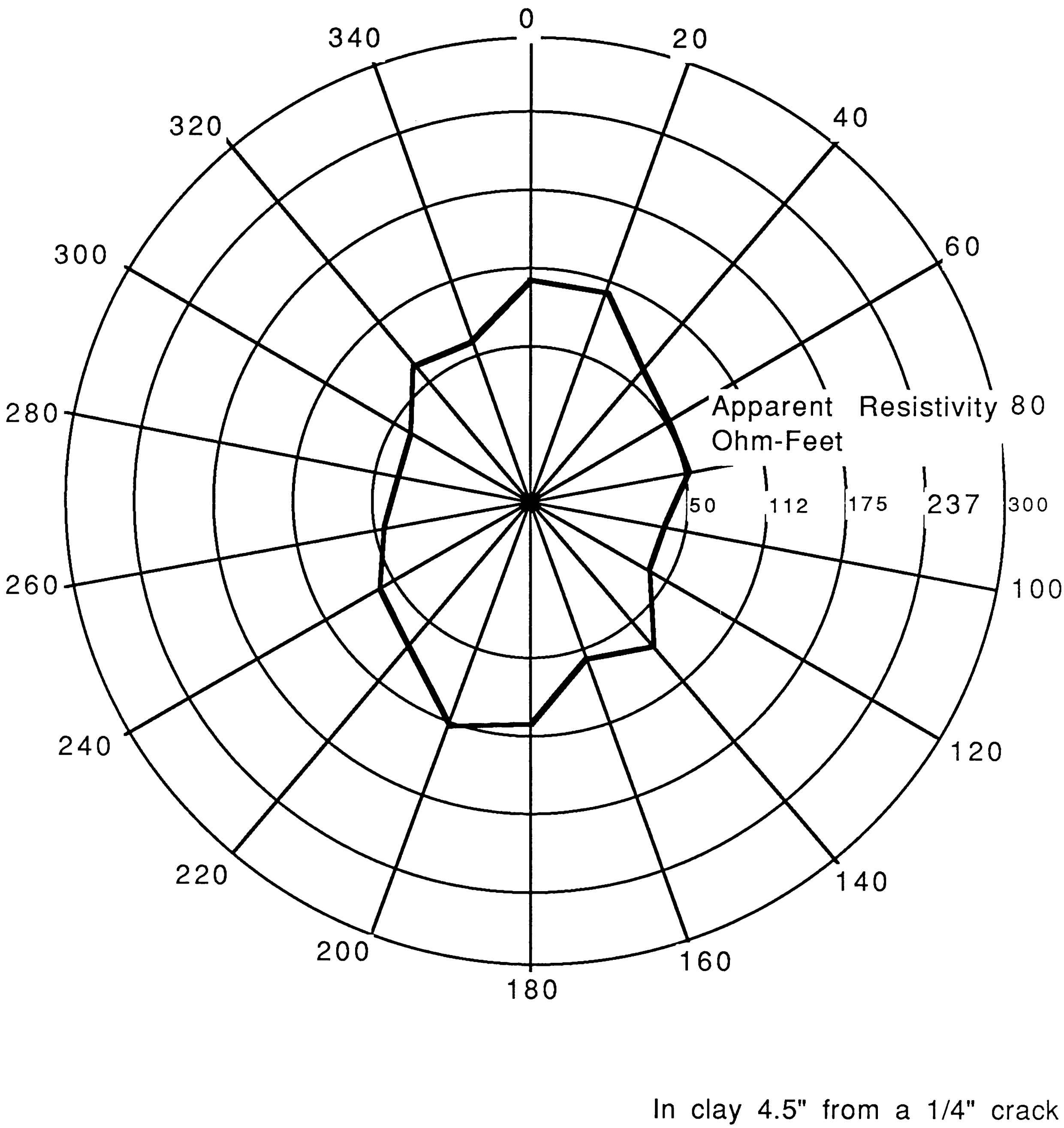


Figure 8. Azimuthal Resistivity Survey with No Cover Layer Present and with Template Offset 4.5 inches from a 1/4 inch Crack.

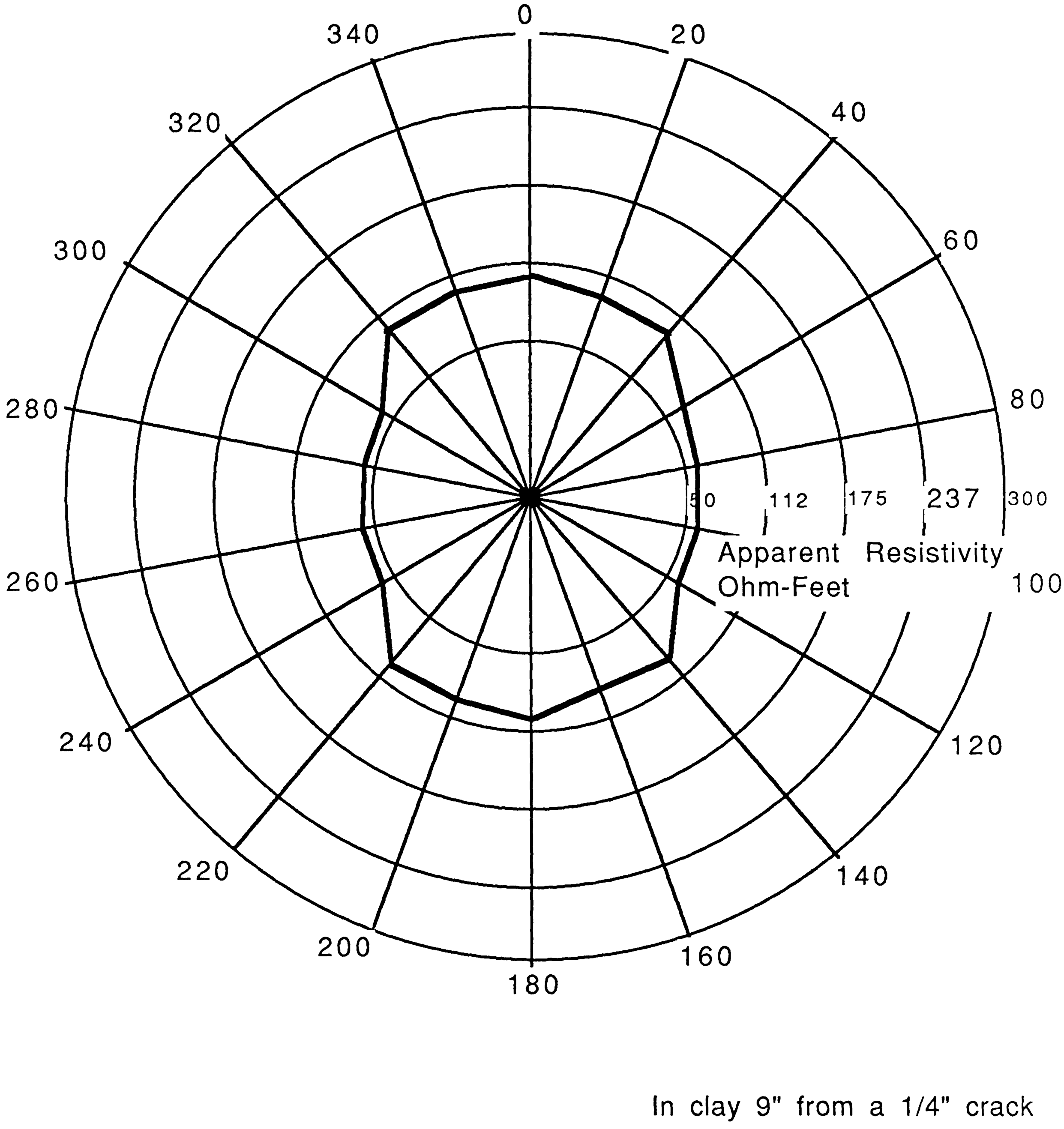


Figure 9. Azimuthal Resistivity Survey with No Cover Layer Present and with Template Offset 9.0 inches from a 1/4 inch Crack.

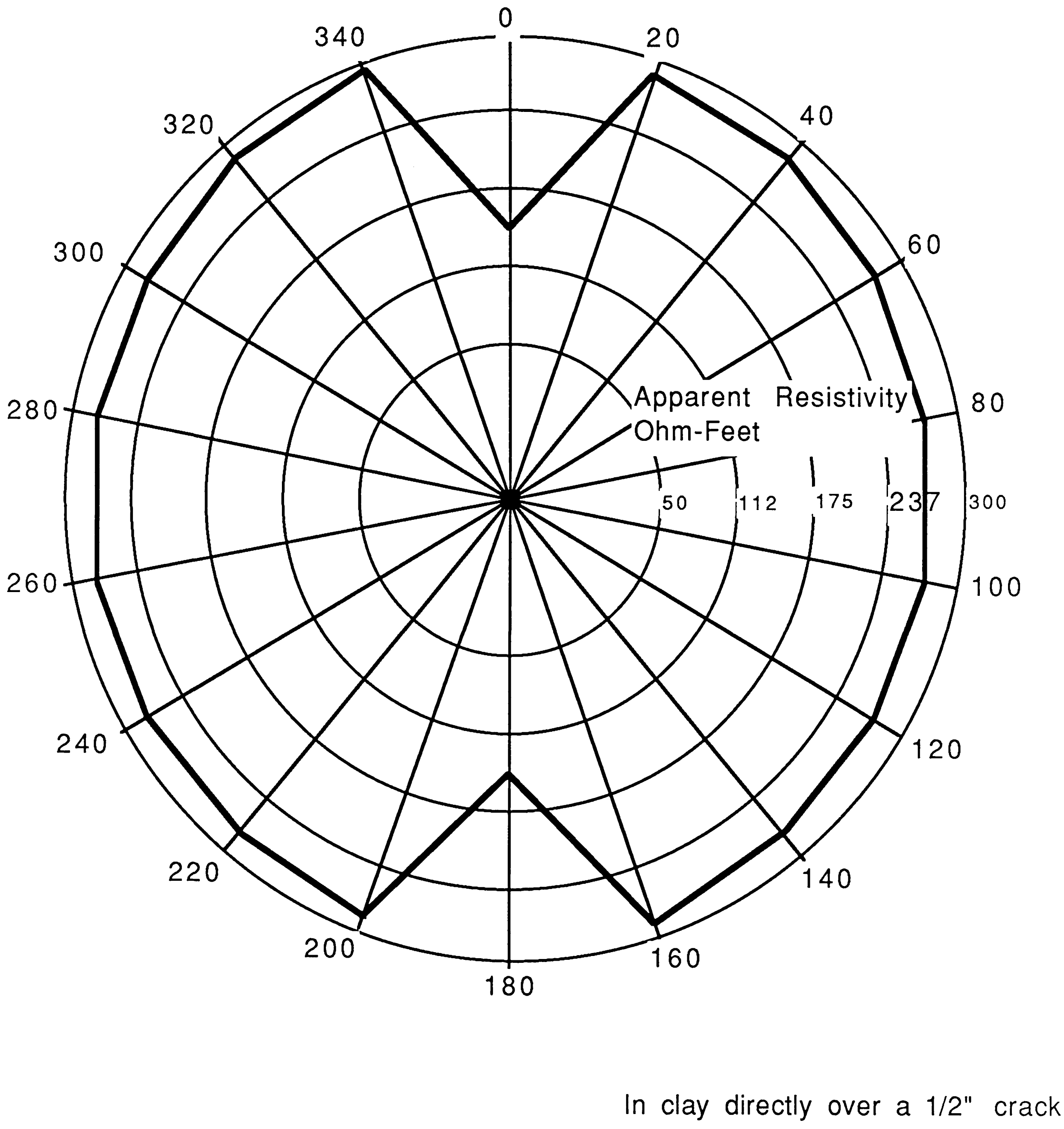
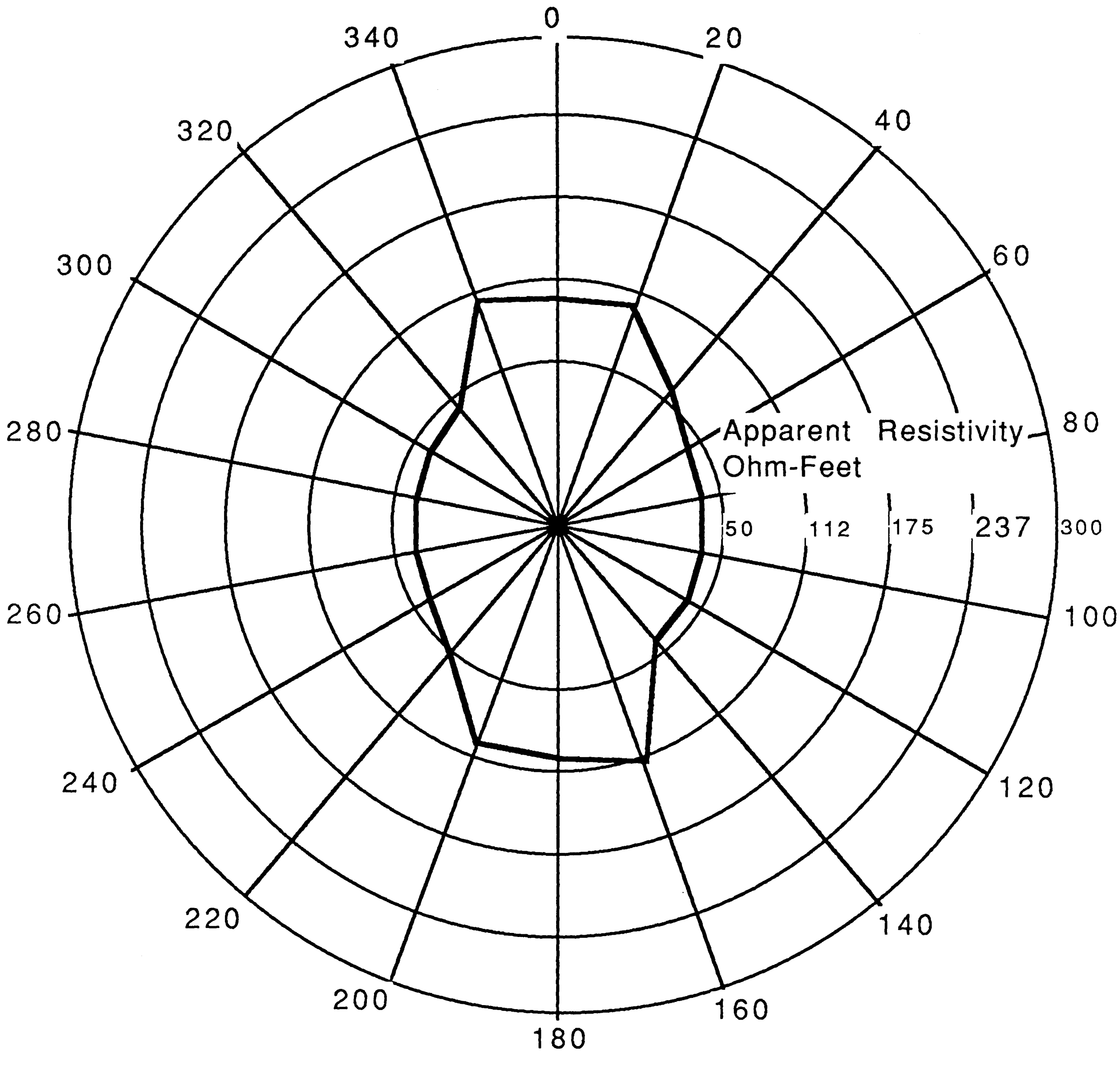


Figure 10. Azimuthal Resistivity Survey with No Cover Layer Present and with Template Aligned Over 1/4 inch Crack.



In clay 4.5" from a 1/2" crack

Figure 11. Azimuthal Resistivity Survey with No Cover Layer Present and with Template Offset 4.5 inches from a 1/2 inch Crack.

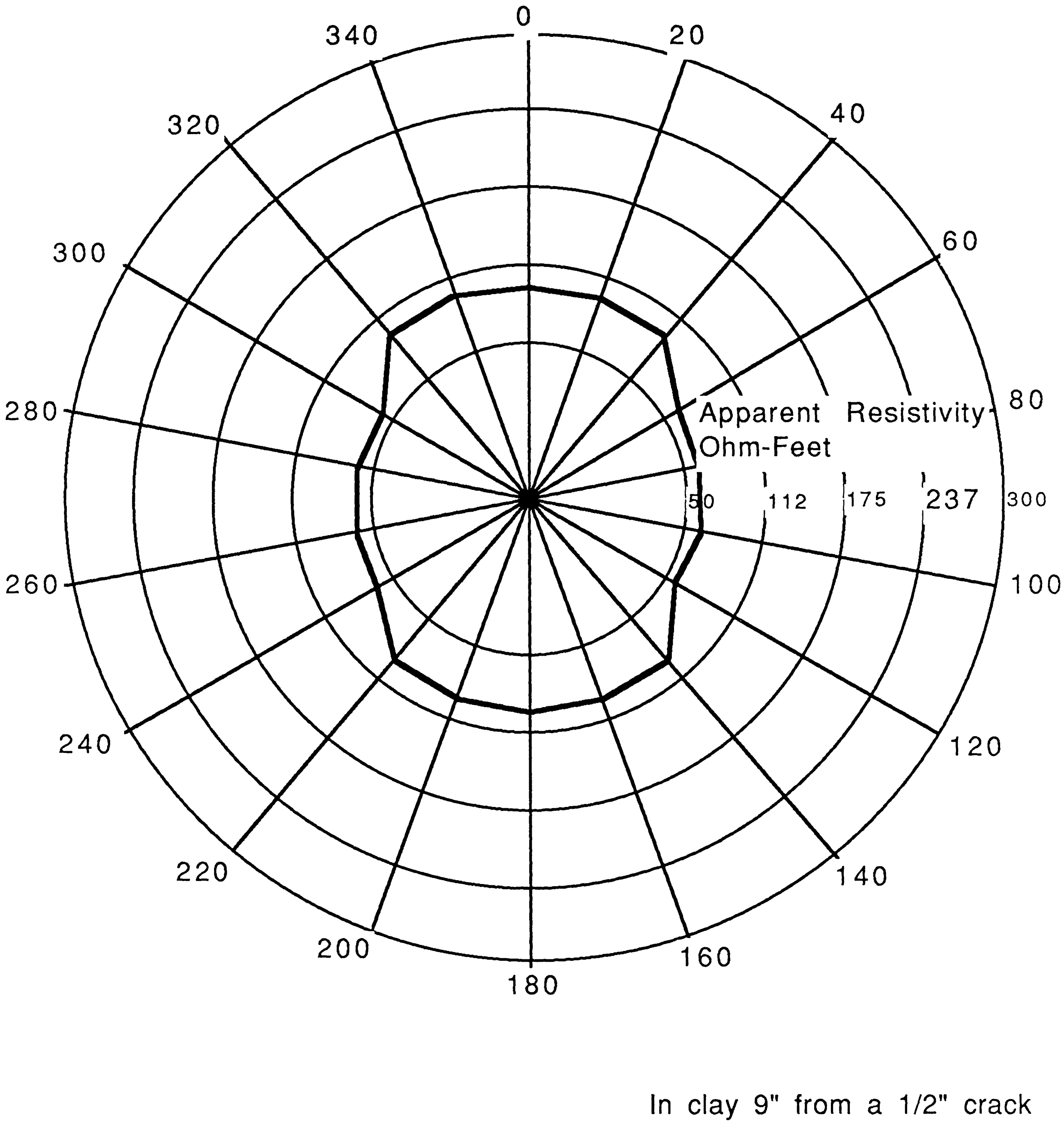


Figure 12. Azimuthal Resistivity Survey with No Cover Layer Present and with Template Offset 9.0 inches from a 1/2 inch Crack.

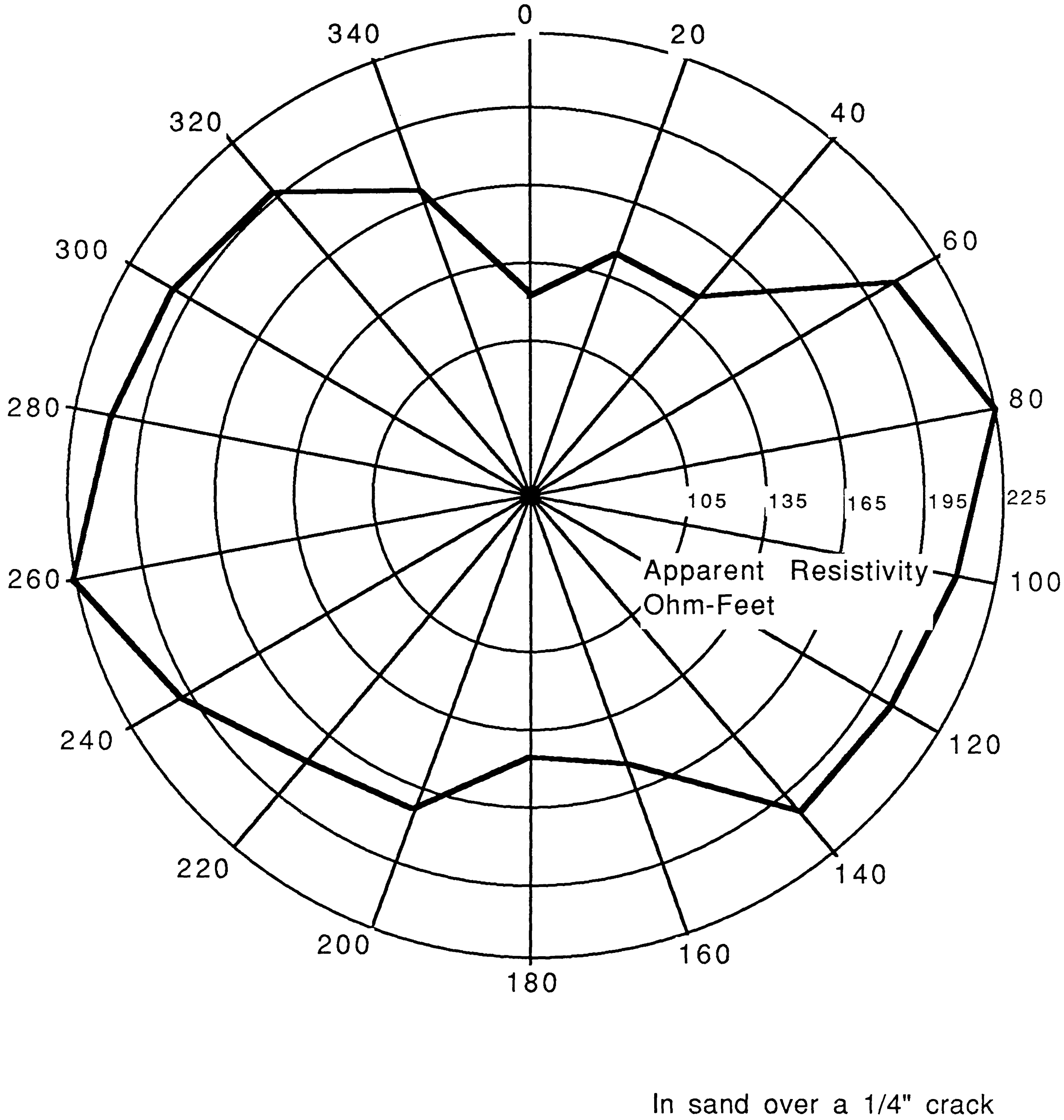


Figure 13. Azimuthal Resistivity Survey with Cover Layer Present and with Template Directly Over a 1/4 inch Crack.

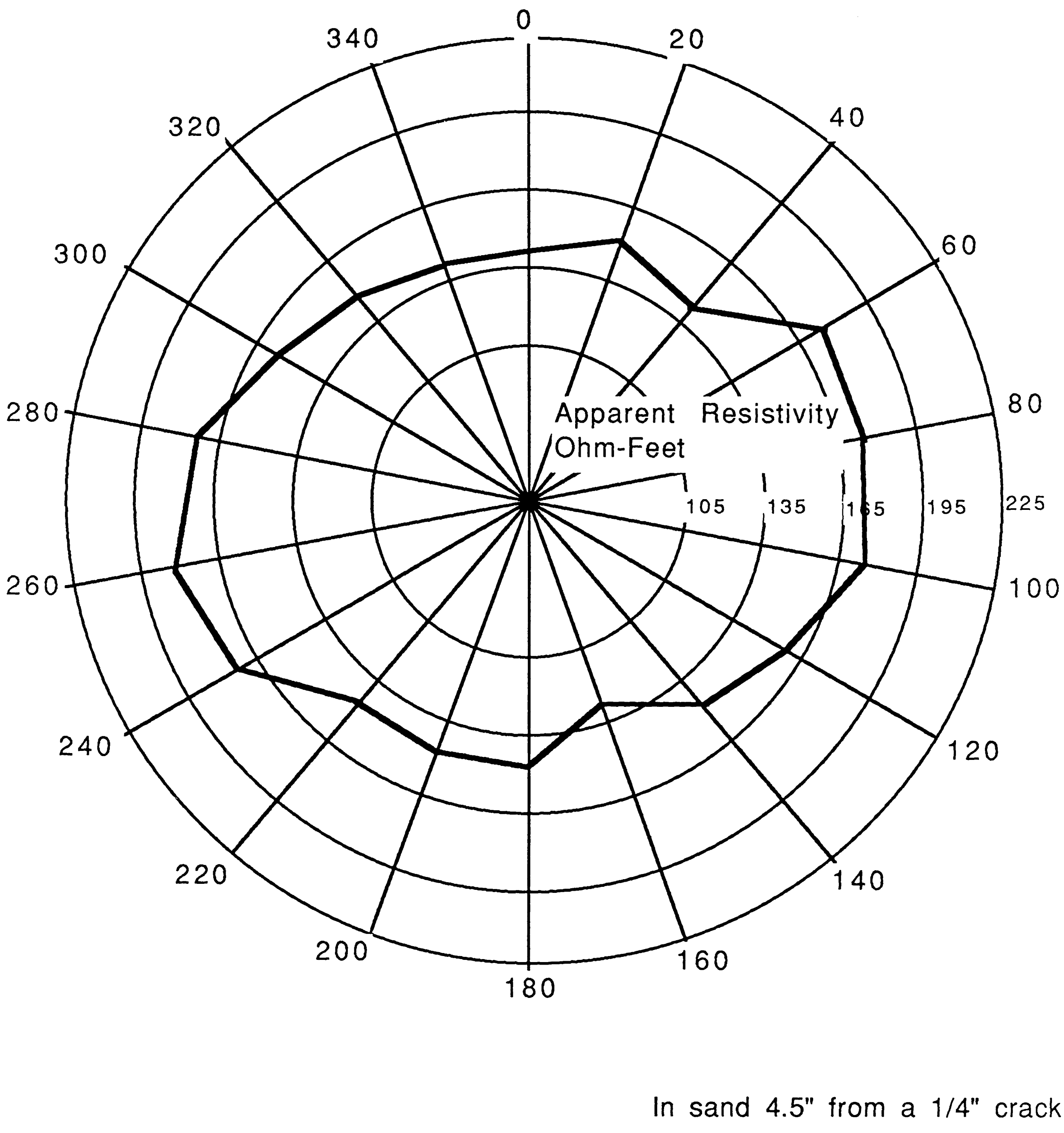


Figure 14. Azimuthal Resistivity Survey with Cover Layer Present and with Template Offset 4.5 inches from a 1/4 inch Crack.

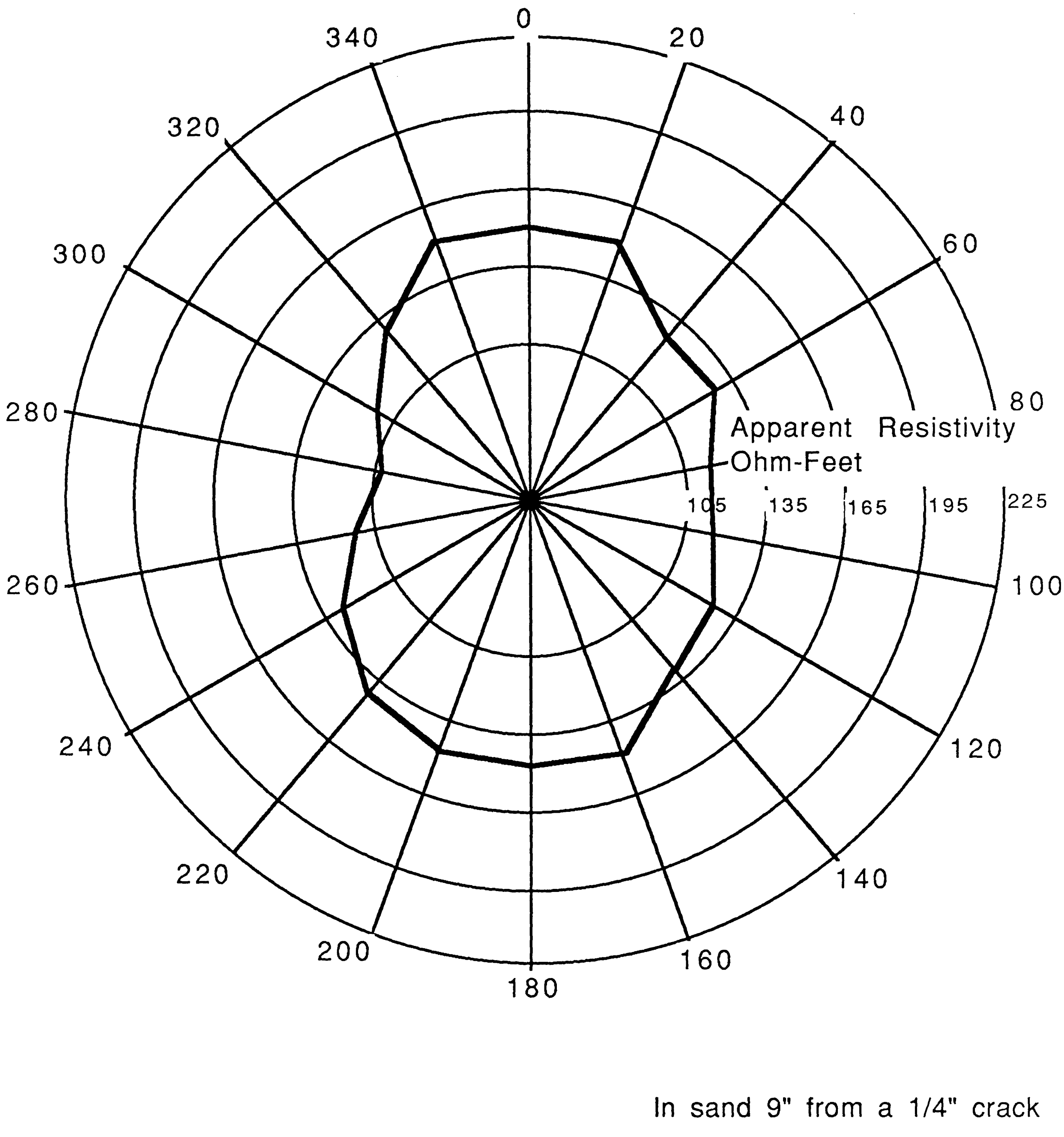


Figure 15. Azimuthal Resistivity Survey with Cover Layer Present and with Template Offset 9.0 inches from a 1/4 inch Crack.

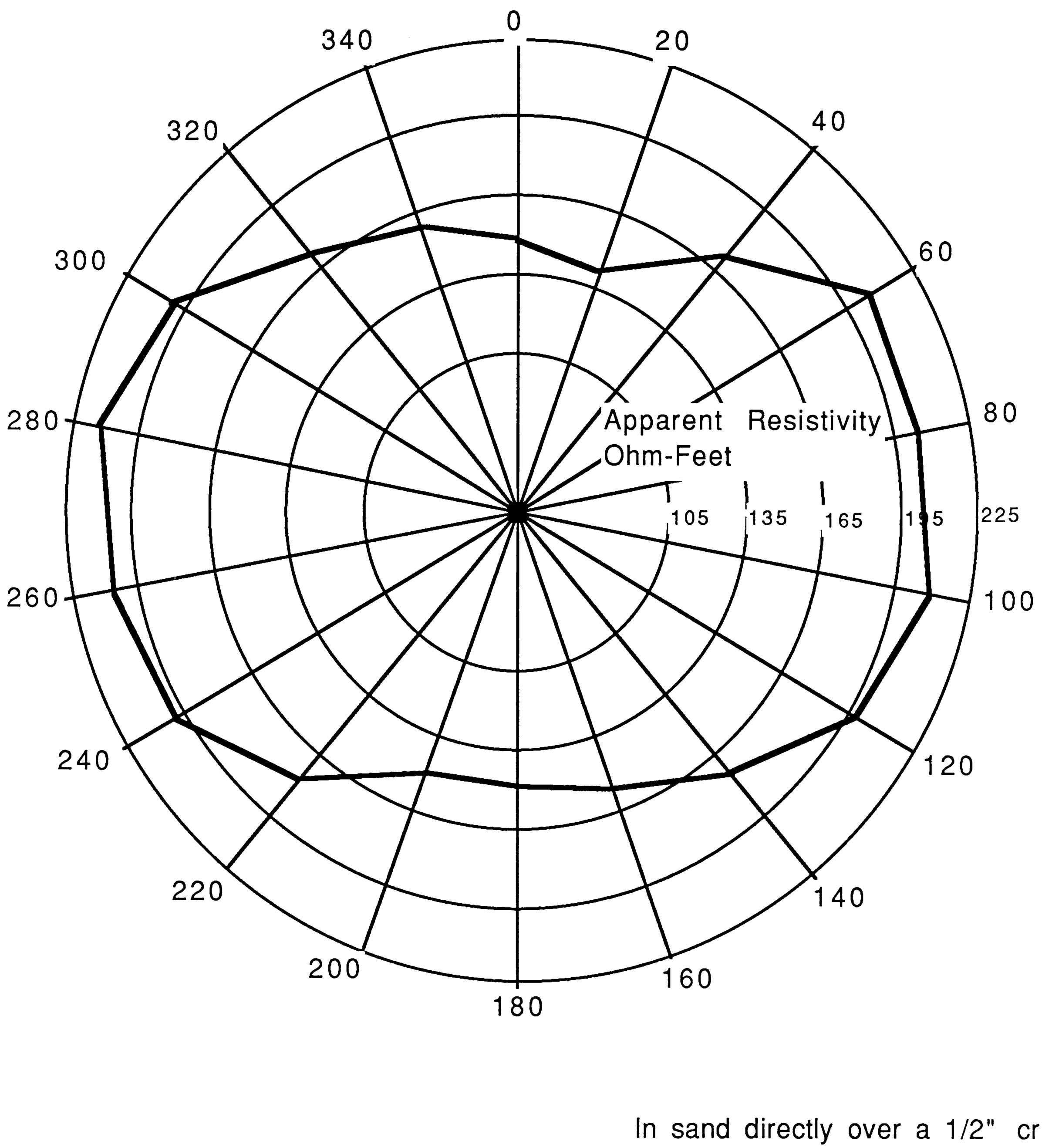


Figure 16. Azimuthal Resistivity Survey with Cover Layer Present and with Template Directly Over a 1/2 inch Crack.

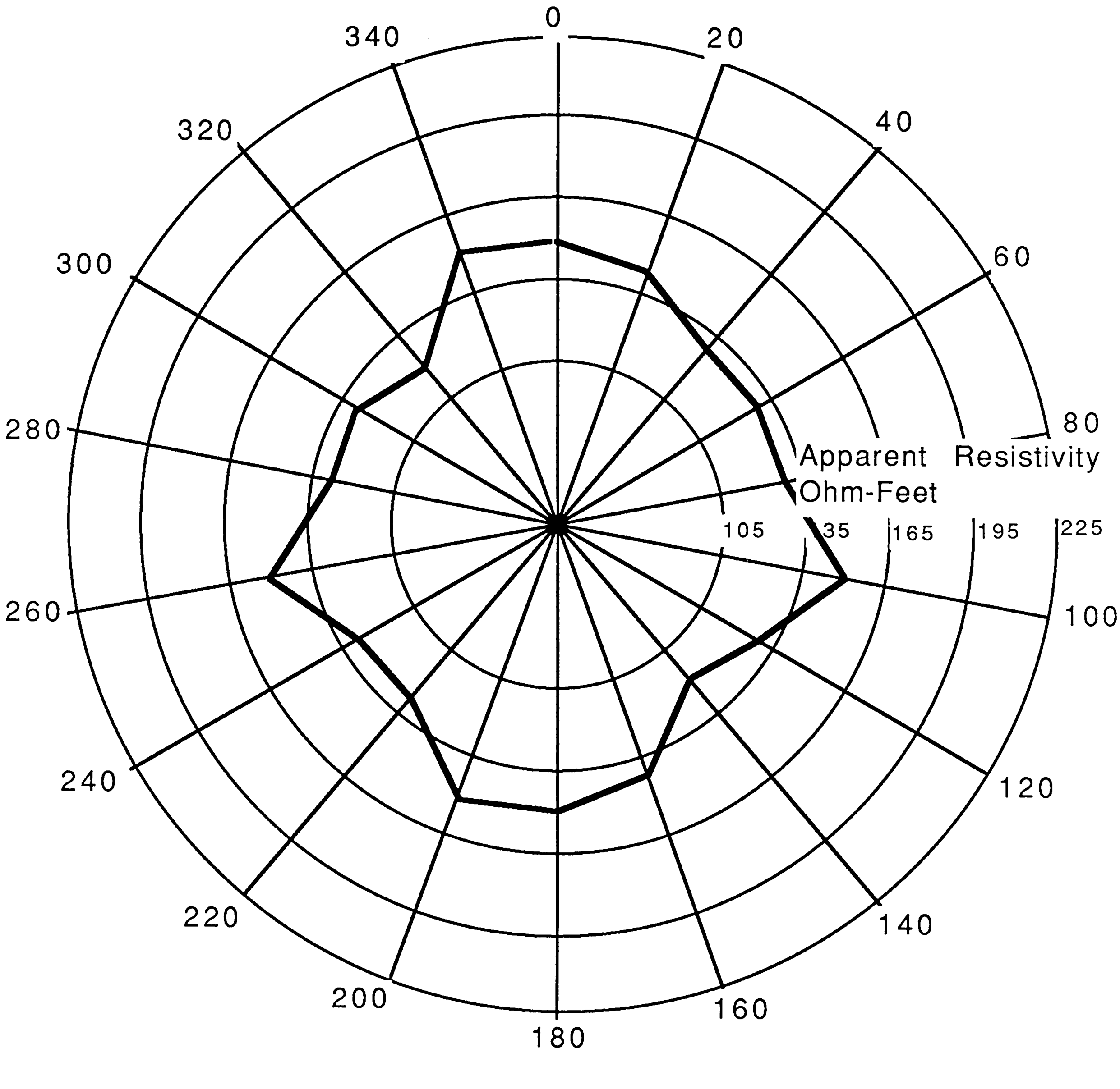


Figure 17. Azimuthal Resistivity Survey with Cover Layer Present and with Template Offset 4.5 inches from a 1/2 inch Crack.

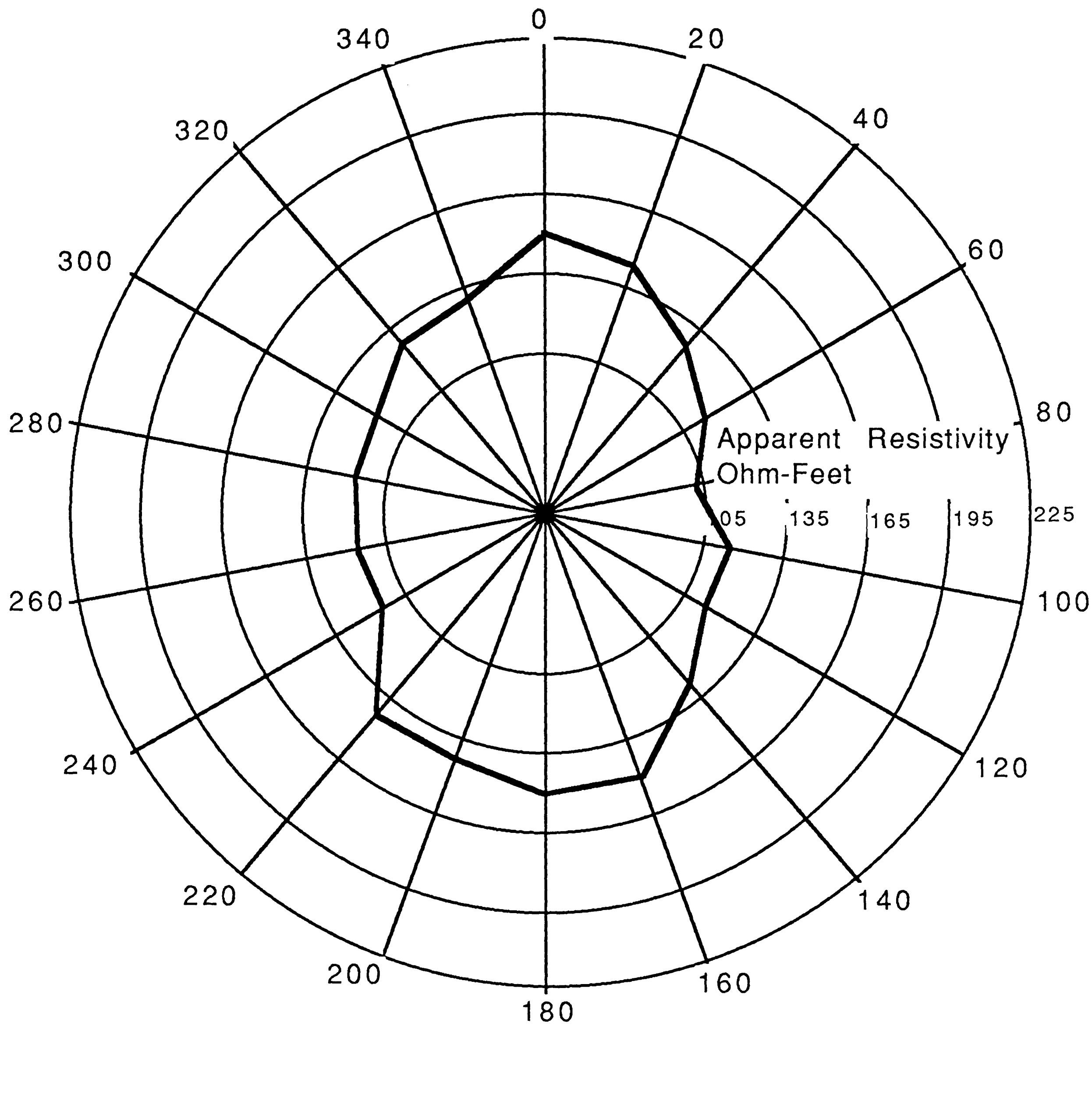


Figure 18. Azimuthal Resistivity Survey with Cover Layer Present and with Template Offset 9.0 inches from a 1/2 inch Crack.

One way to try to calibrate the measure of crack thickness is to compute the ratio of maximum to minimum resistance. Whether an ellipse is fit through the data or simply taking the maximum and minimum resistance values would not change the basic conclusion that the results are insensitive to the crack width. The ratios of maximum to minimum resistance are presented in Table 1. It is seen from Table 1 that there is no real consistent variation to the ratios for the one-quarter and one-half inch cracks and that the differences between the two are within the estimated accuracy of the measurements. Therefore, the electrical resistivity method appears to be incapable of quantifying the crack geometry.

One interesting result is that the sensitivity of the method (as measured by the ratio of maximum to minimum resistance) does not appear to significantly degrade as the crack is offset from the electrode array centerline. This is helpful from the point of view of the potential of the method for crack detection.

Table 1. Ratio of Maximum to Minimum Resistance Values Measured in Laboratory Study.

SITUATION	1/4" Crack	1/2" Crack
With cover layer, directly over crack	1.51	1.55
With cover layer, 4.5" offset	1.36	1.40
With cover layer, 9.0" offset	1.46	1.43
With no cover layer, directly over crack	1.90	2.21
With no cover layer, 4.5" offset	2.51	2.70
With no cover layer, 9.0" offset	1.83	1.68

Field Study

The field investigation portion of the study involved the use of electrical resistivity measurements over the Master Cell No. 5 hazardous waste cell at the Wayne Disposal Landfill near the Willow Run Airport near Ypsilanti, Michigan. As explained in the introduction, this was the same site where a series of vertical arrays of moisture sensing devices had been previously installed in the clay cover liner. The purpose of the field investigation was to determine whether similar patterns of electrical resistivity variation could be observed at the landfill. If the presence of such features could be located, then their behavior over an extended period of time could be observed by repeated measurements over a period of several seasons or years. This latter objective could not be attained within the time constraints of the present study, so the major purpose of the field study was to identify localized areas within the landfill site that indicated anomalies in electrical resistivity and to further isolate a few target locations for further study.

The installation of the clay cover liner for Master Cell 5 took place over an extended period of time in late 1985 and early 1986. The lower lifts in the liner were placed and compacted in the fall of 1985 until the weather forced postponement of the installation until the spring of 1986. After the placement of the final lifts of the clay liner in May of 1986, the cover liner was left exposed without a layer of final cover soil until the late fall of 1986. During the summer of 1986, it was possible to visit the landfill site and observe the state of the liner surface. Dessication cracks were observed to form in the liner during the relatively dry period of the summer months. Some of these cracks could be observed to extend to depths that implied that they were continuous through more than one lift of the clay. During the early fall of 1986, there was an extremely rainy period starting from approximately mid-September to the first week in October. The nearby Ann Arbor weather recording station noted approximately 26 consecutive days with recorded rainfall and during this same time period locations to the north in the area of Saginaw, Michigan recorded rainfalls that were estimated to be events with return periods of approximately 500 years.

The landfill site was visited several days after the end of this rainy period on October 10, 1986. At this point, the final cover had not yet been placed and the state of the clay liner surface was again visually inspected. Standing water was noted in depressions over the clay surface. It was observed that the dessication cracks had largely closed, but were still present. The largest cracks had widths that were of the order of 2-3 cm. but most were on the order of 1.0 cm. or less. The largest cracks could be followed for several meters with a hierarchy of smaller cracks leading off of the major ones. Approximate locations of some of the largest of these were noted and they were inspected to determine their approximate depths of penetration. In some cases a thin flexible stick could be pushed to depths of approximately 25 cm below the ground surface but in most cases smaller depths of penetration were found. Because the cracks were not entirely vertical in alignment, it is suspected that this procedure did not determine the depth of the crack but only the depth to which a significant change in the crack orientation occurred.

In one location, a vehicle path had been established across the landfill apparently as heavy equipment traveled across the landfill surface traveling generally from the northwest corner of the landfill towards the south east and passed approximately 200 feet south of the gas vent pipe near the center of the cell beside which the moisture monitoring arrays had been installed. This vent pipe is referred to in the subsequent discussion as the central gas vent. In the center of the vehicle track, a particularly well-defined crack pattern was noted as cracks with approximately 2 cm widths were aligned in roughly square patterns of approximately 50 cm on a side. Smaller, less extensive cracks branched off these major ones.

The final cover soil was placed over the top of the landfill cell and vegetation was established by the spring of 1987. At this point, it was no longer possible to visually observe the state of the clay liner or to disturb the liner system to determine the state of the liner. All subsequent information thus must come from indirect observations such as the moisture profile measurements, electrical resistivity measurements, or other non-intrusive sampling procedures.

Since the moisture profiles indicated that the clay liner was near the fully saturated state, it was decided to conduct the resistivity profiles during the late part of the summer months when dessication cracks would be most likely to form and after the preliminary laboratory results were obtained to guide the field effort. The dates of the field resistivity surveys were August 5, August 24, and August 31 during the summer of 1987. The weather during the summer of 1987 was not particularly atypical of Michigan summers. It was relatively dry during the early months of the summer and above average in temperature so the tendency for dessication cracking in the landfill may have been enhanced. A thunderstorm passed through the area on the night of August 2, with only localized amounts of significant rainfall. The soil surface was damp under bits of mulch that were still left from the vegetation establishment, but generally the soil was quite dry and difficult to drive the electrodes into. Prior to the second survey, approximately 5 cm of rainfall from a thunderstorm were recorded at the Detroit Metropolitan Airport on August 21 and the soil was noticeably more damp and the electrodes somewhat easier to drive into the ground. The third survey had been scheduled for August 27, but was delayed due to a heavy continuous rainfall nearly the entire daylight hours on that day. Subsequently, measureable rainfall was recorded on August 28, 29, and 30 at nearby meteorological stations with the rainfall stopping in the afternoon of August 30 with approximately 10 cm of rainfall recorded during the four day period. The ground surface on August 31 was damp with near saturation conditions in a few depressions over the landfill surface. The electrodes were noticeably easier to drive into the ground on this day.

Experimental Techniques

The August 5 effort was devoted to the performance of a central electrode survey in order to attempt to locate regions with anomalies in their electrical resistance. The surveys on that days consisted of profiling along a line extending from the center gas vent towards the southwest for a distance of approximately 200 feet. The alignment of the profile line was arbitrary in the sense that the choice for the direction was selected to be aligned with visible landmarks off the landfill site so that it could be reproduced in the future, if necessary. This same consideration dictated the choice of the second profile line run on August 24 as well. The profile was terminated before the position of the former vehicle track was reached so that its influence (due to extra clay compaction or other effects) would not be felt.

The central electrode arrays consisted of spacing the current electrodes at 50 foot spacings along the survey line and moving the potential electrodes within that gap. Since the current electrode spacing was greater than the depth of the entire liner system, the resistance of the synthetic liner to electrical current flow was relied upon to establish the potential field mainly within the clay liner. Potential electrode spacings of four feet were used and two profiles offset by 2 feet from each other were run over each 50 foot interval. Once the two profiles were completed, the current electrodes were set over the next 50 foot interval along the survey line and the process repeated.

After the results from this preliminary survey were completed, it was clear that the data suffered in quality near the ends of the 50 foot profiles (i.e. when the potential electrodes were close to one of the current electrodes), so it was decided to do further profiling with a current electrode spacing of 200 feet. The surveys of August

24 were performed at this greater spacing. Two different survey lines were run; one that repeated the line performed on the August 5 effort and the other along a line that ran approximately west-southwest from the center gas vent. For each of these survey lines, the 200 foot gap was covered with one profile with the potential electrode spacing at four feet and another at six feet. The purpose of the two profiles was to provide redundant information to ensure that an indicated anomaly would not be the result of a measurement problem in a single profile.

As a result of the findings from the August 5 and August 24 surveys, several locations with resistivity anomalies were found as discussed below. Two of these were selected for more detailed investigation on the August 31 date. A profile around a circle using the Wenner arrangement was used in a similar fashion to the laboratory investigation. For these surveys, a 5 foot electrode spacing was employed. A template was constructed of lumber to position a series of wooden stakes that located the electrode positions along 20° segments of a circle starting from a position pointing towards the north. The stakes were driven into the ground and left so that future measurements could be performed at the site if desired. Generally, the sampling procedure was the same as in the laboratory investigation.

Results

The results from the August 5 resistivity profiles using the central electrode configuration are presented in Figs. 19 - 22, one for each of the 50 foot sections. These measurements were made to attempt to locate regions with apparent resistance anomalies and the two profiles were made with the potential electrode spacings offset by two feet in order to obtain independent confirmation of the same. For example, in Fig. 19, there is an apparent anomaly indicated at about 18 ft in one of the profiles, but it is not confirmed in the second profile. This technique was used to screen the data somewhat given the basic accuracy of the method.

Although the method for converting the resistance values to apparent resistivity should obtain a constant apparent resistivity with distance along the profile, this is only valid for a semi-infinite homogeneous medium, while the actual system has three layers (cover soil, clay, sand drain layer) with a depth of only about seven feet from the surface to the top of the synthetic liner. No attempt was made to compute the apparent resistivity based on this vertical profile since the porosities of the

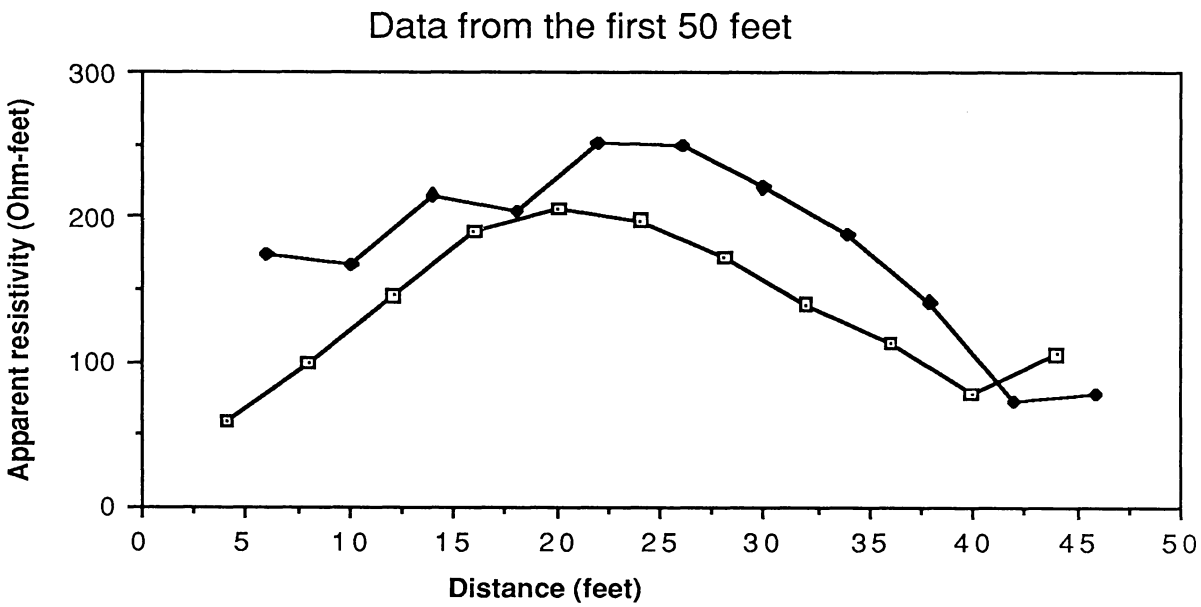


Figure 19. Central Electrode Survey 0-50 feet.

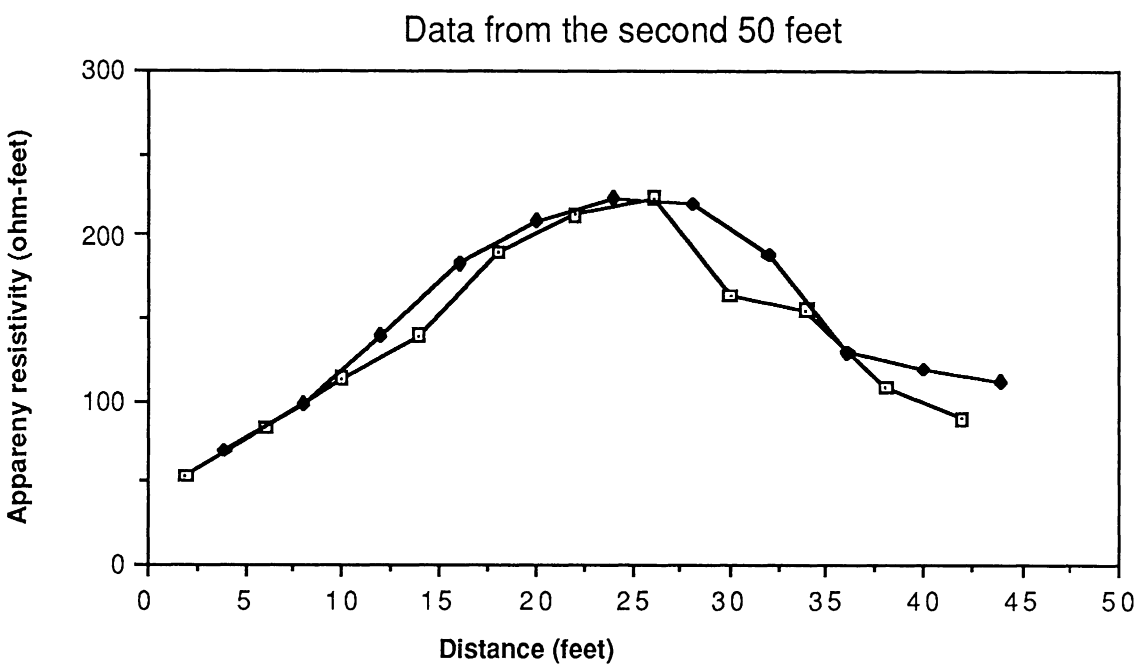


Figure 20. Central Electrode Survey 50-100 feet.

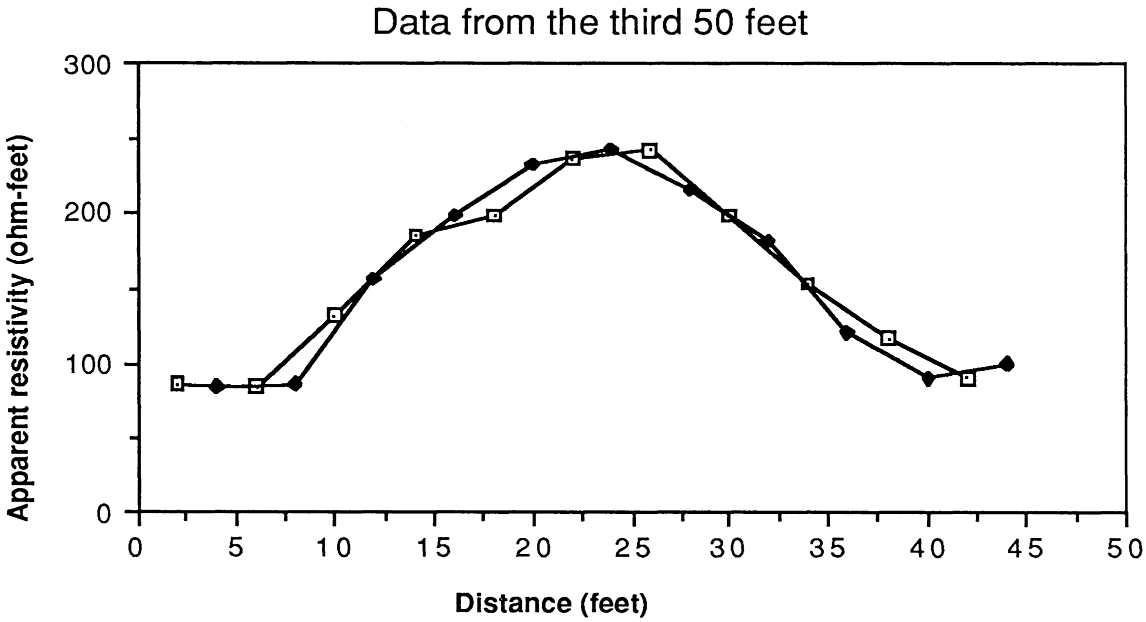


Figure 21. Central Electrode Survey 100-150 feet.

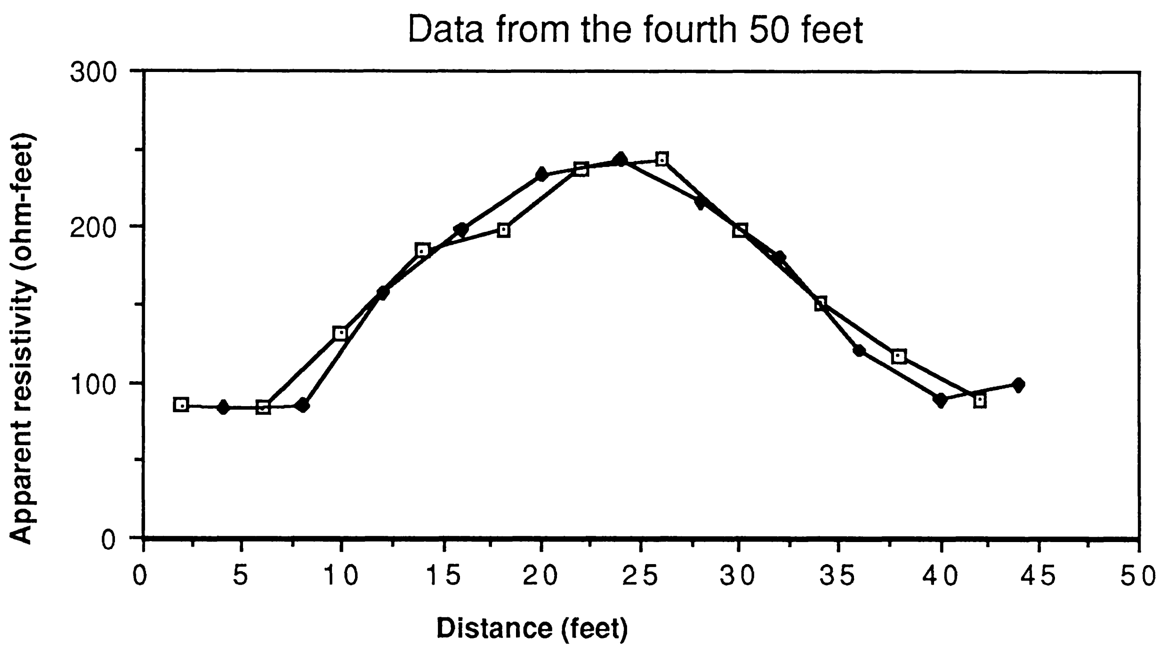


Figure 22. Central Electrode Survey 150-200 feet.

various media were not known as were the degree of saturation in each layer. The apparent resistivity tends to decrease towards the ends of the profile sections due to this vertical variation in media properties. This causes some difficulty in interpreting the results. For example, in Fig. 19, there appears to be an anomaly at around 40-42 feet indicated in both profiles, but since it is near the end of the profile section, it is difficult to determine this with any certainty. In the additional profiles, no anomalies are indicated in the second 50 foot segment (Fig. 20), there may be one at the beginning of the third segment (Fig. 21) and the same is apparent with the fourth (Fig. 22). The results of these initial surveys led to inconclusive results. This led to the decision to go to the greater current electrode spacings in the August 24 surveys.

The same 200 foot survey line was profiled on August 24 with a 200 foot current electrode spacing and both four and six foot potential electrode spacings. The results are indicated in Fig. 23. Although the variations of apparent resistivity are much greater, many more apparent anomalies are indicated over the 200 foot length simply because there are fewer end sections. In this record, the anomaly discussed in Fig. 19 is again observed, at least with the four foot spacing at about 40-45 feet. Similarly, there is an anomaly indicated at about 105-110 feet with both electrode spacings that is in about the same location as that at the beginning of the profile in Fig. 21. An additional one not indicated in Fig. 20 occurs at around 70-75 feet and there are a few additional indications of anomalies between 100 and 150 feet although these are less clear.

A second survey line was run 200 feet towards the southwest from the center gas vent in a similar fashion and the results are presented in Fig. 24. In the two profiles with different electrode spacings, there are only three resistance anomalies confirmed in both; one at about 30 feet, one at about 60 feet, and another one at around 80-85 feet. Because there are some anomalies indicated in one profile and not in the other, it is not clear whether all of the indicated variations are within the range of measurement accuracy or if these differences reflect influences associated with the exact potential electrode spacings; further research would be needed to study this issue.

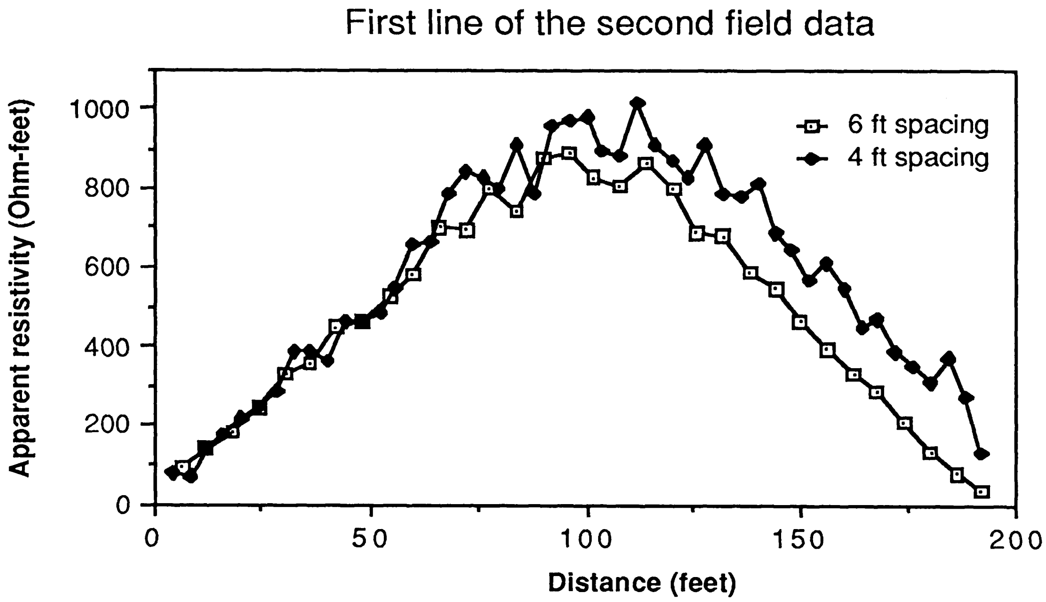


Figure 23. Central Electrode Resistivity Survey, 200 foot Profiles to Southwest of Center Vent Pipe.

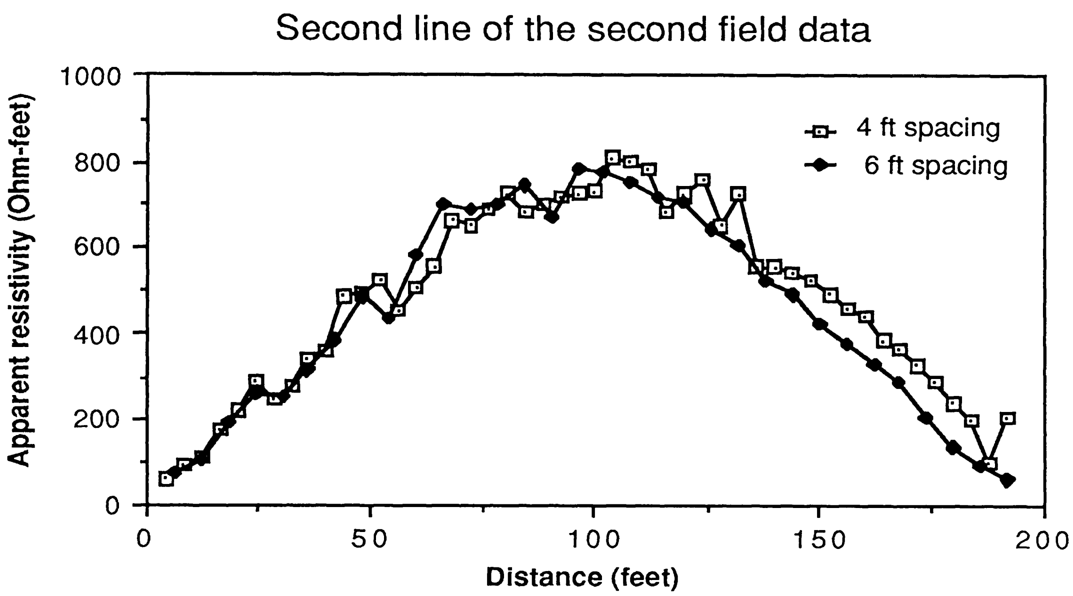


Figure 24. Central Electrode Resistivity Survey, 200 foot Profiles to Southeast of Center Vent Pipe.

Based on the results of the two sets of surveys, it was decided to investigate a few of the regions with apparent resistance anomalies in more detail. There were several candidate locations indicated as discussed in the preceding paragraphs. The two selected for further study were the anomaly at around 40 feet in the first survey line and the one at around 60 feet in the second survey line. Although the first one was not indicated in both profiles in Fig. 23, it was indicated in both profiles in Fig. 19 and was also the general vicinity of a rather large crack that was observed in the site survey on October 10, 1986. The second position is one of the largest local resistance variations. On August 31, these two sites were investigated by profiling in a 360° arc similar to the techniques employed in the laboratory investigations. The profiles were centered over the resistance variation and resistivity readings taken with a Wenner array and 5 foot spacings at 20° segments. The results of this profiling is presented in Figs. 25 and 26. Although the magnitude of the resistance fluctuations is slightly greater in Fig. 25, there are no clear patterns to the variations and it appears possible that the indicated variations are at the limit of the precision in the measurements. The general pattern is somewhat similar to that observed in Fig. 17 indicating that the crack centerline, if present, is offset from the resistance electrode array. On the other hand, Fig. 26 shows a fairly consistent pattern of resistance variation similar to those observed in the laboratory study. This may be taken as indicative of a crack, and in fact, is in the vicinity of a relatively large crack that was observed before the final cover soil was placed. However, the absolute variation in resistance is fairly small and at the limit of accuracy established in the laboratory investigation. Unfortunately, these field surveys took place after several days of fairly heavy rainfall and it is expected that this would minimize the likelihood that a crack would be observed. Further measurements at this and other locations during different hydrological conditions will be required to establish the likely presence of a crack with more certainty.

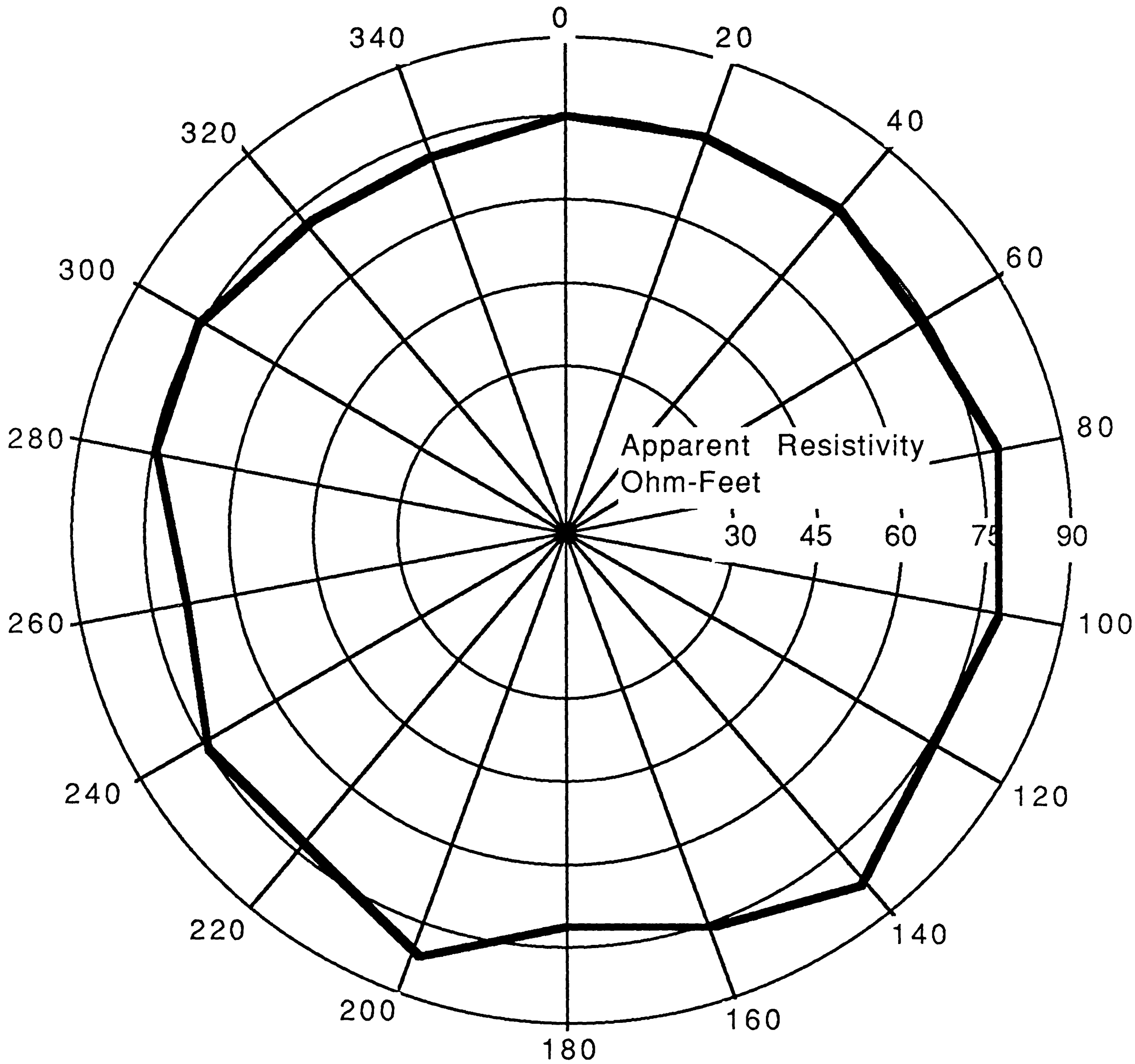


Figure 25. Azimuthal Resistivity Survey with Wenner Configuration at Location of Resistance Anomaly 60 feet South~~east~~west of Center Vent Pipe.

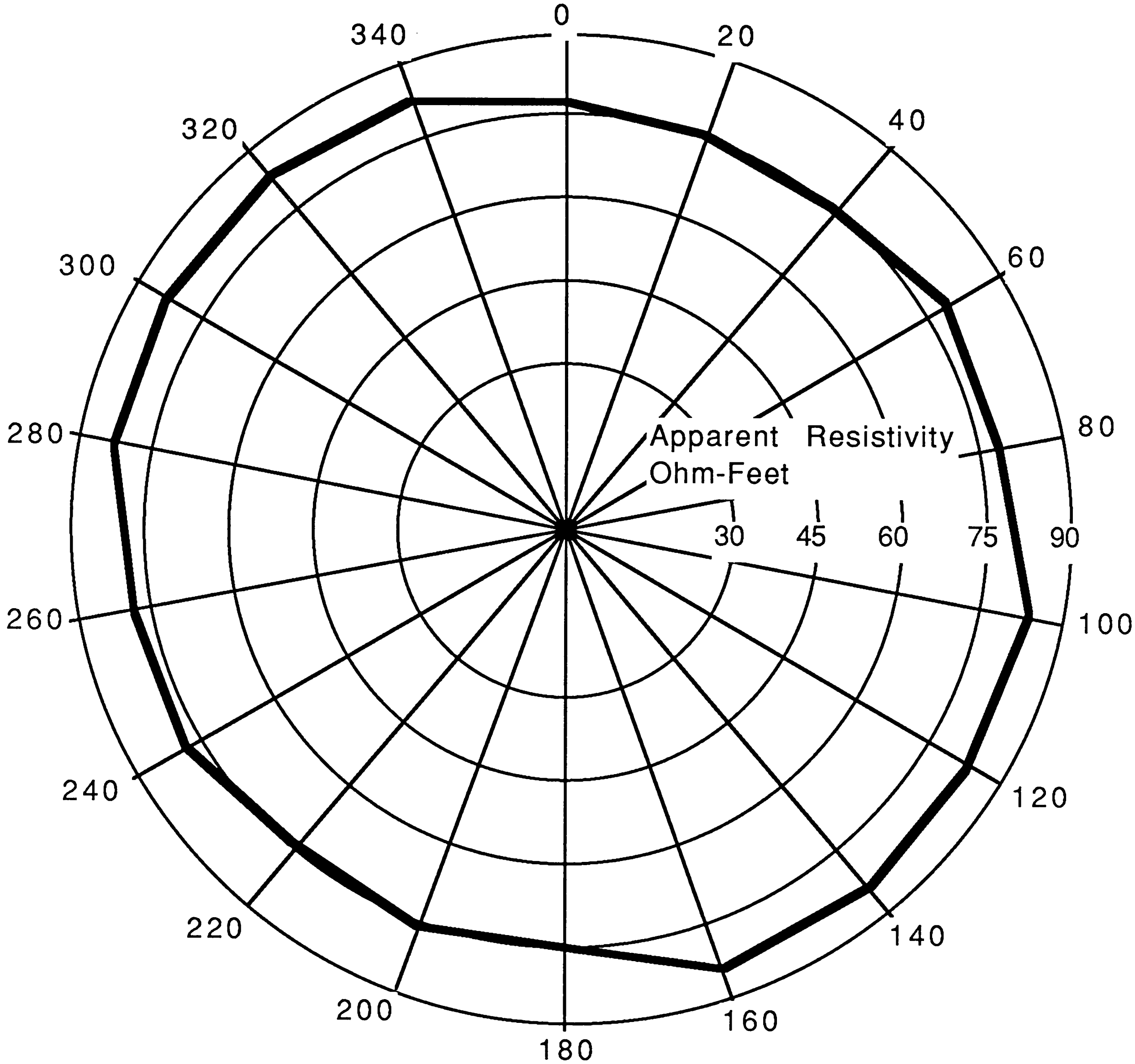


Figure 25. Azimuthal Resistivity Survey with Wenner Configuration at Location of Resistance Anomaly 45 feet Southwest of Center Vent Pipe.

east

When these results are interpreted in light of the laboratory investigation, one possible investigation of the differences may be that the crack does not penetrate through the entire liner in the prototype where it did in the laboratory model. This may imply that the method may be useful for the determination of crack penetration, but this must be investigated further in laboratory investigations before definite conclusions may be drawn.

RECOMMENDATIONS FOR FURTHER STUDY

The findings of the present investigation were sufficiently encouraging to suggest that additional studies of the applicability of the electrical resistivity technique for detecting cracks in clay liners and quantifying the crack geometry. The following recommendations are made in this regard

- Continued monitoring at the field site should be conducted to observe the behavior of the indicated regions with resistivity anomalies;
- In particular, seasonal variations in resistivity patterns should be observed;
- Further laboratory investigations to determine the electrode spacings that provide the most sensitivity in the measurement techniques should be performed;
- In particular, the electrode spacing should be varied in order to determine if the vertical extent of the crack can be estimated with vertical profiling methods;
- A laboratory investigation to determine the influence of water infiltrating into a crack in a relatively dry clay liner may be useful for potential application in other more arid climates, but there is no indication that such a methodology would be useful in the more humid climate of Michigan;
- Monitoring at a similar site where excavation is possible would be useful to verify that the inferred cracks actually exist in order to ensure further validity to the technique.

SUMMARY AND CONCLUSIONS

This study was conducted to determine whether or not geophysical methods could possibly be used to detect cracks in clay landfill liners and to quantify their geometries. A survey of the available methods indicated that electrical resistivity profiling was the most likely candidate for this purpose. A laboratory and field investigation were conducted in order to examine this question in a preliminary fashion. The laboratory study involved the use of azimuthal resistivity profiles in order to determine the relationship between the resistivity when the electrodes are arranged parallel or normal to the crack. Also studied were the effects of crack width and offset of the crack from the plane of the electrodes. The field investigation involved lateral resistivity profiling in order to detect the possible locations of cracks at an actual hazardous waste landfill site. Once regions with resistivity anomalies were detected, azimuthal profiling was performed in order to determine the similarity between the measured resistivity variations and those observed in the laboratory investigation.

With respect to the particular study, the following conclusions have been drawn:

1. Crack detection is possible with electrical resistivity methods if the cracks are relatively large in horizontal extent compared to the electrode spacing;

2. It is not necessary for the instrumentation to be centered on the crack to detect its presence;

3. Location of the crack with respect to electrodes (i.e. whether the crack is offset relative to the azimuthal survey) has a significant influence on angular variations in resistivity and this makes it difficult to establish the crack orientation;

4. The measurement results appear to be insensitive to crack size (width);

5. Conclusions 3 and 4 imply that it will be difficult to quantify crack geometries.

6. The field results appear to indicate the presence of cracks; longer term monitoring of the observed resistivity anomalies is required to validate this conclusion.

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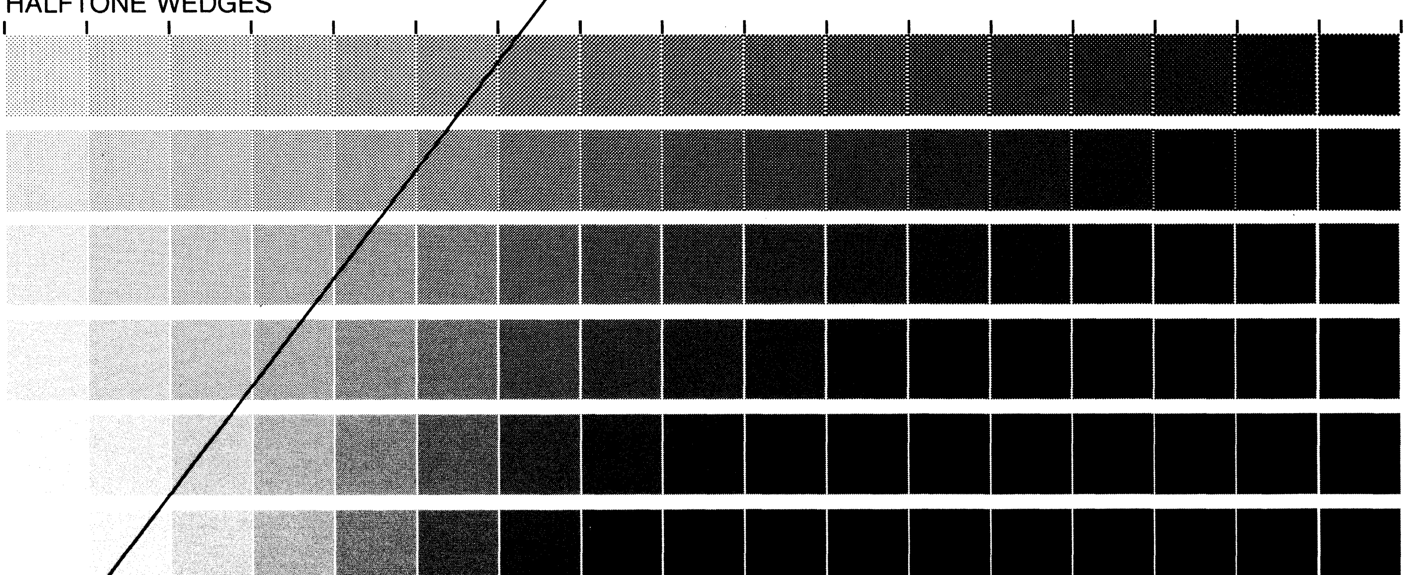

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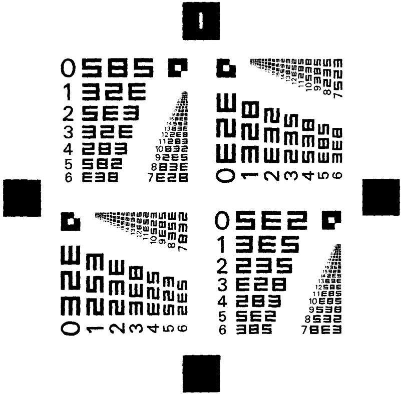

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