Vertical Resistivity Electrode Arrays for Detecting Hydrocarbon Movement and Content in Sands

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VERTICAL RESISTIVITY ELECTRODE ARRAYS FOR DETECTING HYDROCARBON MOVEMENT AND CONTENT IN SANDS

by

Kirt Elliott

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
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Finally, I wish to express my sincere appreciation to my wife, Kristi, for her continued support and patience throughout this endeavor as well as my parents, Mel and Linda Elliott.

Kirt Elliott
In many contamination sites where hydrocarbon is involved an accurate thickness of the contaminant can not be achieved through the most commonly used methods. The purpose of this study is to find an alternate method of determining a precise thickness and monitor the contaminant movement in conjunction with the current methods. Vertical resistivity electrode arrays were tested in a lab environment on singular probes and between probes. The arrays tested were the Wenner, dipole dipole, gradient, parallel and down-hole 3-arrays. Electrode pipes were constructed and placed into a sand tank where the hydrocarbon thickness and the water level could be controlled. Four configurations with different water levels and/or kerosene thickness were used. The results show that the electrode arrays all have the ability to detect resistivity changes from the presence of hydrocarbon in the sand, depending upon several variables. The variables that caused the greatest change in resolution were the spacing of the electrodes, thickness of the kerosene and the electrode array used. As each electrode in an array crosses a resistivity boundary it forms a cusp. These cusps are different for each array, but remain similar for an individual array. There were many arrays that detected the kerosene.
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INTRODUCTION

Statement of the Problem

In our industrialized society we use extreme amounts of fuels, gas and oil. Because of this, during transport, refining and our everyday use of these hydrocarbons they are spilled, poured and allowed to enter our soils and groundwater. When an area that is contaminated with hydrocarbons is investigated varying methods can be used. Geophysical methods have been used to detect hydrocarbon and other contaminants in the ground for years with mixed results. These measurements have been taken from the surface, which allows for non-intrusive, but when trying to determine the thickness of the contaminant they are not very accurate. Lima et al. (1995) describes how the resistivity techniques can be used to determine with some accuracy the size, shape and depth of a hydrocarbon plume, so they are effective tools to use. There are other problems with surface geophysics. Pennington (1985) talks about complications in doing resistivity surveys. The man-made obstacles, power lines, limited space, and unknown environments all affect measurements that are taken. To determine the thickness of the contaminant, monitoring wells were needed. Wells are used in thousands of oil spill sites to delineate contamination by hydrocarbons, but these wells can pose problems, have drawbacks and often can be misleading. Pennington (1985) discusses how drilling wells is more time consuming, more costly, and has the potential of spreading the contamination. In contrast the
resistivity techniques are less expensive and can be used to determine better locations for monitoring wells. Ballestero et al. (1994) describes that contaminant volumes in wells are strongly influenced by fluctuations in the water table and can lead to erroneous assumptions in the thickness of the contaminant layer. Therefore, it would be advantageous if product thickness and location could be determined in the subsurface using geophysical methods in addition to or instead of conventional wells. The combination of the two techniques would provide a more accurate representation of the subsurface contamination. This would then allow for a more precise determination of cleanup costs and viable cleanup procedures. Daily et al. (1995) says that new geophysical methods are being developed to delineate the three-dimensional distribution of a subsurface contaminant. This is especially important if it can be accomplished with minimal drilling. Another need for a new method is to provide detailed information about the progress of remediation efforts. With these reasons in mind, the purpose of this study is to test different vertical electrode arrays for their ability to detect hydrocarbon in a sand filled tank, and to monitor the movement of the hydrocarbon with changes in the water level and/or the thickness of the hydrocarbon contaminant.

Literature Review

The vertical electrical resistivity methods that were used in this experiment have been used in situ in other experiments. Greenhouse et al. (1986) began some preliminary tests with a disposable E-log, which is a PVC probe with equally spaced
electrodes. This was placed in a sandy environment, in which it works quite well and provided information on the formation conductivities at shallow depths. There have also been methods used to follow infiltrating dense non-aqueous phase liquid (DNAPL) contaminant fronts through sands (Schneider et al., 1992). They showed with this experiment that resistivity methods can be very effective in monitoring a highly resistive DNAPL which has water-saturated material above and below. The experiment used perchloroethylene as the DNAPL that was injected into a nine by nine-meter section of a sandy aquifer. Wenner electrode arrays with spacings of 5 cm, 25 cm, 45 cm and 85 cm were used to acquire resistivity measurements. The arrays were in situ along pipes in the aquifer cell. The results from the resistivity readings showed values that were up to ten times the background values. These high resistivity readings allowed the DNAPL front to be tracked very effectively.

Schneider et al. (1993) used similar probes and electrode arrays at 2.5 centimeters to monitor a light non-aqueous phase liquid (LNAPL). The LNAPL used was kerosene and it was placed into the sandy aquifer cell in five separate injections. These injections of kerosene were all monitored and the results show an increase in the vadose zone resistivity. The experiment provided results that were very successful in following the infiltration of kerosene through the sand. Shoop et al. (1996) used an in-situ electrical resistivity probe to monitor hydrocarbon in contaminated sand. The experiment was performed at a field site that had diesel contamination in fine-grained sand. The probes were placed in the sand to intersect the water table. The readings from the probe were compared to the amount of petroleum hydrocarbon from soil
borings taken from the same site. The results show a correlation between the high
resistivity measurements and the amount of hydrocarbon in the samples. The
resistivity monitoring was effective in moist soils but the resistivity of the dry soil
was too high to make a distinction between the hydrocarbon and the soil. Most of
these recent experiments that have been performed have only utilized one type of
electrical array. By using more than one electrode array the data sets could confirm
to a greater degree the results provided by one electrode array. This study compares
electrode arrays in order to determine the pros and cons of different arrays and if they
can be used in conjunction to produce more accurate results.
THEORY

Principles of Electrical Resistivity

This study utilizes the fact that different materials have varying degrees of conductance of electrical current. Electrical current is the movement of charged particles and occurs in three different ways. The first way is by ohmic conduction. This is when electrons flow through the crystalline structure of a material, which usually occurs in metals. The second way charged particles move is by dielectric conduction. This is when the ions and electrons in a crystalline structure and atomic structure shift cyclically when an alternating electric field is applied to the substance. The last way that current is conducted is by dissolved ions in the groundwater. The ions move through the pore spaces in the soil. This method is called electrolytic conduction and is the main way current is conducted in shallow earth materials, and in this experiment. In this study the kerosene and silica sands that are used are considered insulators and will not conduct a significant amount of electricity. The water that was used is tap water and has ions in it that will conduct current so that the kerosene in the tank can be detected when it displaces water. Resistivity is the three-dimensional measure of a substance's ability to resist current flow. In this study the resistivity will be measured in ohm-meters.

The physics behind the measurement of resistivity in this experiment can be explained with the help of Ohm's law. The measurement of resistivity is made
through a circuit. When positive and negative electrodes are placed into the ground, the ground and all materials in it act as a complex of series and parallel resistors. This impedes current flow, which causes a change in the potential as the current flows through the resistive volume. The one dimensional Ohm's law states this relationship between resistance \( r \) of the resistor, current \( I \) and the change in potential \( V \) is:

\[
V = Ir
\]  

(1)

where \( V \) is measured in volts, \( I \) is measured in amperes and \( r \) is measured in ohms. From Robinson et al. (1988) we see that if the resistor is a rectangular solid bar with length \( L \) and has a cross-sectional area \( A \), the resistance \( r \) can be described in terms of the length \( L \) of the path followed by a current paths, the cross-sectional area \( A \) over which the current paths are uniformly distributed, and the resistivity \( R \), which is a bulk physical property of the substance used to make the resistor,

\[
r = RL/A
\]  

(2)

By rearranging this expression, resistivity is expressed as

\[
R = rA/L
\]  

(3)

this shows that resistivity can be expressed in units of resistance times length. The common units of resistivity used in this experiment are ohm-meters. Deep within a uniform earth, where electrodes contact the earth at discrete points, the distribution of current lines is not uniform. If the ground that the current is flowing through is
homogeneous, then the current will flow uniformly outward in all directions from the positive electrode and converge inward at the negative electrode. Because the current spreads out in all directions the surface area of any arbitrary spherical volume centered on a current electrode in this experiment will be $4\pi d^2$, which is the surface area of a sphere of radius $d$. Again from Robinson et al., equation 2 can be expressed by the product of resistivity $R$ and the distance $d$ that the current has traveled divided by the area $4\pi d^2$ across which it must flow:

$$r = \frac{Rd}{4\pi d^2} = \frac{(R / 4\pi) * (1 / d)}{4\pi d^2}$$

(4)

The change in potential can now be found from Ohm’s law:

$$V = Ir = \frac{IR}{4\pi} (1/d) = v_o - v_d$$

(5)

This equation expresses the difference between the electric potential $v_o$ at the source and the electric potential $v_d$ at any point in the ground a distance $d$ from the source. With the potential at the positive electrode being $v_o$, the potential at the negative electrode will be $-v_o$. Using the same procedure from equation 5 the difference between the electrical potential $-v_o$ of the negative electrode and the potential $v_d$ a distance $d$ away from it:

$$-v = Ir = \frac{IR}{4\pi} (1/d) = v_d - v_o$$

(6)

Now in order to find the electrical potential difference, $V$, between two points in the ground, equations 5 and 6 must be combined:
\[ V = \frac{IR}{4\pi} \left( \frac{1}{d_1} - \frac{1}{d_2} \right) \]  

(7)

where \( d_1 \) and \( d_2 \) are the distances to the positive and negative electrodes.

The electrode arrays used in this study have four electrodes, the current electrodes which are the positive and negative electrodes A and B, and the potential electrodes M and N which measure the change in electrical potential. The M electrode is at distances \( d_1 \) and \( d_2 \) from the A and B electrodes. The N electrode is at distances \( d_3 \) and \( d_4 \) away from the A and B electrodes. The electric potential \( v_m \) at the M electrode will be:

\[ v_m = \frac{IR}{4\pi} \left( \frac{1}{d_1} - \frac{1}{d_2} \right) \]  

(8)

and the potential \( v_n \) at the N electrode will be:

\[ v_n = \frac{IR}{4\pi} \left( \frac{1}{d_3} - \frac{1}{d_4} \right) \]  

(9)

Therefore the potential difference between the M and N electrodes will be:

\[ V_{mn} = v_m - v_n = \frac{IR}{4\pi} \left( \frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4} \right) \]  

(10)

This equation determines the change in potential of the zone between the M and N electrodes, not at a specific point. Equation 10 can be rearranged to express the resistivity in this zone.

\[ R = 4\pi \left( \frac{V_{mn}}{I} \right) \left( \frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4} \right)^{-1} \]  

(11)
The resistivity that is found with this equation is a weighted average of the resistivity values between M and N called the apparent resistivity \( R_a \). The resistivity between a set of electrodes in this experiment will be the apparent resistivity. The expression for this is:

\[
R_a = \frac{V_{mn}}{I} G \tag{12}
\]

Where

\[
G = \frac{(4\pi)}{\left(1/d_1 - 1/d_2 - 1/d_3 + 1/d_4\right)} \tag{13}
\]

is the geometrical factor that depends on the electrode arrangement. Equations 12 and 13 were used to find the apparent resistivities between the M and N electrodes in this study. If the subsurface electrodes are mounted on an insulating cylinder, then an additional correction for the presence of the infinite resistivity cylinder must also be applied.

In order for the previous formulas to be useful there must be a method used that will give the results of some of the variables. The electrode arrays are a way that this data may be provided. The various electrode arrays have patterns that are evident when they cross a resistivity boundary. Many of them will form cusps, which are the points at which the resistivity values will make anomalous jumps up or down depending on the array. When the Wenner array crosses a planar boundary into a significantly different resistivity zone there are usually two cusps formed. These cusps are formed because of the electrodes being close to the boundary, on either side
Griffiths and King (1981) describe how the cusps form. As the potential electrodes approach the boundary, the current density changes and with it the apparent resistivity. As each electrode crosses the boundary, reversal of the direction of resistivity charge occurs. When the electrodes are across and still near the boundary its influence decreases and the apparent resistivity gradually approaches its true value. Examples of the Wenner array, dipole-dipole array and the gradient array can be seen in Figures 1 and 2.

Well logging has been used since the first part of the century. The first resistivity well logs were electrical surveys. The normal logs use a four electrode configuration with two of the electrodes M and N measuring the potential difference and the other two electrodes A and B had current passed between them. The A and M electrodes are down in the well while the B and N electrodes are at the surface. In petroleum well logging there are two standard normal logs, the short normal which has a 16 inch space between the A and M electrodes and the long normal which has a 64 inch space between the A and M electrodes. The short normal measures the resistivity close to the borehole, while the long normal measures the resistivity farther away from the borehole. The short normal gives detailed measurements of the formation that has been invaded by the drilling fluid or disturbed by the drilling processes. The long normal is measuring the resistivity beyond the invaded zone. These methods along with many others are used to determine the geologic formations in the subsurface and also to determine if there are any hydrocarbons in specific rock formations.
Figure 1. Expected Resistivity Cusp Patterns From the Wenner Array and the Dipole Dipole Array. Modified From Parasnis (1966).
Figure 2. Expected Resistivity Cusp Patterns From the Wenner Array and the Gradient Array. Modified From Tsokas et al. (1994).
Previous Work

In any hydrogeologic study there are many variables. One of the most difficult to interpret and see the effect of is the history of imbibition/drainage cycles. A sandstone sample can have different resistivity values even with the same amount of saturation because the water and air in the rock have different geometries depending on the imbibition/drainage cycle that it is going through. Knight (1991) performed experiments on sandstone samples to find out how the wetting history of a rock determined the resistivity values. What Knight found was that the samples had differences in resistivity values from 12 percent saturation to 75 percent saturation. The samples that were tested during imbibition had lower resistivity values in that range while the drainage resistivities were up to three times as high. The reason for the differences is that as the water is added to the rock the air is in the center of the pore spaces and the water is in layers on the surface of the sand grains. With this arrangement the resistivity values are lower until the water can not coat the sand grains in layers any more and a new stable geometric arrangement is formed. When this happens the resistivity values increase to the level of the drainage values. The reason that the drainage resistivity values remain higher is that when the air returns into the pore spaces it removes most of the layers of water at one time except for those that are held tightly to the particles in the rock. Having only a small amount of water in the pore spaces causes the resistivity values to be higher.

In a soil a thin layer of hydrocarbon does not reach full saturation. The hydrocarbon does not force the air and water completely out of the pore space.
Endres and Redman (1996) showed models of how a layer of hydrocarbon only reaches partial saturation even at 1.25 meters in thickness. They began with a sample that had a .5 meter thickness. At this point the saturation with respect to the hydrocarbon was only at 15 percent, the next step had a thickness of .75 meters and a saturation percentage of 48. The third test was not as abrupt and saturation rose to 68 percent for a one-meter hydrocarbon layer, then up to 75 percent at the 1.25-meter thickness. Essaid and Herkelrath (1993) touched on the percent saturation of hydrocarbon of the Bemidji oil spill in Minnesota. They showed how the saturation of the oil only reached 50 percent at any point in the subsurface determined from borehole samples taken. For most field cases and experiments the thickness of the hydrocarbon is less than a meter, which does not allow the saturation to reach 100 percent. Because of this there is water and air mixed in the pore spaces, which allows for paths to have current flow through them. The presence of a hydrocarbon layer does not necessarily have an abrupt change in resistivity values, instead it may be a transitional zone between the water table and the vadose zone above the hydrocarbon. Endres and Redman (1996) have models that show how combining hydrocarbon, air and water leads to resistivity profiles that are more transitional than in a sample that has only water and air in it. DeRyck et al. (1993) shows the same type of result in a controlled kerosene spill. They show examples of the varying amounts of kerosene and how the results define a transitional zone rather than as a high resistivity zone between the water table and the vadose zone. This type of resistivity profile can be seen later in the results of the experiments performed in this study. Monier-Williams
(1995) shows a similar change from a more abrupt increase in resistivity values to a transitional zone, which has a more gradual increase when hydrocarbon is introduced into the system. Monier-Williams (1995) also cites Goldie (1983) who observed a similar transitional zone.

Monier-Williams (1995) also discusses effects that could either increase or decrease resistivity values due to the change in the aqueous content in the material. According to Monier-Williams the four reasons for a possible increase in resistivity values are: (1) the depletion of the aqueous phase within the spill zone due to polyphasic flow and dynamic displacement; (2) depletion of the aqueous phase by reducing aqueous/air surface tension from LNAPL replacement of air as the wetting fluid to the aqueous phase, partial dissolution of associated organic compounds and replacement of air with an LNAPL gas/air mixture; (3) LNAPL replacement of the aqueous phase as the wetting phase to solids and subsequent reduction in connectivity of the aqueous phase; (4) loss of the capillary fringe and depression of the water table due to dynamic displacement from pooling of LNAPL’s. Conversely Monier-Williams (1995) describes how a decrease in resistivity may be caused by four reasons also: (1) enhanced aqueous phase connectivity due to LNAPL or LNAPL/air gas mixtures replacing air as the aqueous wetting phase, reduction in aqueous surface tension and reduction in volume of the aqueous pendular ring at grain contacts allowing the aqueous phase to spread and increase connectivity; (2) formation of emulsions increasing the water/LNAPL surface contact area and aqueous connectivity; (3) release of LNAPLs with polar additives which may act as inorganic
surfaces in contact with the aqueous phase to enhance surface conductance, and (4) wetting (imbibition) which may serve to increase the air/LNAPL-aqueous phase interface surface area. This last reason is what Knight (1991) described in detail.

An experiment that used resistivity probes to determine the vertical distribution of hydrocarbon was performed by Shoop et al. (1996). In this experiment they ran tests on field and lab samples in order to test the probes. Their results seem to indicate the presence of the hydrocarbon layer, but the methods that they used are questionable. The electrode configuration only had two electrodes to measure the resistivity. With this arrangement the electrodes are not measuring the earth only, but rather will mainly be measuring the contact resistances at the two electrodes. This contact resistance is normally much larger than the equivalent resistance of the earth paths. The electrode array needs to have a four-electrode configuration in order to avoid this contact resistance. The skewed results in this experiment are probably directly measuring the fouling of the electrode by hydrocarbon.
METHODOLOGY

Experiment Overview

In order to test the vertical resistivity methods of delineating free product, probes were installed into a sand-filled tank. The probes have electrodes placed into the side of them, which enable various vertical electrode arrays to be used. The tank had two different sand layers and a water table that varied depending on the test being performed. The kerosene free product was located in the upper layer for the entire experiment. The transparent walls of the tank allowed for the direct observation of the kerosene, which was dyed blue in order to distinguish it from the water. The resistivity results could therefore be easily compared to the observed product distribution in the tank.

Resistivity Probe Construction

The *in situ* probes that were used in this experiment had to be constructed specifically for the objectives of the study. The probes were made of schedule 40 PVC that was cut into one-meter sections in order to fit in the tank being used. There were two different size PVC pipes used: one was 1.5 inch inner diameter while the two other probes were made from 1.25 inch inner diameter pipe. There is no significance in using the two different size pipes other than availability at the time. Holes were drilled into the pipes at the desired spacings using a drill press, .0254
meter spacings for the one and a quarter inch-inner diameter pipes and .0508 meter spacings for the inch and a half-inner diameter pipe. The holes were counter sunk into the pipes so that the screws had a flat surface to seal and make contact with the PVC. Once the holes were drilled they were tapped to fit the stainless steel screws. The screws were fit with an o-ring before being screwed into the pipes to provide a tight seal between the pipe and screw head. The screw heads were on the outside of the pipe acting as the electrode that would be in contact with the sand, water and kerosene. These beginning stages were modeled after probes built by Marty Harmless. The next steps are different because of the aim of the experiment. After the screws were in place the pipes were to be cut in half lengthwise with a band saw in order to access the inner side, to connect the wires and the screws. The twenty-gauge wire used in the probes was connected to the screws by circular wire connectors and fastened with stainless steel nuts. The opposite end of the wires were then connected to banana plugs to provide a good connection to the resistivity meter (Syscal R-2), which was used for the measurements of the electrode arrays. Each wire was numbered to provide proper alignment when specific electrodes were to be used. In the next step the two halves of the pipes were fused back together with PVC cement and some C clamps to hold them in place while the cement dried. The PVC cement was applied many times to insure a watertight seal. The last step was to cement a cap over the end of the pipe. Once complete the probes were tested for leaks and for any variance in the electrode spacings. An example of a completed probe is shown in Figure 3.
Testing the Probes

In order to test the probes' structural integrity they were placed into a water tank. The probes had to be water tight because the resistivity measurements would be
skewed if any liquid leaked inside of the probes. There were other aspects of the probes that were tested also. The first was the variance between electrode spacings. This could best be accomplished in a homogeneous environment using an electrode array that was to be used in the experiment. A second concern was to see if the walls of the tank would affect the resistivity readings. The final aspect checked was the difference the two diameters of the probes had on resistivity readings. This was done to find geometric constants that fit both size probes.

The fiberglass-coated water tank contained approximately .75 meters of water. The probes were left in the tank for a week to see if any slow leaks would develop. After one week there was one probe that did have a small leak so it was resealed with the PVC cement to insure the leak was corrected. To test the construction error of the spacing between electrodes, the probes were tested using the Wenner electrode array. The Wenner array consists of two potential electrodes placed between two current electrodes with equal spacing between all of the electrodes, a diagram of this array can be found in Figure 4. The Wenner electrode array was moved up the probe one electrode spacing at a time to provide measurements, which can be calculated by using equations 12 and 13 at every point along the probe (Table 1). When the measurements between electrodes were compared on a point by point basis they were found to be similar enough that the effects on the resistivity results would be minimal for resolution in this study. The small difference in the readings could be assessed to the screws being screwed in on an angle, the presence of air bubbles on the electrodes, the holes for the screws being drilled in the wrong position or any moved
ELECTRODE ARRAYS

Dipole Dipole

\[ \uparrow \text{M} \quad \downarrow \text{N} \quad \uparrow \text{A} \quad \downarrow \text{B} \]

Wenner

\[ \uparrow \text{A} \quad \downarrow \text{M} \quad \uparrow \text{N} \quad \downarrow \text{B} \]

Gradient

\[ \uparrow \text{A*} \quad \downarrow \text{M} \quad \downarrow \text{N} \quad \downarrow \text{B} \]

Parallel

\[ \uparrow \text{M} \quad \downarrow \text{N} \quad \uparrow \text{A} \quad \downarrow \text{E} \]

Down Hole 3-Array

\[ \uparrow \text{M} \quad \downarrow \text{N} \quad \uparrow \text{A} \quad \downarrow \text{B} \]

A=Current Electrode
B=Current Electrode
M=Potential Electrode
N=Potential Electrode
A*=Stationary Current Electrode
B*=Stationary Current Electrode

Figure 4. Electrode Array Schematic.
Table 1
Water Tank Test Data for the 1.25 Inch Inner Diameter Probe

<table>
<thead>
<tr>
<th>Depth to Electrode Array Midpoint (m)</th>
<th>Resistivity (ohm*m) Center of the Tank</th>
<th>Resistivity (ohm*m) Edge of the Tank</th>
<th>Difference (ohm*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.0381</td>
<td>14.5</td>
<td>14.4</td>
<td>.1</td>
</tr>
<tr>
<td>.0635</td>
<td>14.1</td>
<td>14.2</td>
<td>.1</td>
</tr>
<tr>
<td>.0889</td>
<td>14.3</td>
<td>14.3</td>
<td>.0</td>
</tr>
<tr>
<td>.1143</td>
<td>14.6</td>
<td>14.5</td>
<td>.1</td>
</tr>
<tr>
<td>.1397</td>
<td>14.4</td>
<td>14.3</td>
<td>.1</td>
</tr>
<tr>
<td>.1651</td>
<td>14.7</td>
<td>14.7</td>
<td>.0</td>
</tr>
<tr>
<td>.1905</td>
<td>14.4</td>
<td>14.3</td>
<td>.1</td>
</tr>
<tr>
<td>.2159</td>
<td>14.7</td>
<td>14.6</td>
<td>.1</td>
</tr>
<tr>
<td>.2413</td>
<td>14.7</td>
<td>14.8</td>
<td>.1</td>
</tr>
<tr>
<td>.2667</td>
<td>14.3</td>
<td>14.3</td>
<td>.0</td>
</tr>
<tr>
<td>.2921</td>
<td>15.1</td>
<td>15.0</td>
<td>.1</td>
</tr>
<tr>
<td>.3175</td>
<td>14.4</td>
<td>14.4</td>
<td>.0</td>
</tr>
<tr>
<td>.3429</td>
<td>15.1</td>
<td>15.0</td>
<td>.1</td>
</tr>
<tr>
<td>.3683</td>
<td>14.8</td>
<td>14.7</td>
<td>.1</td>
</tr>
</tbody>
</table>

combination of these. The tests that were run were performed two times, first in the center of the tank and second near the walls of the tank. The comparison of the two sets of results (Table 1) shows that for the electrode array spacings used in this study, the walls have a negligible effect with the electrodes positioned away from the walls. The last aspect tested in the water tank was the correction factor for the two different diameter probes. This was accomplished by using the test results (Table 1 and Table 2) and comparing the average resistivity to a floating tray on which the same tests were performed (Table 3). The floating tray had electrode spacings of 4 cm and was
Table 2
Water Tank Test Data for the 1.5 Inch Inner Diameter Probe

<table>
<thead>
<tr>
<th>Depth to Electrode Array Midpoint (m)</th>
<th>Resistivity (ohm*m) Center of the Tank</th>
<th>Resistivity (ohm*m) Edge of the Tank</th>
<th>Difference (ohm*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.1270</td>
<td>12.6</td>
<td>13.5</td>
<td>.9</td>
</tr>
<tr>
<td>.1778</td>
<td>12.1</td>
<td>13.0</td>
<td>.9</td>
</tr>
<tr>
<td>.2286</td>
<td>12.6</td>
<td>12.9</td>
<td>.3</td>
</tr>
<tr>
<td>.2794</td>
<td>12.3</td>
<td>13.3</td>
<td>1.0</td>
</tr>
<tr>
<td>.3302</td>
<td>12.3</td>
<td>12.8</td>
<td>.5</td>
</tr>
<tr>
<td>.3810</td>
<td>12.8</td>
<td>13.1</td>
<td>.3</td>
</tr>
<tr>
<td>.4318</td>
<td>12.4</td>
<td>13.0</td>
<td>.6</td>
</tr>
<tr>
<td>.4826</td>
<td>12.8</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>.5334</td>
<td>13.1</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

NA = not accessible due to the electrodes being above the water level one cm after each measurement. Dividing the average resistivity calculated from the probes by using the half-space formation for the floating tray average resistivity gives a correction factor that could be applied to subsequent measurements (Table 4).

Sand Tank Purpose and Description

The sand tank is where all of the experiments were performed for this study (Figures 5A and 5B). The tank is four feet deep, four feet long and one foot wide. The walls of the tank are made of Plexiglas. The tank has four slotted pipes, which were cut in half lengthwise and then positioned along the walls of the tank so that the liquid in them was visible. These pipes were used as pumping wells, which can be
Table 3

Water Tank Test Data for the Floating Tray

<table>
<thead>
<tr>
<th>Position of the Clips From the Starting Point (cm)</th>
<th>Resistivity (ohm*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17.0</td>
</tr>
<tr>
<td>1</td>
<td>NA</td>
</tr>
<tr>
<td>2</td>
<td>17.2</td>
</tr>
<tr>
<td>3</td>
<td>16.5</td>
</tr>
<tr>
<td>4</td>
<td>17.4</td>
</tr>
<tr>
<td>5</td>
<td>17.7</td>
</tr>
<tr>
<td>6</td>
<td>17.2</td>
</tr>
<tr>
<td>7</td>
<td>17.2</td>
</tr>
<tr>
<td>8</td>
<td>16.8</td>
</tr>
<tr>
<td>9</td>
<td>17.0</td>
</tr>
<tr>
<td>10</td>
<td>17.0</td>
</tr>
<tr>
<td>11</td>
<td>17.1</td>
</tr>
<tr>
<td>12</td>
<td>17.2</td>
</tr>
<tr>
<td>13</td>
<td>17.4</td>
</tr>
</tbody>
</table>

Average = 17.12

NA = not accessible due to a bad contact

seen in Figure 6. There were two different sands used in the tank. In the top twenty inches the tank consists of medium grained sand and the bottom of the tank consists of previously existing medium-fine grained sand. The reason for the two sands was to determine how a boundary would affect the electrode array results as the arrays crossed over the boundary.
Table 4
Correction Factors Determined From the Water Tank Data

<table>
<thead>
<tr>
<th></th>
<th>1.25 (in) ID</th>
<th>1.25 (in) ID</th>
<th>1.5 (in) ID</th>
<th>1.5 (in) ID</th>
<th>Floating Tray</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Center</td>
<td>Edge</td>
<td>Middle</td>
<td>Edge</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>14.58</td>
<td>14.55</td>
<td>12.55</td>
<td>13.08</td>
<td>17.12</td>
</tr>
<tr>
<td>Resistivity (ohm*m)</td>
<td>1.17</td>
<td>1.18</td>
<td>1.36</td>
<td>1.31</td>
<td></td>
</tr>
<tr>
<td>Correction Factor</td>
<td>1.17</td>
<td>1.18</td>
<td>1.36</td>
<td>1.31</td>
<td></td>
</tr>
</tbody>
</table>

ID = Inner Diameter

Resistivity Probe Installation

The bottom layer of sand was in the tank before the probes were inserted. Holes were made with a separate pipe that allowed the sand to be removed when it was retracted. This provided holes for the probes in the bottom layer of sand, with a minimal amount of disruption to the surrounding sand. The holes that were left were large enough to fit the probes into and any space around them was back filled. Once they were in place with the bottom electrodes all at the same elevation the medium grain ed sand was placed on top of the lower sand.

The probes were placed in an isosceles triangle pattern in the tank, which is seen in Figure 7. The two similar probes with electrodes spaced every .0254 m were placed .22 m away from each other (Figure 5). They were set .4 m from the end of
Figure 5. View of the Sand Tank
(A) = Top View of the Sand Tank
(B) = Side View of the Sand Tank
the tank with the electrodes facing the interior of it. A third probe with electrodes .0508 m apart was placed .81 m from the end of the tank midway between the two sides. The distance between the electrodes from the .0508 meter probe and the electrodes on the other two probes was .41 m.

Electrode Arrays

The five electrode arrays used and compared in this study all contain four electrodes, two current electrodes and two potential electrodes (Figure 4). Three
electrode arrays are on individual probes and there are two electrode arrays that are between two probes. The first of the individual probe electrode arrays is the Dipole Dipole array. This electrode array has the two current electrodes below the two

Figure 7. Probe Configuration in the Tank.
potential electrodes with equal spacing between all of the electrodes. The set of four electrodes is then moved together up the probe one electrode spacing at a time taking a measurement at every new set. The second electrode array for a singular probe is the Wenner array. This electrode array has been used in similar experiments (Schneider et al. 1992). The Wenner array consists of the potential electrodes placed between the current electrodes with equal spacing between all of the electrodes. This electrode array is moved together just as the previous one was described. The last of the individual electrode arrays is the Gradient array. This electrode array is different than the previous two because the current electrodes are fixed on the top and bottom while the potential electrodes are moved together from the bottom to the top. The spacing between the two potential electrodes remains constant as they are moved.

The two electrode arrays that involve the use of two probes are the Parallel array and the Down Hole 3-Array. The Parallel Array has one current and one potential electrode on each of the two probes (Figure 4). The two current electrodes are at the same elevation and the two potential electrodes are both one electrode spacing higher than the current electrodes. The set of four electrodes is simultaneously moved together one spacing at a time. The Down Hole 3-Array has both potential electrodes and one of the current electrodes on the first probe and the other probe contains the second current electrode at the same elevation as the first. This set of four is also moved together one spacing at a time. At the beginning of the experiments the only advantages of any of the arrays is that some require less movement of electrode wires between measurements.
Configurations in the Sand Tank

To begin the experiment resistivity measurements were taken for background data. These measurements were taken when the tank was saturated with water. Then the water was lowered and kerosene was added at two different times with approximately 3 liters per time. The configurations in the sand tank between the water and kerosene changed four times over the course of the study. The reason for this was to provide different situations in which to test the various electrode arrays. The addition of water and kerosene to the tank was done at the surface by pouring the liquid into slotted PVC pipes that were cut in half lengthwise and resting on the surface of the sand. The first configuration that was used consisted of the water level below the sand boundary with the vadose zone crossing the two sands. This configuration posed a problem, which was when the kerosene was added to the tank it did not penetrate the sand boundary and remained perched. The two sand grain sizes were different enough to cause this barrier. The second configuration used alleviated this situation. The water level was increased so it completely saturated the lower sand and part of the upper sand. The kerosene was able to be at the water surface with the sand boundary not being a factor. When the kerosene layer that was perched on the sand boundary was forced up by the addition of water there was residual kerosene left in the water saturated zone. The kerosene thickness was the variable that was changed from this point. With the water level at a fixed position the kerosene layer was changed three times. The first thickness was at .08 m, the second
layer was increased to .15 m then lowered to .045 m on the last configuration. The four configurations provided a range of different situations to be tested.
RESULTS AND DISCUSSION

Initial Tests

Wenner Array

In order to begin discussing the results it is important to know that the points on the graphs are at the middle of the electrode arrays. This means that there are electrodes on either side of the points, which accounts for the cusps not coinciding exactly with the various boundaries. The initial Wenner Array tests run in the sand tank were performed with the sand fully saturated with water (Figures 8 and 9). The results as each set of electrode connections were moved up the probes (Figure 8) demonstrate that there are good connections between the electrodes and the saturated homogeneous sand. The boundary between the two sands provided a small change in the resistivity values, which were between 50 and 80 Ohm-meter when the sand was fully saturated. The reason for this is that there is a comparable amount of water in the pore spaces which makes the resistivity values close (Mazac et al. 1990). The results from these first tests can be seen on Figures 8, 9 and 10. The next test was run after the water level was lowered below the sand boundary (Figures 8, 9 and 10). The results show a distinct difference in the resistivity of the two sands. The reason for this is that the water level was below the boundary and the vadose zone was through both sands. The finer sand below held more of the water as the water table was
Figure 8. Pipe 1 Wenner Array, Varing Stages, .0254 m Electrode Array Spacing.
Figure 9. Pipe 2 Wenner Array, Varying Stages, .0254 m Electrode Spacing.
Approximate Boundary Between the Fine Sand (below) and the Coarse Sand (above), and Perched Kerosene

- 1/20/97 Resistivity H2O Only
- 1/25/97 Resistivity H2O Lowered
- 1/27/97 Resistivity Kerosene Added
- 1/31/97 Resistivity More Kerosene Added
- 2/3/97 Resistivity No Change
- 2/7/97 Resistivity No Change
- 2/24/97 Resistivity No Change

Figure 10. Pipe 3 Wenner Array, Varying Stages, .0508 m Electrode Spacing.
lowered, providing a greater area for the electric current to flow through. The slight difference in the sands’ grain sizes provided a significant change in the resistivity values which produced the cusps that are characteristic for a Wenner Array crossing into a different zone of resistivity (Figures 1 and 2). Mazac et al. (1990) describes how a small percentage change in the amount of saturation can dramatically affect the resistivity. The other results shown in Figures 8, 9, and 10 were run at various times during the addition and subtraction of water and also the adding of approximately one gallon of kerosene in two separate phases. The kerosene, which was not measured for its intrinsic resistivity, is usually considered to be an insulator. Mazac et al. (1990) describes the affect of an aquifer contaminates by oil products as independent of the porosity and approaches the apparent resistivity of the matrix. The resistivity of the contaminated matrix does not approach “infinity” as is often wrongly assumed, but approaches a finite value. These initial tests were performed to get a better feel of how the following tests should be run and to see how the resistivities changed when kerosene and water were added.

Configuration One

Overview

In the first configuration the addition of kerosene caused the vadose zone to become less resistive compared to the vadose zone with water only. This seems counter intuitive at first because the kerosene should be more resistive. The reason
for the lowering in resistivity is that the kerosene while infiltrating through the upper sand brought with it some of the residual water in the upper vadose zone and with the combination of water and kerosene caused a transition zone that is lower in resistivity than the vadose zone, which had been drained (Knight, 1991). In this configuration the kerosene layer has perched on the sand boundary for two reasons. First, the lower sand not only was a smaller grain size but packed tighter because of the over burden weight and the fact that it has had more time to settle in the tank. Second the kerosene was not thick enough to provide the hydrostatic pressure needed to force its way through the sand boundary. There are more cusps formed with this configuration because the kerosene layer causes another resistivity boundary.

**Wenner Array**

The test that was run with the water only in the tank shows how the cusps form when the electrode array crosses into a different resistivity zone. With the layer of kerosene in the tank the array crosses into the kerosene zone and then out of it into the vadose zone, crossing two resistivity boundaries. This causes more cusps to form as seen in Figure 8 and 9. Probe two has similar results compared to probe one but the cusps are not as distinct. This could be caused by connections between the electrodes and materials in the tank that have more water or kerosene around them so the difference in resistivity values across the boundaries is not as abrupt. The results from probe three (Figure 10) with the .0508 meter electrode spacings, did not provide results that were useful. The larger electrode spacings and the relatively thin upper
layer that contained enough water to provide resistivity readings caused the cusps to be lost and "smoothed out". There are a few reason for the difference in the overall resistivity values from line to line while changes were made in the tank. First after the kerosene was added for the second time it finally worked its way down from the upper vadose zone which then caused the increase in resistivity values for the tests run with no changes applied to the system from the previous tests. The last test run was performed seventeen days later which allowed gravity to settle the water in the vadose zone so the resistivity values were lower on this last measurement.

**Down Hole 3-Array**

The Down Hole 3-Array was run with .0254 and .0508 meter electrode spacings. The .0254 meter spacing test was performed between the first and second probes. These electrode array results (Figure 11) show a small cusp as they cross the perched kerosene layer. The cusp is not as distinct as the previous .0254 meter Wenner array because of the distance between the two pipes, .22 meters. This allows the current to find paths to flow in and causes a less distinct boundary as well as the boundary not being a perfectly horizontal layer. It can vary over a distance like this, which would have a negative affect on the sharpness of the boundary. Without the kerosene present the resistivity measurements increased sharply as the electrode array crossed the sand boundary into the vadose zone. The kerosene decreased the resistivity measurements because of air and water mixed with it that causes a transition zone (Knight, 1991). The results in Figure 12 from the .0508 meter spacing
Figure 11. Pipe 2-1 Down Hole 3-Array, Varying Stages, .0254 m Electrode Spacing.
Figure 12. Pipe 2-3 Down Hole 3-Array, Varying Stages, .0508 m Electrode Spacing.
test do not show any cusps. They only have a slightly depressed curve just over the boundary between the sands. Again the distance between the electrodes and probes in combination with the thickness of kerosene did not allow the kerosene layer to be detected from the results.

Configuration Two

Overview

The water level was increased enough in the second configuration so that the sand boundary would not be a factor in the resistivity measurements around the kerosene layer. The amount of kerosene remained constant throughout this configuration at .08 meters. The resistivity measurements below the kerosene layer increased slightly as a result of some residual kerosene mixed in the sand with water as the level of water was increased.

Wenner Array

Similar cusps were again present in the results of probe one and probe two (Figures 13 and 14). Probe three has large electrode spacings and a sampling interval that was too large to produce the cusps (Figure 15). In this configuration on probe one, measurements were taken at specific time increments to show how the resistivity of the vadose zone changes when water is added at the surface and allowed to percolate down through the vadose zone which contains the kerosene. The resistivity
Approximate Position of the Kerosene Layer

Approximate Boundary Between Fine Sand (Below) and Coarse Sand (above)

- 2/26/97 Resistivity After 45 Min
- 2/26/97 Resistivity After 90 Min
- 2/27/97 Resistivity After 24 Hours
- 3/3/97 Resistivity After 5 Days

Figure 13. Pipe 1 Wenner Array, .08 Meter Kerosene Layer, H2O Level Increased, .0254 m Electrode Spacing.
Figure 14. Pipe 2 Wenner Array, .08 Meter Kerosene Layer, H2O Level Increased, .0254 m Electrode Spacing.
Figure 15. Pipe 3 Wenner Array, .08 Meter Kerosene Layer, H2O Level Increased, .0508 m Electrode Spacing.
values increase with time showing that the water is moving down below the kerosene and less is remaining in the vadose zone above it.

**Dipole Dipole Array**

The Dipole Dipole array was not used in the initial tests and with the perched kerosene layer. It was used when the water level was elevated. This array has a different cusp pattern than the Wenner array results. The first probe results (Figure 16) show a similar pattern of cusps when compared to Figure 1. The pattern should be seen two times in the figure, once as the electrode array crossed into the kerosene and the second as it crossed into the vadose zone above the kerosene layer. But with the thin layer of kerosene the two cusp patterns are overlapping in the middle of the layer.

**Gradient Electrode Array**

The Gradient Electrode Array has a more simple cusp pattern (Figure 2) than the previous electrode arrays. With this array the resistivity measurements gradually increase below the kerosene layer, then increase more abruptly until the potential electrodes are in the center of the kerosene. At this point the resistivity measurements are at a peak which is an effect of the array crossing the boundary. Once the array is inside the kerosene layer the level of resistivity begins to level off, but is increased again as the array moves out of the top of the kerosene layer (Figure 17).
Figure 16. Pipe 1 Dipole Dipole Array, .08 Meter Kerosene Layer, .0254 m Electrode Spacing.
Figure 17. Pipe 1 Gradient Array, .08 Meter Kerosene Layer, .0254 m Electrode Spacing.
Parallel Electrode Array

The only parallel electrode array test done at this configuration was the .0508 meter electrode spacing array between probes two and three. The results for this array are not what would be expected with a kerosene layer in the tank. The spacing for the electrodes was too large and the layer of kerosene too small to detect the high resistivity zone. The results in Figure 18 show a sweeping curve, which does not necessarily indicate an abrupt linear change in resistivity values, but only a gradual change.

Down Hole 3-Array

The results between probes one and two in Figure 19 show a cusp as the array begins to go out of the top of the kerosene layer. At this point the resistivity measurements were beginning to level off, but are interrupted when the array goes out of the top of the kerosene. The resistivity then increases sharply as the electrodes leave the layer of kerosene. The tests between probe two and three (Figure 20) show only an increasing curve without cusps. The .0508 meter spacing is again too large to pick up the layer of kerosene.
Configuration Three

Overview

The water level was dropped a few centimeters to allow for the addition of kerosene so that the kerosene level was not too close to the surface, thus eliminating most or all of the vadose zone readings. This increase was done to see how the electrode arrays would react when all of the electrodes in some of the arrays could be in the kerosene at the same time. The thickness of the kerosene was to be enough so the cusps would not interfere with each other, as the arrays move in through the bottom of the kerosene layer and then out of the top.

Wenner Array

The increase in the kerosene thickness allowed for a slight leveling off of the resistivity measurements in the center of the layer (Figures 21 and 22). The leveling off was caused by the electrode array to be contained in the kerosene for one or two measurements, whereas before with a thinner layer of kerosene part of the electrode array would be outside of the kerosene at any given time. There is a problem with the resistivity readings for this configuration, as the array enters the higher resistivity kerosene the typical cusps are not present. A possible reason for this is that the water left in the pore spaces when the kerosene was lowered slightly has not allowed for a definite boundary, which caused only a gradual increase in the measurement. The
Figure 18. Pipes 2-3 Parallel Array, .08 Meter Kerosene Layer, .0508 m Electrode Spacing.
Figure 19. Pipes 2-1 Down Hole 3-Array, .08 Meter Kerosene Layer, H2O Level Increased, .0254 Electrode Spacing.
Figure 20. Pipes 2-3 Down Hole 3-Array, .08 Kerosene Layer, H2O Level Increased, .0508 m Electrode Spacing.
Figure 21. Pipe 1 Wenner Array, .15 Meter Kerosene Layer, .0254 m Electrode Spacing.
Figure 22. Pipe 2 Wenner Array, .15 Meter Kerosene Layer, .0254 m Electrode Spacing.
cusp pattern can be seen as the array moves out of the top of the kerosene layer into the vadose zone.

**Dipole Dipole Electrode Array**

The .15 meter kerosene layer provided a better set of results (Figure 23) than the second configuration for probe one (Figure 16). The two pairs of cusps can be seen more clearly. Probe two did not have results (Figure 24) that were as distinct when compared to probe one. The first cusp can be seen but then the resistivity increases and no readings were possible above this point. The changes around the sand interface could be the result of more residual kerosene in the electrode’s vicinity, an electrode to sand contact that is not being made properly or by the slight difference in sand size. The changes in the resistivities at these points are relatively small.

**Gradient Electrode Array**

The results of this array (Figures 25 and 26) with this configuration are very similar to the .08 meter kerosene layer. The thicker layer allowed the resistivities to level off when the array was in the kerosene. Resistivity from probe two increased dramatically at the top of the kerosene layer when compared to that of probe one. This may have been caused by one of the electrodes being out of the layer before the corresponding electrode in probe one was out.
Figure 23. Pipe 1 Dipole Dipole Array, .15 Meter Kerosene Layer, .0254 m Electrode Spacing.
Figure 24. Pipe 2 Dipole Dipole Array, .15 Meter Kerosene Layer, .0254 m Electrode Spacing.
Figure 25. Pipe 1 Gradient Array, .15 Meter Kerosene Layer, .0254 m Electrode Spacing.
Figure 26. Pipe 2 Gradient Array, .15 Meter Kerosene Layer, .0254 m Electrode Spacing.
Parallel Electrode Array

The tests done on the .15 meter kerosene layer were performed with a .0254 meter electrode spacing and were taken between probe 1 and probe 2. The two probes used in this configuration were probes one and two. The results in Figure 27 differ from the sweeping curve that was evident in the previous Parallel array test. There is a decline in the steep slope as the array is entirely in the kerosene. It then increased sharply once entering the vadose zone. The results for this configuration have a slight change in the curve, which indicate a different resistivity layer.

Down Hole 3-array

The last configuration tried with the Down Hole 3-Arrray was the .0254 meter electrode spacing between probes one and two. The results in Figure 28 are very similar to the .08 meter kerosene layer results. The cusps are in the same area and provide an indication that the electrode array is passing into a different resistivity zone. With this configuration there is no distinct boundary between the kerosene and water. There is only a gradual increase in resistivities as the electrode array enters up trough the bottom of the kerosene.
Figure 27. Pipes 2-1 Parallel Array, .15 Meter Kerosene Layer, .0254 m Electrode Spacing.
Figure 28. Pipes 2-1 Down Hole 3-Array, .15 Meter Kerosene Layer, .0254 m Electrode Spacing.
Configuration Four

Overview

Most of the kerosene was pumped out of the tank leaving only .045 meter layer in the tank. The water level was increased to keep the layer in a central location in the tank. This thin layer was used for the final configuration so that the various electrodes could be tested on a thickness more often found in the environment than the thicker layers tested. This configuration can be expected to have residual kerosene above and below the layer of kerosene.

Wenner Electrode Array

The decrease in thickness of the kerosene for the last configuration to .045 meters provided results similar to probe three with the .08 meter kerosene layer. The resistivity measurements are again smoothed out to the point that there are no cusps visible (Figures 29 and 30). As with probe three the resolution is lost when the electrode spacings are large relative to the thickness of the high resistivity zone.

Dipole Dipole Electrode Array

The results for probes one and two do not provide results that were expected (Figures 31 and 32). The results do show the beginning of the cusp set but the layer of kerosene is too thin to provide any more information. The data series terminates halfway through the kerosene, probably due to the vadose zone drying out causing the
Figure 29. Pipe 1 Wenner Array, .045 Meter Kerosene Layer, .0254 m Electrode Spacing.
Figure 30. Pipe 2 Wenner Array, .045 Meter Kerosene Layer, .0254 m Electrode Spacing.
Approximate Boundary Between Fine Sand (below) and Coarse Sand (above)

Approximate Position of the Kerosene Layer

Figure 31. Pipe 1 Dipole Dipole Array, .045 Meter Kerosene Layer, .0254 m Electrode Spacing.
Figure 32. Pipe 2 Dipole Dipole Array, .045 Meter Kerosene Layer, .0254 m Electrode Spacing.
contact resistance to exceed that required for a valid measurement. In probe two the cusps caused by the high contact resistance can be seen again.

**Gradient Electrode Array**

The gradient array resistivity results for the .045 meter kerosene layer along with the sampling interval cause the characteristic patterns seen from a change in resistivity zones to be absent from these results (Figure 33 and 34). The results show only a gradual increase in resistivity values.
Figure 33. Pipe 1 Gradient Array, .045 Meter Kerosene Layer, .0254 m Electrode Spacing.
Figure 34. Pipe 2 Gradient Array, .045 Meter Kerosene Layer, .0254 m Electrode Spacing.
CONCLUSIONS

In this study, it was shown that it is possible to use a wide range of vertical electrode arrays to detect the abrupt change in the resistivity values between two layers. If the change is not distinct and instead gradual, which seems to be the case with a few of the tests, the distinct cusp patterns may not be visible. This is due to the transitional affect that kerosene/air/water combination causes when the saturation is not high for any of these. The vertical electrode arrays with an electrode spacing of .0254 meters were the most effective in showing the layer of kerosene. The arrays with the .0508 meter spacing do not provide enough resolution to detect the high resistivity layer and can not provide any data to support its existence. Even though the .0254 meter electrode spacing arrays worked well for the majority of the experiments the thin kerosene layer provides a challenge when using the vertical electrode arrays. The electrode arrays would be able to detect a thin layer of high resistivity, if the electrode spacings and sampling intervals were much smaller and the electrode spacings were in relative proportion to the layer thickness to provide adequate resolution. In order to get this adequate resolution there needs to be at least a one to four ratio of the electrode spacing to thickness of the contaminant. This ratio may be difficult to attain with a very thin layer of hydrocarbon and an alternate construction method would need to be applied. The possibility of having smaller electrodes closer together may run the risk of not having good electrical contact with
the soil. The vertical electrode array can be a very helpful tool in monitoring the vertical movement and thickness of hydrocarbon in a known environment. The vertical resistivity electrode arrays would be most effective in a homogeneous environment. It would take very precise readings in conjunction with other methods of investigation in an area with many different sand and clay layers to get significant results. Overall the electrode arrays were effective and will be useful when the more complex variables are better understood.
BIBLIOGRAPHY


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