Groundwater Studies Near the Dowagiac Landfill Area, Dowagiac, Michigan, Using Seismic Resistivity Methods

Baharom

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GROUNDWATER STUDIES NEAR THE DOWAGIAC LANDFILL AREA, DOWAGIAC, MICHIGAN, USING SEISMIC RESISTIVITY METHODS

by

Saiful B. Baharom

A Thesis
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Faculty of The Graduate College
in partial fulfillment
of the requirements for the
Degree of Master of Arts
Department of Physics

Western Michigan University
Kalamazoo, Michigan
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GROUNDWATER STUDIES NEAR THE DOWAGIAC LANDFILL AREA, DOWAGIAC, MICHIGAN, USING SEISMIC AND RESISTIVITY METHODS

Saiful B. Baharom, M.A.
Western Michigan University, 1992

Groundwater contamination has occurred in the vicinity of the Dowagiac landfill, Dowagiac, Michigan. The groundwater has been degraded by the presence of organic hydrocarbons, trichloroethylene in particular. At least two aquifers are thought to be present in the area with the upper unconfined aquifer being contaminated while a lower confined aquifer remains uncontaminated. This lower aquifer is thought to be protected from above by a clay layer. A combined geophysical survey consisting of seismic refraction and electrical resistivity surveys was conducted to determine the continuity and thickness of this clay layer as well as the extent of the contamination. A continuous clay layer ranging from 20 to 50 feet thick was found throughout the area. Two sources of contamination, the landfill and another site within the area, are indicated by the results. The combination of geophysical techniques proved to be most useful in this hydrogeologic investigation.
ACKNOWLEDGEMENTS

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Saiful B. Baharom
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CHAPTER I

INTRODUCTION

Problem and Previous Investigations

Groundwater contamination has occurred in the vicinity of the Dowagiac landfill, Dowagiac, Michigan. The City of Dowagiac retained the firm of Dell Engineering, Holland, Michigan, to conduct a hydrological investigation of the landfill. That investigation was one of the requirements set by the Michigan Department of Natural Resources in the closure of the landfill. The important findings of the investigation are summarized below.

The location of the observation wells, soil borings and residential wells are shown in Figure 1. It was determined that the general direction of the groundwater flow across the site is westerly, although mounding might cause some northwesterly and southwesterly flow at the site.

The quality of the groundwater in the area has been degraded by the presence of organic hydrocarbons, notably trichloroethylene (TCE). TCE was identified in five residential wells: WW2, WW4, WW6, WW7, and WW8 (Figure 1). Two residential wells located west of the landfill (WW5 and WW3) were not found to be contaminated.
Figure 1. Location Map of Observation Wells, Soil Borings and Residential Wells. (From Dell Engineering, 1984)
It was believed that at least two aquifers are present in this area. An upper unconfined aquifer and a lower confined aquifer are thought to be separated by a clay aquitard. It was also believed that the contamination occurs only in the upper aquifer and that the five contaminated wells tap the water from this aquifer. The two residential wells that are not contaminated seem to be tapping water from a lower aquifer.

Objectives

One of the objectives of this survey is to determine whether the clay layers in this area are continuous and whether they are thick enough to prevent contamination of the lower aquifer which is believed to be uncontaminated. Dell Engineering (1984) has suggested that a thickness of at least 10 feet of clay is needed in order for that clay layer to be considered as an aquitard. The current study investigates the thickness of the clay layer in the area.

Two other objectives of this study are to determine the extent of contamination from the landfill and whether any source of contamination other than the landfill exists. The level of contamination found in the wells in the area is shown in Table 1. From the table it can be seen that the level of contamination in wells near the landfill (WW4 and WW7) was lower than the level of contamination in wells further from the landfill (WW6 and WW2). This may suggest
### Table 1

Levels of Trichloroethylene in Wells Near the Dowagiac Landfill

<table>
<thead>
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<th>Sampling Date</th>
<th>2/21/81</th>
<th>9/9/81</th>
<th>9/30/81</th>
<th>11/10/81</th>
<th>12/1/81</th>
<th>12/15/81</th>
<th>6/22/83</th>
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<td>353</td>
<td>56</td>
<td>2000</td>
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<td>35</td>
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<tr>
<td>W-2</td>
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<td>N.D.</td>
<td>-</td>
<td>42</td>
<td>1050</td>
<td>35</td>
<td>110</td>
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<tr>
<td>W-3</td>
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<td>-</td>
<td>N.D.</td>
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<td>W-4s</td>
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<td>W-5</td>
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<td>WW4</td>
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<td>N.D.</td>
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<td>WW5</td>
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<td>N.D.</td>
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<td>WW6</td>
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<td>N.D.</td>
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<td>1300</td>
<td>1050</td>
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<td>110</td>
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<td>WW7</td>
<td>136</td>
<td>172</td>
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<td>42</td>
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<td>WW8</td>
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<td>N.D.</td>
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Trichloroethylene Levels in μg/l (N.D. is non-detectable)

that another source of contamination is present in the area. DNR has suggested that another disposal site may be present. From the groundwater flow information gathered by Dell Engineering it is estimated that this site is located northeast of WW3.

Location

The Dowagiac landfill is located in the east one-half of the northwest one-quarter of Section 33, Township 5 South, Range 15 West, Wayne Township, Cass County, Michigan (Figure 2). It is located on Nubour Road, between Hatch Street and Dutch Settlement Road, approximately one mile east of the Dowagiac city limits (Figure 3).

Description

The site is approximately 67.4 acres in area. It consists of a northern portion and a southern portion (Figure 4). The southern portion consists of the landfill, the monitoring wells and the borrow area (area from which the landfill cover material is extracted). The northern portion, approximately 39 acres in size, is an area wooded with hardwood and sassafras trees on a rolling hill topography.

The disposal area is located on the southernmost portion of the property and occupies approximately 23 acres. The exact thickness of the fill on the site is not
Figure 2. Area Location Map.
Figure 4. Landfill Description Map.  
(from Dell Engineering, 1984)
known since past disposal methods were not documented. It is believed that the thickness of the fill ranges between 5 to 40 feet.

Approach

A geophysical survey using seismic refraction and electrical resistivity methods was made. The information gathered in this survey was then combined with well log data and soil boring logs to create a geologic profile of the area. The profile will show the depth, continuity and thickness of the clay layers. This information will in turn indicate whether clay layers may act to separate a lower uncontaminated aquifer from the upper contaminated one. The cross-section will also provide information on the size and direction of flow of the contaminated zone. This information can then be used to determine the extent of contamination and also to determine the location of other possible disposal sites.
CHAPTER II

GEOLOGIC SETTING

The regional glacial geology of this area has been discussed by Zumberge (1960) and by Leverett and Taylor (1915). The local geology of this area was also outlined in a hydrogeological investigation report by Dell Engineering (1984). The important facts are summarized below.

The present areal topography and surface geology of the area are the result of glacial events and post glacial erosion and deposition. The rolling hills in the immediate vicinity of the site are glacial end moraine deposits and the relatively flat plains were formed as glacial lake bed.

Sediments in this area were deposited during the advance, temporary halt and then retreat of the Lake Michigan Lobe during the Wisconsinan Glacial Period of the Pleistocene Epoch. In southwest Michigan the apparent terminal morainic ridge of the Lake Michigan Lobe is the Kalamazoo Moraine (Figure 5). It consists of two ridges aligned in a northeast-southwest direction. The two ridges, an inner or western ridge and an outer or eastern ridge, are separated by an outwash plain as shown in Figure 6. This outwash plain is approximately 5 to 7 miles wide and it contains a high percentage of gravel.
Figure 5. Regional Glacial Geology Map (from Zumberge, 1960).
Figure 6. Local Glacial Geology Map (from Dell Engineering, 1984).
The effects of complex glacial action in this area are also shown by the subsurface geology. A cross-section of the soil borings shows sand and gravel layers of varying thicknesses which grade into one another (Dell Engineering, 1984). On the site it is believed that a large portion of the thick clay layer in the area was eroded by glacial meltwater and redeposited with sand and gravel. Based on the available well log data, the thickness of the clay formation tends to increase immediately east and south of the site. The exact size, depth, and areal extent of the clay depression north and west of the site are not known.

The Coldwater Shale is believed to be the bedrock in this area. It is a Lower Mississippian formation composed primarily of shale with some interbedding of limestone, sandstone and dolomite. It is believed that the Coldwater Shale is approximately 320 to 360 feet beneath the site. Its thickness varies from 45 feet to 78 feet. Due to its lack of effective porosity, the Coldwater Shale is viewed as an excellent confining layer.
CHAPTER III

FIELD METHODS

Seismic Survey

Theory and Applications

Seismic surveys have been made extensively for petroleum, mineral and engineering investigations. There are two main types of seismic methods: reflection and refraction.

The seismic reflection method is the most widely used of the two methods (especially in oil exploration) and has somehow overshadowed the usefulness of seismic refraction methods. However, during recent years the seismic refraction method has been used extensively for hydrological investigations and has been shown to be an effective and economical way for obtaining groundwater information.

Refraction has been used by Haeni (1986) for groundwater studies in New England to determine: (a) depth of underlying bedrock; (b) depth of the water table; (c) saturated thickness of an aquifer in areas not accessible to heavy drilling equipment; (d) areas where thick, unsaturated sediments overlie thickly saturated parts of the aquifer; and (e) locations of test holes and type of

14
drilling equipment needed.

The theory of seismic refraction was discussed in Dobrin (1976) and Telford, Geldard, Sheriff, and Keys, (1976) as well as in Haeni (1986). The important fundamentals are summarized below.

The basic principle used in seismic theory is Snell's Law. This law concerns the refraction and reflection of a wave as it crosses the boundary between layers of different velocities. Figure 7 shows the effects on a wave passing from a layer of lower velocity to a layer of higher velocity. Sound waves traveling from a layer of lower velocity \((v_1)\) to layer of higher velocity \((v_2)\) are reflected and may also be refracted depending on their angle of incidence. At angles of incidence less than the critical angle \(i_c = \arcsin \frac{v_1}{v_2}\) the waves will be both refracted and reflected while at angles of incidence greater than the critical angle total reflection will occur.

The seismic refraction method utilizes critically refracted waves, waves which are transmitted along the surface of the second layer at the second layer velocity. Huygen's Principle states that every point in an advancing waveform can be regarded as the source of a new wave. These new sound waves are in turn propagated back to the surface at the critical angle at the velocity of the first layer. An example of a wave path diagram is shown in Figure 8.
(a) When the angle of incidence is less than the critical angle, the rays will be partially reflected and partially refracted. (b) When the angle of incidence is equal to the critical angle the rays will be critically refracted (transmitted along the boundary between the two layers at the second layer velocity). (c) When the angle of incidence is greater than the critical angle the rays will be totally reflected.
Figure 8. Seismic Ray Path Diagram (from Dobrin, 1976).
Seismic data are gathered using a controlled source, a set of detectors and a recording instrument. The recorded seismic signals can then be used to determine the seismic velocities and depths of the layers present. From this information a seismic profile or cross-section of an area can be obtained. In cases where only a few layers are present and where there is little variation in elevation, topography and layer depth, simple calculations, using the geophone distances and first arrival times of direct and direct and critically refracted waves, can be made to determine the approximate layer depths and velocities. A seismic profile or cross-section can be obtained quite easily in this case. But as the number of layers becomes larger and where elevation and topography vary significantly, computers are useful since the calculations become complex.

The quality of seismic data varies tremendously depending on the signal and the noise in the seismic record. A signal is any event on the seismic record from which we wish to obtain information. Everything else in the seismic record is noise. Seismic noise may be either coherent (noise that can be followed across at least a few traces) or incoherent (noise which is dissimilar on all traces and often referred to as random noise).

A good seismic record usually has a high signal-to-noise ratio. The signal-to-noise ratio is the ratio of the
signal energy in a specified portion of the record to the total noise energy in the same portion (Telford et al., 1976). Proper enhancement is needed in order to produce a good seismic record with a high signal-to-noise ratio. Enhancement can be accomplished by digital filtering and by a method called stacking.

Bandpass filtering is a process in which seismic noise is reduced by allowing only a certain range of frequencies to be recorded. In this method a low-pass filter and a high-pass filter are used to discriminate against seismic noise above and below certain frequencies. Some knowledge of the frequency of the seismic signal and noise in the area is obviously useful in selecting the filters.

Vertical stacking is a process in which several records having the same source and geophone location are combined. In this procedure, no trace-to-trace corrections are applied, but corresponding traces on separate records are merely added to each other. The result is essentially the same as if multiple shots or multiple receivers are used simultaneously. The signals will be more distinctive in this case, and the noise reduced significantly.

Two special cases usually determine the success or failure of the seismic refraction investigation (Haeni, 1986). These two cases are referred to as the velocity reversal and the blind zone problems. One of the conditions necessary for seismic refraction to work is that each
layer must have a greater seismic velocity than the layer above it. A velocity reversal occurs when an underlying layer has a lower velocity than the layer above. In this case no critically refracted wave is produced. When the velocity of underlying layers does increase but there are thin layers or a small velocity contrast between layers, a blind zone may exist. In this case critically refracted waves are produced but cannot be identified using standard seismic refraction techniques as first arrivals from these layers are not observed. The velocity reversal and blind zone problems may limit the use of the seismic refraction method in some cases.

Additional problems in refraction surveys may arise from assumptions which are generally made in gathering, processing and interpreting refraction data. In particular, the layers within the earth are assumed to be homogeneous. This assumption might produce some errors in the results. In reality no layer is completely homogenous since the seismic velocities vary horizontally as well as vertically. The inhomogeneities present can produce some inaccurate first arrival times, thus the velocities and depths may not be determined precisely. Some errors might also be produced due to topographic effects; however, they are usually not very significant since the differences in the elevations can be accounted for during the processing of the seismic data.
Instrumentation

The instrument used in this survey was a GeoPro 8012A signal processing seismograph manufactured by Bison Instruments (Minneapolis, MN). It is a microprocessor controlled twelve channel seismograph used for reflection and refraction seismology. A non-saturating form of signal enhancement is used by the GeoPro 8012A system.

In this study, a 10 lb. sledge hammer (an impact source) was used to create seismic signals. An impact switch which serves to trigger the seismograph was attached to the hammer. The seismic signals are detected by a set of geophones and converted to electrical signals. These signals are filtered and amplified and are then passed to the analog-to-digital converter. The resulting digitized signals are then received and stored by the Preview Memory. Different commands can then be used to display, enhance and/or print the signals. Figure 9 shows the data flow through the system during data acquisition and display. Also shown are some of the Command Functions that can be used. A more detailed description of the field operation of the instrument and its Command Functions is outlined in the GeoPro 8012A manual.

Field Procedure

A typical seismic field set-up is shown in Figure 10.
Figure 9. Data Flow Through the Geopro 8012A System During Data Acquisition, (from Bison Instrument, 1984)
Figure 10. Seismic Field Set-Up (from Bison Instruments, 1984).
For this study each spread consisted of a 12-geophone array with a shotpoint location at each end of the spread. The two shotpoint locations are for a forward shot and a reverse shot. This is necessary in order to investigate the dip of the layers present.

A preliminary survey was conducted in order to find the various seismograph settings necessary to provide a good quality seismogram. These settings include the gain (amplification of the geophone responses), the high and low-pass filters, and the sweeptime necessary to provide the signal coverage to the depth of interest. The preliminary survey was also necessary in order to estimate the most practical geophone spacing and shotpoint offset for the survey.

It was determined from the preliminary survey that a geophone spacing of 20 feet and a shotpoint offset of 10 feet should be used. During the preliminary survey a larger spacing (30 feet) was tried as this would provide deeper coverage. With this spacing the first arrival signals were not properly detected by the geophones located far from the shotpoint. This was due to insufficient energy provided by the source. A smaller geophone spacing (10 feet) was also tried. The first arrival signals in this case were much more distinctive but the depth coverage was inadequate for this survey. As a geophone spacing of 20 feet provided adequate depth coverage and signal
resolution, this spacing was selected for the survey.

Since most of the residential wells are located near Nubour Road, it seemed very practical to conduct the survey along this road. The well data are useful for correlating seismically defined layers with observed subsurface layers along the survey line. Nineteen spreads in all were made along Nubour Road. Fifteen spreads covering 3880 feet were made west of the landfill and four spreads covering 960 feet were made south of the landfill. The positions of the spreads are shown in Figure 11.

Two seismograms were made at each shotpoint. The sweeptime used for the first seismogram was from 0 to 192 milliseconds. This seismogram was made in order to determine if any seismic reflection interpretation was possible.

As explained earlier in the theory and application section of this chapter, stacking and digital filtering are necessary in order to obtain a better seismogram with more distinctive signal. Approximately 10 hammer blows were stacked in order to obtain this proper enhancement of the seismic record. The band pass filter used in most areas was 75 Hz-440 Hz. The low frequency seismic noise (road traffic, construction, footsteps etc.) and the high frequency seismic noise were reduced quite significantly. At a few locations, slightly different filters were used to obtain optimum noise reduction. Such changes might be
Figure 11. Seismic Spread Location Map.
expected due to differing ground conditions and/or different sources of seismic noise.

Resistivity Survey

Theory and Applications

The resistivity method has been widely used in geophysical exploration. It is especially important in mineral exploration and hydrological investigations. The theory of resistivity was discussed in Telford et al. (1976) and Keller and Frischknecht (1966). Basically the method used changes in electrical resistivity within the earth to deduce variations in hydrologic and geologic conditions within the earth. There are two main applications of the resistivity method: Vertical Electrical Sounding (VES) and Lateral Resistivity Profiling (LRP). VES is used to investigate variations with depth while LRP is used to detect lateral changes in near surface conditions.

A typical resistivity setup is shown in Figure 12. Electric current (I) is introduced into the ground using the two current electrodes while the potential difference (V) due to the current is measured using the two potential electrodes. The apparent resistivity (\( \rho_a \)) of the ground is then calculated as

\[ \rho_a = K \times \left( \frac{V}{I} \right) \]
Figure 12. Resistivity Field Set-Up (from Telford et al., 1976).
where $K$ is a geometric factor related to the configuration of the electrodes. Various electrode configurations can be used although the most common ones are the Wenner and the Schlumberger arrays (Figure 13). The uses and advantages of these arrays were discussed in Keller and Frishknecht (1966), Telford et al. (1976), and Mooney (1980).

Since vertical variations in the soil layers are the primary interest in this study a VES survey was conducted. In a VES survey the array is expanded about a fixed center. As discussed below, expanding the array increases the depth of current penetration and thus the depth of investigation. As it is easier to use, the Schlumberger array was chosen for the survey. Unlike some other arrays (the Wenner array, for example) the Schlumberger array does not require the movement of the potential electrodes as the current electrode spacing is increased.

For two point current electrodes separated by a distance $L$ in homogenous medium, the horizontal current density at a point $P$ is given by equation $A$ (Figure 14). It is desirable to get as much current into the ground as possible, since the potential measured at the surface depends on the current flow through the earth. For this case the current density above a depth $Z$ is maximum when $L = 1.414 \ Z$. Equation $A$ suggests the proper current electrode spacing required in order to adequately energize the ground at a particular depth with a limited power.
Figure 13. Electrode Spreads in Common Use.
(a) Wenner Spreads;
(b) Schlumberger spread.
(from Telford et al., 1976).
\[ j_x = \frac{1}{2\pi} \left[ \frac{X^3}{r_1^3} - \frac{X - L}{r_2^3} \right] \]

If \( x = \frac{L}{2} \) and \( r_1 = r_2 \):

\[ j_x = \frac{1}{2\pi} \frac{L}{(Z^2 + L^2/4)^{3/2}} \]  \hspace{1cm} \text{EQUATION A}

\[ \frac{j_x}{\frac{L}{T}} = \frac{2}{\pi} \left( \arctan \frac{2Z_2}{L} - \arctan \frac{2Z_1}{L} \right) \]

In homogenous ground, when \( Z_2 \to \infty \):

\[ \frac{j_x}{\frac{L}{T}} = 1 - \frac{2}{\pi} \arctan \frac{2Z_1}{L} \]

\( j_x \) : Current density  
\( L \) : Current electrode separation  
\( z \) : Depth  
\( C_1 \) and \( C_2 \) : Current electrodes

Figure 14. Determining the Current Density Below Two Surface Electrodes (from Telford et al., 1976).
source. In other words, the maximum current electrode spacing for all VES locations should be larger than the target depth.

Since the Schlumberger array is designed to measure the potential gradient resulting from the current flow, another important condition is that the current electrode spacing should be large compared to the potential electrode spacing for the Schlumberger array. For the geometric factor to be within 5% of the ideal value (that is, the value it would have if a true potential gradient were measured) when the Schlumberger array is used, it may be shown that the potential electrode spacing should be less than 0.435 times the current electrode spacing (Keller & Frishknecht, 1966).

The variation of apparent resistivity with current electrode spacing can be used to develop a subsurface resistivity model consisting of layer resistivities and thicknesses for the various geoelectric layers within the earth. The apparent resistivities are calculated using equation B, Figure 15. A more detailed outline of the data processing is presented in Chapter IV.

Similar to the seismic survey, the assumption that the layers are homogenous is also made for the resistivity survey. Apparent resistivities, like seismic velocities vary horizontally as well as vertically. The
\[ \rho_a = \frac{2\pi V}{I\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{R_1} + \frac{1}{R_2}\right)} \]  \hspace{1cm} (1) 

(From Keller and Frischknecht, 1966)

**EQUATION B:**

\[ \rho_a = \frac{\pi (AB^2 - MN^2) V}{4MN I} \]  \hspace{1cm} (2)

(Equation (2) is a simplification of Equation (1))

Figure 15. Determining the Apparent Resistivity Using the Schlumberger Array.
inhomogeneities present might produce some errors since average apparent resistivities will be assigned to each layer in deriving the subsurface models and plotting of the geoelectric cross-section. Errors might also be produced due to the topographic effects. However, the topographic errors in this study are quite insignificant since the variation in elevation is very small compared to the size of the electrode spacings involved in the survey. Non-uniqueness is another problem that might cause some errors in the result. This problem arises since the data may not allow one to distinguish between different subsurface models. The interpretation made will merely select a reasonable subsurface model.

Instrumentation

The instrument used for this survey was a Johnson-Keck IC-69 Earth Resistivity Meter. This instrument is capable of making precise determination of resistance for any application involving the four electrode method. Other equipment included cables, reels and four electrodes (two steel electrodes to apply the current and two non-polarizing electrodes to measure the potential drop).

The IC-69 uses a direct current source supplied by up to four 45-volt batteries. To avoid the effects of electrolytic polarization caused by unidirectional current, a reversing switch is used to reverse the current.
Polarization due to chemical disequilibrium between the potential electrodes and the ground is minimized by the use of non-polarizing electrodes (copper electrodes in a saturated solution of copper sulfate). The IC-69 also provides a compensation voltage which may be used to reduce the effect of spontaneous, naturally occurring earth potentials. Further reduction of spurious potentials of all types is obtained by averaging the resistivity measurements made using the two different current directions.

Procedure

This survey, like the seismic survey, was conducted along Nubour Road. The survey also included a portion of the landfill. A total of twenty-two VESs were made. They were placed on two lines intersecting at the south-west corner of the landfill. The east-west trending line consisted of 15 VES, 13 along Nubour Road west of the landfill and 2 along the southern boundary of the landfill. The north-south trending line consisting of 6 VES, 4 along Nubour Road south of the landfill and 2 along the western boundary of the landfill. A VES was made along the western boundary of the landfill. A VES was also made at the intersection of the lines. The positions of the VESs are shown in Figure 16.

At all VES locations, 11 array expansions were made. As stated above, the maximum current electrode spacing
Figure 16. VES Location Map.
should be larger than the target depth. In this survey the maximum current electrode spacing used was 500 feet while the maximum target depth was approximately 200 feet. A current electrode spacing of 700 feet was also tried but the current provided by the battery was too weak to supply an adequate current density. This inadequate current density resulted in a weak signal and a low signal-to-noise ratio. The minimum current electrode spacing used was 10 feet. The range of spacing used allowed adequate coverage to the depths of interest in this study. The potential electrode spacing used in most places was 3 feet. At larger current electrode spacings the potential electrode spacing used was 30 feet. This change was necessary since at larger current electrode spacings, the measured potential using the smaller spacing was very low compared to the applied current, resulting in an inaccurate resistance measurement.
CHAPTER IV

DATA PROCESSING

Seismic Data Processing

The seismograms obtained in the field are shown in Appendix A. The two seismograms from each shotpoint (one for 0-192 ms and one for 100-292 ms) were combined to produce a continuous seismic record from 0 millisecond to 292 milliseconds. From the seismograms the first arrival times were identified. The first arrival times were the first rapid change in signal above the background noise. These first arrival times were then plotted against the geophone distances. An example of the plotted graph is shown in Figure 17. From the plotted curves, layers were assigned based on the arrival times. For example, in Figure 17, the first segment, second segment and third segment represent the first arrival times due to the first layer, second layer and third layer, respectively.

The seismic refraction data were then processed using the program FSIP1 (Scott, Tibbetts, & Bordick, 1972). This program is very helpful since it is capable of handling seismic data of up to five spreads, with up to twelve geophones and seven shotpoints each, and for as many as five layers with layer velocity increasing with depth.
Figure 17. Graph of First Arrival Times Vs. Geophone Spacings.
Since FSIP1 originally used the card reader as the input device, minor modifications were made in the input statements. The output statements of the program were modified as well. The input device was changed from the card reader to the file FOR21 and the output device was changed from the line printer to the file FOR23. A complete listing of the format of the input data, except the noted modification that FSIP1N reads from a data file instead of cards, is found in Scott et al. (1972).

Since the program can only interpret up to five seismic spreads and nineteen seismic spreads were made in the field, the data were grouped into four sets of profiles. The east-west trending line consists of three profiles of five spreads each, and the north-south trending line made up the fourth profile consisting of the remaining four spreads.

Different types of output can be obtained using the program FSIP1N. A list of the output commands or exits can be found in Scott et al. (1972). The typical data processing routine used is summarized below.

The first step in the processing was to input the data in the input file FOR21. The first execution of the program was then made using exit 1. This exit provides a datum corrected raw time-distance plot. Since layer representations made previously did not take into account the elevations, the layer representations were rechecked.
New layer representations were then made with the help of the time-distance graph plotted. These were then used in the next execution.

The next execution uses exit 6. Using this exit, the velocity of the layers was calculated. Table 2 shows the velocities computed by the program. Average values of the layer velocities from each data set were then calculated manually.

The final execution was made using exit -6. During the execution, average values of the layer velocities were used. This has provided a more standard profile of the whole area, assuming that the layers were homogenous, i.e., there were no variations in the velocities (horizontally or vertically) within each layer. An example of the computer output plotted by the program is shown in Figure 18.

Resistivity Data Processing

Using formula B mentioned in Chapter III, the apparent resistivities for each electrode spacing used at each VES location were calculated. The VES data were analyzed and a subsurface model showing the resistivities of each layer present and the thicknesses of each of those layers were developed. Three methods were used to develop and refine the models.

The first method used to interpret the resistivity data was partial curve matching. In this method the
### Table 2
Layer Velocities Obtained Using the Program FSIP1

**SEISMIC VELOCITY OF LAYERS (ft/s)**

<table>
<thead>
<tr>
<th>PROFILE</th>
<th>SEISMIC VELOCITY</th>
<th>LAYER 1</th>
<th>deviation from average</th>
<th>LAYER 2</th>
<th>deviation from average</th>
<th>LAYER 3</th>
<th>deviation from average</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1306</td>
<td>-106</td>
<td>4736</td>
<td>+257</td>
<td>8828</td>
<td>+1136</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1408</td>
<td>-4</td>
<td>3811</td>
<td>-668</td>
<td>7305</td>
<td>-387</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1528</td>
<td>+116</td>
<td>4902</td>
<td>+423</td>
<td>6786</td>
<td>-906</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1406</td>
<td>-6</td>
<td>4466</td>
<td>-13</td>
<td>7849</td>
<td>+157</td>
<td></td>
</tr>
<tr>
<td>AVERAGE</td>
<td>1412</td>
<td></td>
<td>4479</td>
<td></td>
<td>7692</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STANDARD DEVIATION</td>
<td>±58</td>
<td>±340</td>
<td>±646</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% DEVIATION</td>
<td>±4.1%</td>
<td>±7.6%</td>
<td>±8.4%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Apparent resistivities calculated were plotted against the \((AB)/2\) spacings on logarithmic paper. The segments from the plotted curves were then matched with available standard curves. These curves include the Schlumberger array two layer curves and different types of auxiliary curves. The auxiliary curves used were the K-type curves for a bell-shaped sequence, the H-type curves for a bowl-shaped sequence, the Q-type curves for a descending type sequence and the A-type curves for an ascending type sequence. These curves are shown in Appendix D. By matching the segments of the VES curves with a combination...
Figure 18. An Example of the Computer Output Plotted by the Program FSIP1.
of these two layers curves and auxiliary curves, the approximate number of layers, the approximate resistivities of the layers, and the approximate thickness of each of those layers were determined. A detailed description of the partial curve matching method was outlined in Keller and Frischknecht (1966).

The second method was the use of the program RESIST. This program was obtained from Mooney (1980). It was written and developed by Philip A. Davis at the University of Minnesota, Duluth. Further details and information on the program can be found in Davis (1979). This program was modified by William A. Sauck in 1980 for terminal use on Western Michigan University's DEC 10 system.

The original concept for this method of computing apparent resistivities is due to Ghosh (1971). The program calculates the apparent resistivities at various spacings using a suggested earth mode. The suggested model used here was the one provided by the partial curve matching procedure. The program then calls a routine to plot the apparent resistivities calculated from the suggested model (model rho), and the apparent resistivities obtained from the field (field rho), on a graphics terminal. Visual comparison was then made and the parameters of the suggested model were changed in such a way that the two curves were as similar as possible.

The models determined with the program RESIST were
further refined using the program INVERS. This program was also obtained from Mooney (1980). The program was developed and written by Philip A. Davis at the University of Minnesota based on a concept presented by N.P. Merrick (1977). It was also modified by William A. Sauck in 1980 for terminal use on the Western Michigan University DEC 10 system.

This program is similar to the program RESIST in that it also calculates the resistivities at various spacings using a suggested model. INVERS uses the Ghosh Linear Filter method (Ghosh 1971) to calculate apparent resistivities for the suggested model. The root mean square (RMS) error between the model and field resistivities is then calculated. Next the program uses the Marquardt algorithm (Davis, 1979) to modify the initial model in an attempt to lower the RMS error. The program continues to modify successive models until (a) fifteen iterations are completed, (b) the RMS error increases or (c) the RMS error falls below a set value.

The INVERS program allows one or more model parameters (layer resistivities and/or thicknesses) to be held constant. These fixed parameters will not be adjusted as the model is modified by the program. It can be important to have certain parameters fixed, especially if those parameters are known (for example, from soil borings or well data). This is because the iterative adjustment might
produce a model which is geologically unreasonable even though the adjusted model has a low RMS error.

Further details of the Ghosh Linear Filter method and the Marquardt algorithm can be found in Ghosh (1971), Merrick (1977) and Davis (1979). A step by step description of the program INVERS can be found in Barton (1984).
CHAPTER V

INTERPRETATION

Seismic Interpretation

The seismic cross-sections produced are shown in Plates I, II, III, and IV. An example of the computer output plotted by the program FSIP1 is shown in Figure 18. The processing of the data was based on a three layer case. Misties between layers on different cross-sections may be noted in Plates I-IV, as indicated by the dashed lines and question marks. These misties are caused by a lack of resolution at the ends of the sets of seismic spreads. This lack of resolution results in slightly different layer depth values being calculated at the ends of adjacent sets of seismic spreads.

Haeni (1986) has found that the velocity of sound in an unsaturated, unconsolidated stratified drift ranges from 0.3 km/s (1000 ft/s) to 0.6 kms (2000 ft/s). The average first layer velocity calculated for this area was 1412 ft/s (±4.1%). Given this velocity and the fact that sand and gravel are the prominent surface material in this area, the first layer was interpreted as sand and gravel above the water table.

Haeni (1986) has also found that the velocity of sound
in saturated stratified drift ranges from 1.2 km/s (3900 ft/s) to 1.8 km/s (5900 ft/s). The average second layer velocity calculated in this area was 4479 ft/s (±7.6%). Again, since it falls within the range of values mentioned and since sand and gravel are the most abundant material in this area (as shown in the well logs and soil borings, Appendix C), the second layer was interpreted as sand and gravel below the water table.

Published values for the seismic velocity of clay layers range from 3630 ft/s to 8250 ft/s (Clark, 1966). The third layer detected in this survey has an average velocity of 76926 ft/s (±8.4%). This high velocity layer was interpreted as a clay layer. The presence of clay layers in the area is noted from the well logs and soil borings (Appendix C).

Table 3 shows the depths to the water table detected by the seismic method as compared to the depths of the water table indicated in the well data and soil borings. From the table it can be seen that the depths matched quite well at several locations, exceptions being at WW2, WW8 and SB4. The differences for some sites might be due in part to the fact that the sites were not located close to the survey line. For example, WW8 is located approximately 200 feet west of the line and WW6 is located approximately 130 feet south of the line (Figure 1). Localized variation in
Table 3

Depth to Water Table Detected by the Seismic Method as Compared to the Depths to the Water Table Indicated in the Soil Borings and Well Data

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Depth to Water Table (ft)</th>
<th>Difference (ft)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seismic Method</td>
<td>Soil Boring &amp; Well Data</td>
<td></td>
</tr>
<tr>
<td>SB1</td>
<td>33.0</td>
<td>34.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>SB2</td>
<td>27.0</td>
<td>28.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>SB3</td>
<td>36.0</td>
<td>43.0</td>
<td>-7.0</td>
</tr>
<tr>
<td>SB4</td>
<td>24.0</td>
<td>40.0</td>
<td>-16.0</td>
</tr>
<tr>
<td>WW2</td>
<td>30.0</td>
<td>58.0</td>
<td>-28.0</td>
</tr>
<tr>
<td>WW4</td>
<td>48.0</td>
<td>45.0</td>
<td>+3.0</td>
</tr>
<tr>
<td>WW6</td>
<td>42.0</td>
<td>50.0</td>
<td>-8.0</td>
</tr>
<tr>
<td>WW7</td>
<td>27.0</td>
<td>N.A.</td>
<td>-</td>
</tr>
<tr>
<td>WW8</td>
<td>39.0</td>
<td>91.0</td>
<td>-52.0</td>
</tr>
</tbody>
</table>

Note: N.A. - not available

The formation thickness and variation in elevations may contribute to the observed differences. It may also be possible that the water level measured in these wells corresponds to a lower aquifer beneath the aquifer identified by the seismic survey. There may also have been real differences in the water table position between the times that it was measured from the wells and from the geophysical survey.
Table 4 shows the depths to the first clay layer detected by the seismic method as compared to the depths of the first clay layer indicated in the well data and soil borings. From the table it can be seen that the values matched very well at almost all the locations, the exception being at WW4. Again, local variations may account for the observed differences. At WW4 the comparison might be an improper comparison since the seismic method might detect a thin clay lens rather than the clay layer identified in the well data. A thin clay lens could be present at this location since the well data indicate that some clays were found to be intermixing with sand, gravel and stones in the depth range of 47 to 57 feet (Appendix C).

As mentioned in Chapter III, two special cases usually determine the success or failure of a seismic refraction investigation. The two cases are the blind zone problem and the velocity reversal problem. Both cases seem to be present in this area.

In the first case, it is possible that an important layer cannot be detected. This happens when that layer does not have a sufficient velocity contrast or thickness. Thus the thin clay layer shown to be present in this area from the well data and soil borings (e.g., at WW7) were not detected.

In the second case, a velocity reversal would exist where sand and gravel layers are interlayered with clay
layers. A clay layer (higher seismic velocity) which is overlain and underlain by sand and gravel layers (lower

Table 4

Depth to the First Clay Layer Detected by the Seismic Method as Compared to the Depth to the First Clay Layer Indicated in the Well Data and Soil Borings

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Depth to First Clay Layer Difference (\text{(ft)})</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic</td>
<td>Soil Boring &amp; Well Data</td>
<td></td>
</tr>
<tr>
<td>SB1</td>
<td>39.0</td>
<td>+0.5</td>
</tr>
<tr>
<td>SB2</td>
<td>39.0</td>
<td>-0.5</td>
</tr>
<tr>
<td>SB3</td>
<td>75.0</td>
<td>-5.0</td>
</tr>
<tr>
<td>SB4</td>
<td>60.0</td>
<td>+1.0</td>
</tr>
<tr>
<td>WW2</td>
<td>48.0</td>
<td>-9.0</td>
</tr>
<tr>
<td>WW4</td>
<td>69.0</td>
<td>-42.0</td>
</tr>
<tr>
<td>WW7</td>
<td>63.0</td>
<td>N.A.</td>
</tr>
<tr>
<td>WW8</td>
<td>57.0</td>
<td>-8.0</td>
</tr>
</tbody>
</table>

Note: N.A. - not available

seismic velocity) would produce a typical refracted wave at the upper boundary (sand and gravel/clay) but not at the lower boundary (clay/sand and gravel). Thus the boundary between the clay layer and the underlying sand and gravel layer will be undetected by the refraction method. Because this boundary is undetected, erroneous results will be
obtained for any deeper layers which do produce a refraction—for example, the next boundary where sand and gravel overlie clay. The velocity reversal problem, which is obviously present in this area (e.g., at WW4), limits the use of the seismic refraction method, allowing the accurate detection of only the first clay layer below the surface. Thus the clay layer detected by the refraction method in this area may not be the clay aquitard of interest.

Resistivity Interpretation

The resistivity models determined using the various methods mentioned earlier were used to draw the geoelectric cross-section. The VES curves and the subsurface resistivity models for each VES are shown in Appendix B. The geoelectric cross-sections are shown in Plates V, VI, VII and VIII. The layers were classified into three resistivity zones.

Zone I is a high resistivity zone. It was interpreted as the sand and gravel layer above the water table. Telford et al. (1976) have suggested a range between 33 ohm-ft to 2600 ohm-ft to 20,000 ohm-ft seem to be high compared to the values mentioned; however, this may be due to the very high percentage of gravel in this area. In layers where the pore spaces lack water, the larger the pore spaces, the higher the resistivity. Thus gravel layers, which have larger pore spaces than sand layers,
produce a higher resistivity measurement. In this area it was mentioned that large stones are present in a few areas (e.g., WW4, Appendix C). Thus the high apparent resistivity values are not unreasonable.

Zone II is a moderate resistivity zone (500 ohm-ft to 2500 ohm-ft). This layer was interpreted as the sand and gravel layer below the water table. Even though this zone consists of the same material as in Zone I (sand and gravel), the presence of water causes the resistivities to be lower. Water in the spaces between the sand and gravel will allow more electric current to flow through by means of ionic conduction.

The boundary between Zone I and Zone II is interpreted as the position of the water table. Table 5 shows the depths to the water table detected by the resistivity method as compared to the depths of the water table indicated in the well data and soil borings. Most of the values matched very well, the exceptions being WW2 and WW8. The reasons discussed above for discrepancies with the refraction data may account for the differences. Note that at the sites corresponding to WW2 and WW8, the water table position determined by the seismic and resistivity methods agree more closely with one another than with the well data. This is a further indication that there is some real difference in the water table position between the survey sites and the wells or that there is some problem with the
The moderate resistivity zone that was detected near the surface at a few locations (for example, VES 1W, Plate V) might be due to the presence of vegetation and topsoil. Barton (1984) has investigated the effects of vegetation

Table 5

Depth to Water Table Detected by the Resistivity Method as Compared to the Depth to the Water Table Indicated in the Well Data and Soil Borings.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>DEPTH TO WATER TABLE DIFFERENCE (ft)</th>
<th>%DIFFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seismic Method</td>
<td>Soil Boring &amp; Well Data</td>
</tr>
<tr>
<td>SB1</td>
<td>22.0</td>
<td>34.0</td>
</tr>
<tr>
<td>SB2</td>
<td>27.0</td>
<td>28.5</td>
</tr>
<tr>
<td>SB3</td>
<td>36.0</td>
<td>43.0</td>
</tr>
<tr>
<td>SB4</td>
<td>42.0</td>
<td>40.0</td>
</tr>
<tr>
<td>WW2</td>
<td>30.0</td>
<td>58.0</td>
</tr>
<tr>
<td>WW4</td>
<td>57.0</td>
<td>45.0</td>
</tr>
<tr>
<td>WW6</td>
<td>48.0</td>
<td>50.0</td>
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and climate on resistivity measurements. It appears that resistivity is lower in places where vegetation is present and also during rainy seasons. Vegetation lowers the apparent resistivities since ions present near the roots (e.g., from fertilizers) increase the conduction of electric current. Topsoil lowers the apparent resistivities since it is able to hold moisture (e.g., moisture from rain). The water in the moist soil will act as an ionic conductor, thus lowering the apparent resistivities.

Zone III is a low resistivity zone. This zone was interpreted as clay layers and contaminated zones. Telford et al. (1976) have reported a value ranging from 3.3 ohm-ft to 330 ohm-ft for the resistivities of clays. The values obtained in the field range from 50 ohm-ft to 500 ohm-ft. Contaminated zones have low resistivities since the contaminants include ionic compounds like chlorides, sulfates and nitrates. These ionic compounds will lower the resistivities since they allow more conduction of electric current. The low resistivities measured are due to the ionic compounds and are not due to the primary contaminant, TCE; however, the presence of TCE may be inferred from the presence of the other compounds.

The exact position of the clay layers in this study cannot be determined using only the resistivity method since the clay layers and the contaminated zones have approximately the same apparent resistivities. The
conductivities of the contaminated zones have approximately the same apparent resistivities. The conductivities of the contaminated groundwater range from 485 mhos/cm at WW9 to 780 mhos/cm at WW6 (Dell Engineering, 1984). Converting these values to resistivities, we have a range of resistivities between 39 ohm-ft to 69 ohm-ft. As mentioned earlier, the resistivity of clays ranges between 3.3 ohm-ft to 300 ohm-ft (Telford et al., 1976). Due to the similarities in the resistivity values, other information is needed in order to separate the two zones (contaminated zones and clay layers).

Final Interpretation

A final interpretation was made by combining the seismic, resistivity, soil boring and well data. The high resistivity/low velocity zones were correlated with the sand and gravel layer above the water table. The moderate resistivity/moderate velocity zones were correlated with the sand and gravel layer below the water table. An example of the correlation made is shown in Figure 19.

The high seismic velocity layers were correlated with clay layers indicated in the well data and soil borings. Low resistivity zones were not simply correlated to the clay layers noted on the driller's logs since the low resistivities might not be due to the clay but may be due to contaminated zones. Consider the VES location 4W
Figure 19. Correlation to Locate the Sand and Gravel Formation Above and Below the Water Table.
(Figure 20). First, correlation was made between the high seismic velocity layer and the clay layer. The low resistivity zone above the correlated clay layer shows the location of the contaminated zone. This method was applied to other VES locations as well. The vertical resolution of the resistivity method does not allow a definite interpretation as to the lower boundary of the contaminated zone.

It is important to realize that at a few places the correlations made may not produce an accurate geologic model since the well data (used during the correlation) are not always accurate. It should also be noted that more complicated models with multiple, discontinuous clay layers which are relatively thin and closely spaced could also fit the available data. More detailed data would be necessary to distinguish this possibility. In general the interpretation made is thought to be reliable. The seismic velocities and resistivities of the layers, used in producing the models were comparable to values listed in literature (Haeni, 1986; Telford et al., 1976). Furthermore, the depths to the water table and clay layers are comparable to the values indicated in the well data and soil borings (Tables 3, 4, and 5). The geologic cross-sections produced are shown in Plates IX, X, XI, and XII.
REMAINING LOW RESISTIVITY ZONE ABOVE THE HIGH SEISMIC ZONE (CLAY) INDICATES THE CONTAMINATED ZONE

RESISTIVITY ZONES

- HIGH
- MODERATE
- LOW

SEISMIC ZONES

- A - LOW VELOCITY
- B - MODERATE VELOCITY
- C - HIGH VELOCITY

Figure 20. Correlation to Locate the Clay Layers and Contaminated Zones.
CHAPTER VI

CONCLUSIONS

In the area west of the landfill a continuous clay layer was detected (Plates IX - XI). The clay layer varies in thickness, ranging from 20 feet to 50 feet. The depth to the clay layer varies from 50 feet to 120 feet below the surface. As mentioned earlier in Chapter II, a thickness of at least 10 feet of clay is needed in order for the clay layer to act as an aquitard. Thus it appears that this clay layer might be thick enough to serve as an aquitard layer in preventing contamination of the lower aquifer.

In the area south of the landfill two clay layers seem to be present (Plate XII). The upper clay layer was detected by both the seismic and resistivity methods. The average thickness is about 30 feet and it is approximately 60 feet deep. This clay layer is thicker in the south and it seems to truncate or pinch out approximately 250 feet south of the landfill. The second clay layer was detected by the resistivity method. This second layer dips to the south and seems to be continuous and thick enough to serve as an aquitard layer. Its thickness varies from 30 feet to 40 feet. The depth to this clay layer varies from 120 feet to 160 feet.
Low resistivity zones indicate clay layers or contaminated zones. From the resistivity method, the depth to the low resistivity zone in this area is determined to be approximately 100 feet. From the well data WW8, the depth to the second clay layer is determined to be approximately 150 feet. It can then be interpreted that approximately 50 feet of low resistivity zone above the clay layer is actually the contaminated zone. In this way, the clay layer can be distinguished from the contaminated zone.

Two contaminated areas were detected (Figure 21). Since both areas were located quite far from each other and since no contamination was detected in between the two areas, it is probable that the contamination is from two separate sources.

The contaminated area near the landfill is most probably due to the contamination leaving the landfill. The contamination seems to extend approximately 600 feet to the south and 1600 feet to the west. From the profile it can be seen that the contaminated area is located at the southwest corner of the landfill. This indicates that the groundwater flow in this area is generally in the westerly direction or slightly to the southwest towards Mill Pond.

The second contaminated area is located approximately 2200 feet west of the landfill. The contamination here most probably originates from a nearby source rather than from the landfill. The Michigan Department of Natural
Figure 21. Map Indicating the Contaminated Areas and Possible Disposal Sites.
Resources has suggested that another disposal site could be present north-east of the WW3 residence. If such a disposal site were present, then the groundwater flow in this area is in the southwest direction.

It has been found that there is an aquifer in this area that could be safe from contamination. The aquifer may be protected from the near-surface contamination by an overlying clay layer. This lower aquifer seems to vary in depth. It is shallower in areas west of the landfill and deeper in areas south of the landfill. If wells are drilled deep enough this aquifer could possibly be utilized as a source of non-contaminated water. However, other factors need also be considered in order to be sure that this aquifer could really be utilized as a source of non-contaminated water. These factors include the quality of the clay and the absence of fracturing.

The presence of two clay layers in areas south of the landfill could be questionable. The upper clay layer was detected by both the seismic and resistivity survey while the lower clay layer could only be detected by the resistivity survey. The presence of this second clay layer was suggested by the clay layer encountered in WW8, approximately 200 feet south of the landfill. Correlation between this clay layer and the clay layer found in the soil boring SB 1 (Appendix C) is unlikely considering the difference in depth (approximately 60 feet) compared to the horizontal
distance of 300 feet (Figure 1). In order to be sure that
two clay layers are present, a soil boring approximately
350 feet south of the landfill is recommended.

From the survey it may be seen that seismic refraction
and electrical resistivity can be used jointly in hydrogeo-
logic and groundwater studies. Seismic refraction works
very well in areas where there are layers of sufficient
thickness and a sufficient velocity contrast between
layers. The combination of methods can be especially
useful. The information gathered using these geophysical
techniques can be used with the well and soil boring data
to detect, locate, and map clay layers, the water table and
contaminated zones in an area.
Appendix A

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GUIDE TO SEISMIC DATA

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SEISMOGRAM IDENTIFICATION

X/Y/Z

X - Profile
Y - Spread
Z - Shot

A - Forward
B - Reverse

↓ - Arrows indicate first arrival picks
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Appendix B

Resistivity Data
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RMS ERROR = 10.328
APPARENT RESISTIVITY (OHM-FT)

10000
1000
100

AB/2 SPACING (FEET)

10 100 1000

LAYER THICKNESS ELEV RHO THICK/RES THICK/RES
1 7.00 812.0 2000.0 14000.0 0.0035
2 16.00 835.0 3000.0 12000.0 0.0020
3 32.00 789.0 1000.0 7000.0 0.0032
4 70.00 757.0 100.0 7000.0 0.7000
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MODEL RHO

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2977.4
3521.1
3853.2
3653.4
3795.1
1599.1
676.0
324.4
323.8
413.6

FIELD RHO

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2642.7
3309.6
3355.3
3229.6
2686.6
1349.9
767.0
277.6
301.0
623.6

AB/2 FIELD RHO

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2681.17
3226.42
3363.93
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2609.29
1349.9C
729.98
740.36
750.73
341.3F
272.50
705.86

RMS ERROR = 15.967

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### Model Resistivity vs. Field Resistivity

**Apparent Resistivity (Ohm-FT)**

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**Spacing (Feet) vs. AB/2 Spacing (Feet)**

### RMS Error

RMS Error = 15.726
APPARENT RESISTIVITY (OHM-FT)

107

0-MODEL RHO

A-FIELD RHO

AB/2 SPACING (FEET)

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RMS ERROR = 12.615

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APPARENT RESISTIVITY (OHM-FT)

AB/2 SPACING (FEET)

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AB/2 FIELD RHO

RMS ERROR = 10.193

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APPARENT RESISTIVITY (OHM-FT)

O-MODEL RHO
△-FIELD RHO

AB/2 SPACING (FEET)

LAYER THICKNESS ELEV RHO THICK*RES THICK/RES
1 5.00 805.0 300.0 1500.0 0.0066
2 33.00 800.0 500.0 16500.0 0.0056
3 60.00 767.0 50.0 3000.0 1.2000
4

SPACING MODEL RHO FIELD RHO AB/2 FIELD RHO
10.00 552.0 493.7 10 493.66
14.68 758.0 674.3 15 686.61
21.54 1030.5 946.7 20 884.66
31.62 1352.5 1352.7 30 1287.31
46.42 1671.4 1970.6 50 2129.05
68.13 1870.7 2710.4 70 2727.20
100.00 1791.3 2333.5 100 2333.54
146.78 1363.6 1560.2 150 1436.41
215.44 775.5 642.2 200 1506.24
316.23 373.4 345.0 300 1576.86
464.16 273.5 227.8 500 209.14

RMS ERROR = 16.953

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APPARENT RESISTIVITY (OHM-FT)

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<td>96000.0</td>
<td>0.0015</td>
<td></td>
</tr>
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</table>

SPACING | MODEL RHO | FIELD RHO | AB/2 | FIELD RHO
---------|-----------|-----------|------|-----------
10.00    | 1181.2    | 1120.3    | 15   | 1120.32   |
14.69    | 1064.6    | 947.8     | 15   | 946.74    |
21.54    | 1105.5    | 884.5     | 20   | 836.74    |
31.62    | 1257.5    | 959.4     | 30   | 939.64    |
46.44    | 1359.4    | 1162.3    | 50   | 1205.20   |
68.13    | 1243.8    | 1310.5    | 70   | 1307.21   |
100.00   | 929.1     | 1046.4    | 100  | 1046.43   |
146.78   | 582.2     | 597.7     | 150  | 565.14    |
215.44   | 400.5     | 378.2     | 150  | 575.16    |
316.23   | 351.7     | 451.9     | 150  | 585.15    |
464.16   | 327.2     | 365.5     | 200  | 383.01    |

RMS ERROR = 15.655

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APPARENT RESISTIVITY (OHM-FT)

10000

1000

100

10

100

1000

APPARENT RESISTIVITY (OHM-FT)

10000

1000

100

10

100

1000

AB/2 SPACING (FEET)

LAYER THICKNESS ELEV

1 15.00 836.0

2 45.00 821.0

3 78.00 776.0

MODEL RHO

1055.0

1071.5

1000.0

1000.0

FIELD RHO

1149.8

1245.0

1000.0

1000.0

THICKNESS RES

1969.5

2392.2

1071.5

1071.5

THICK/RES

3.0

5.0

10.0

10.0

RMS ERROR = 12.575
APPARENT RESISTIVITY (OHM-FT)

10000

1000

AB/2 SPACING (FEET)

10

100

1000

1 2 0

1000

0-MODEL RHO

A-FIELD RHO

THICKNESS ELEV

32.00 835.0

12.00 804.0

44.00 742.0

45.00 703.0

AB/2 FIELD RHO

RMS ERROR = 5.559

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APPARENT RESISTIVITY (OHM-FT)

1 2 1

IOOOO-1

O-MODEL RHO
A-FIELD RHO

AB/2 SPACING (FEET)

1 2 3 4 5 6

THICKNESS ELEV

00 845.0
00 833.0
00 812.0
00 794.0
00 751.0

7 0 5 .0

RHO
4 0 0 .0
2000.0
6000.0
20000.0

THICK/RES
4800.0
42000.0
85000.0
9200.0

SPACING
10.00
14.68
21.54
31.62
46.92
68.13
100.00
146.73
215.44
316.23
464.16

MODEL RHO
435.2
490.2
599.9
774.4
1004.9
1263.2
1509.1
1635.0
1522.5
1340.9
1197.5

FIELD RHO
479.8
559.5
679.3
919.5
1075.9
1637.6
1731.9
1623.4
1454.3
1221.1
1122.4

AB/2 FIELD RHO
10
15
20
30
50
70
100
100
100
150
200
300
500

RMS ERROR = 11.557
### Layer Details

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Elevation</th>
<th>Model Rho</th>
<th>Field Rho</th>
<th>AB/2 Field Rho</th>
<th>RMS Error</th>
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<td>1</td>
<td>22.00</td>
<td>836.0</td>
<td>300.0</td>
<td>6000.0</td>
<td>0.0733</td>
<td>11.073</td>
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<tr>
<td>2</td>
<td>17.00</td>
<td>794.0</td>
<td>1500.0</td>
<td>24000.0</td>
<td>0.0107</td>
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</tr>
<tr>
<td>3</td>
<td>17.00</td>
<td>794.0</td>
<td>1500.0</td>
<td>24000.0</td>
<td>0.0021</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>57.00</td>
<td>731.0</td>
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<td>6</td>
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<td>50000.0</td>
<td>0.5700</td>
<td></td>
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</table>

**Diagram:**
- **Apparent Resistivity (OHM-FT)**
- **AB/2 Spacing (Feet)**

**Legend:**
- **O-Model Rho**
- **Δ-Field Rho**

**Model Rho Values:**
- 30.0
- 50.0
- 100.0

**Field Rho Values:**
- 100.0
- 200.0
- 300.0

**RMS Error:**
- 11.073
Appendix C
Soil Boring Data and Well Data
SOIL BORING DATA

LOCATION: SB1

<table>
<thead>
<tr>
<th>FORMATION DESCRIPTION</th>
<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine Sand &amp; Gravel</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Fine-Coarse Sand</td>
<td>15.5</td>
<td>28.5</td>
</tr>
<tr>
<td>Sand</td>
<td>5.0</td>
<td>33.5</td>
</tr>
<tr>
<td>Fine-Medium Sand</td>
<td>5.0</td>
<td>38.5</td>
</tr>
<tr>
<td>Clayey Sand With Silt</td>
<td>3.5</td>
<td>42.0</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>18.0</td>
<td>60.0</td>
</tr>
</tbody>
</table>

Groundwater encountered at 34.0 ft.
Depth of boring: 60.0 ft.
SOIL BORING DATA

LOCATION: SB2

<table>
<thead>
<tr>
<th>FORMATION DESCRIPTION</th>
<th>DESCRIPTION STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
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</thead>
<tbody>
<tr>
<td>Sand &amp; Gravel</td>
<td>11.0</td>
<td>11.0</td>
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<tr>
<td>Fine Sand</td>
<td>20.0</td>
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<tr>
<td>Silty Sand</td>
<td>7.5</td>
<td>38.5</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>22.5</td>
<td>71.0</td>
</tr>
<tr>
<td>Clay with occasional Gravel</td>
<td>3.0</td>
<td>74.0</td>
</tr>
<tr>
<td>Clay</td>
<td>8.5</td>
<td>82.5</td>
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<tr>
<td>Sand</td>
<td>6.0</td>
<td>88.5</td>
</tr>
<tr>
<td>Sand with occasional Gravel</td>
<td>5.0</td>
<td>93.5</td>
</tr>
<tr>
<td>Fine Sand with occasional Silt</td>
<td>19.0</td>
<td>98.5</td>
</tr>
<tr>
<td>Sand</td>
<td>28.5</td>
<td>127.0</td>
</tr>
<tr>
<td>Med-Fine Sans w/occas. Cobble</td>
<td>19.0</td>
<td>146.0</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>4.0</td>
<td>150.0</td>
</tr>
</tbody>
</table>

Groundwater encountered at 28.5 ft.

Depth of soil boring 150.0 ft.
SOIL BORING DATA

LOCATION: SB3

<table>
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<tr>
<th>FORMATION DESCRIPTION</th>
<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand with occasional Gravel</td>
<td>43.5</td>
<td>43.5</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>7.5</td>
<td>51.0</td>
</tr>
<tr>
<td>Fine Silty Sand w/ occas. Clay</td>
<td>29.0</td>
<td>80.0</td>
</tr>
<tr>
<td>Clay</td>
<td>25.0</td>
<td>105.0</td>
</tr>
</tbody>
</table>

Ground water encountered at 43.0 ft.

Depth of boring: 105.0 ft.
SOIL BORING DATA

LOCATION: SB4

<table>
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<tr>
<th>FORMATION DESCRIPTION</th>
<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium-Fine Sand &amp; Fine Gravel</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Medium-Fine Sand</td>
<td>4.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Coarse-Fine Sand &amp; Fine Gravel</td>
<td>11.0</td>
<td>53.0</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>4.5</td>
<td>57.5</td>
</tr>
<tr>
<td>Very Fine Sand</td>
<td>1.5</td>
<td>59.0</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>3.5</td>
<td>62.5</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>5.5</td>
<td>68.0</td>
</tr>
<tr>
<td>Clayey Silt</td>
<td>9.5</td>
<td>77.5</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>9.5</td>
<td>87.0</td>
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<tr>
<td>Silty Clay</td>
<td>23.0</td>
<td>110.0</td>
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</table>

Groundwater encountered at 40.0 ft

Depth of well: 110.0 ft.
WELL DATA

LOCATION: WW 2

<table>
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<th>FORMATION DESCRIPTION</th>
<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand &amp; Gravel</td>
<td>42.0</td>
<td>42.0</td>
</tr>
<tr>
<td>Sand</td>
<td>15.0</td>
<td>57.0</td>
</tr>
<tr>
<td>Fine Sand with Silty Clay</td>
<td>26.0</td>
<td>83.0</td>
</tr>
<tr>
<td>Clay</td>
<td>27.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Sand, Gravel &amp; Clay</td>
<td>9.0</td>
<td>109.0</td>
</tr>
<tr>
<td>Gravel &amp; Sand</td>
<td>113.0</td>
<td>222.0</td>
</tr>
<tr>
<td>Fine Sand with some Gravel</td>
<td>15.0</td>
<td>252.0</td>
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<tr>
<td>Coarse Sand-Fine Gravel</td>
<td>23.0</td>
<td>275.0</td>
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</table>

Groundwater encountered at 58.0 ft.
Depth of well: 270.0 ft.
WELL DATA

LOCATION: WW 4

<table>
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<th>FORMATION DESCRIPTION</th>
<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
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<tbody>
<tr>
<td>Sand &amp; Gravel</td>
<td>47.0</td>
<td>47.0</td>
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<tr>
<td>Sand, Gravel, Stones &amp; Clay</td>
<td>10.0</td>
<td>57.0</td>
</tr>
<tr>
<td>Gravel &amp; Sand</td>
<td>54.0</td>
<td>111.0</td>
</tr>
<tr>
<td>Clay</td>
<td>13.0</td>
<td>124.0</td>
</tr>
<tr>
<td>Fine Sand &amp; Clay</td>
<td>5.0</td>
<td>129.0</td>
</tr>
<tr>
<td>Medium Sand</td>
<td>5.0</td>
<td>134.0</td>
</tr>
<tr>
<td>Fine Gravel-Coarse Sand</td>
<td>16.0</td>
<td>150.0</td>
</tr>
</tbody>
</table>

Groundwater encountered at 45.0 ft.

Depth of well: 149.0 ft.
WELL DATA

LOCATION: WW 6

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<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
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</thead>
<tbody>
<tr>
<td>Sand &amp; Gravel</td>
<td>44.0</td>
<td>44.0</td>
</tr>
<tr>
<td>Sand with streaks of Clay</td>
<td>35.5</td>
<td>79.5</td>
</tr>
<tr>
<td>Clay with Silty Sand</td>
<td>6.5</td>
<td>86.0</td>
</tr>
<tr>
<td>Clay</td>
<td>19.0</td>
<td>105.0</td>
</tr>
<tr>
<td>Sand &amp; Gravel</td>
<td>19.0</td>
<td>124.0</td>
</tr>
<tr>
<td>Gravel &amp; Sand</td>
<td>49.0</td>
<td>173.0</td>
</tr>
<tr>
<td>Clay</td>
<td>1.0</td>
<td>174.0</td>
</tr>
<tr>
<td>Gravel &amp; Sand</td>
<td>18.0</td>
<td>192.0</td>
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<tr>
<td>Silty Clay</td>
<td>1.5</td>
<td>193.5</td>
</tr>
<tr>
<td>Silty Fine Sand w/streaks of Clay</td>
<td>16.5</td>
<td>210.0</td>
</tr>
<tr>
<td>Clay</td>
<td>4.0</td>
<td>214.0</td>
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<tr>
<td>Fine Gravel-Coarse Sand</td>
<td>20.0</td>
<td>234.0</td>
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Groundwater encountered at 50.0 ft.
Depth of well 233.0 ft.
# SOIL BORINGS DATA

**LOCATION:** WW 7

<table>
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<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
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</thead>
<tbody>
<tr>
<td>Sand &amp; Gravel</td>
<td>27.0</td>
<td>27.0</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>12.0</td>
<td>39.0</td>
</tr>
<tr>
<td>Clay</td>
<td>1.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Fine Sand &amp; Clay</td>
<td>17.0</td>
<td>57.0</td>
</tr>
<tr>
<td>Clay</td>
<td>27.0</td>
<td>84.0</td>
</tr>
<tr>
<td>Sand &amp; Gravel</td>
<td>10.0</td>
<td>94.0</td>
</tr>
<tr>
<td>Gravel &amp; Sand with some Clay</td>
<td>5.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Gravel &amp; Sand</td>
<td>16.0</td>
<td>116.0</td>
</tr>
<tr>
<td>Sand with streaks of Clay</td>
<td>10.0</td>
<td>126.0</td>
</tr>
<tr>
<td>Sand &amp; Fine Gravel</td>
<td>111.0</td>
<td>237.0</td>
</tr>
<tr>
<td>Gravel &amp; Sand</td>
<td>18.0</td>
<td>255.0</td>
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<tr>
<td>Clay</td>
<td>1.0</td>
<td>256.0</td>
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<td>Clay &amp; Gravel</td>
<td>3.0</td>
<td>259.0</td>
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<td>Clay</td>
<td>52.0</td>
<td>311.0</td>
</tr>
<tr>
<td>Clay &amp; Gravel</td>
<td>8.0</td>
<td>319.0</td>
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Not indicated where groundwater is encountered.

Depth of boring 323.0 ft.
**WELL DATA**

LOCATION: WW 8

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<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
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<tr>
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<td>Gravel &amp; Sand</td>
<td>43.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Gravel &amp; Clay</td>
<td>5.0</td>
<td>55.0</td>
</tr>
<tr>
<td>Gravel &amp; Sand</td>
<td>10.0</td>
<td>65.0</td>
</tr>
<tr>
<td>Clay</td>
<td>3.0</td>
<td>68.0</td>
</tr>
<tr>
<td>Gravel &amp; Sand</td>
<td>84.0</td>
<td>152.0</td>
</tr>
<tr>
<td>Clay</td>
<td>11.0</td>
<td>163.0</td>
</tr>
<tr>
<td>Sand-Gravel-Clay</td>
<td>5.0</td>
<td>168.0</td>
</tr>
<tr>
<td>Clay</td>
<td>10.0</td>
<td>178.0</td>
</tr>
<tr>
<td>Gravel &amp; Sand</td>
<td>4.0</td>
<td>182.0</td>
</tr>
<tr>
<td>Clay</td>
<td>13.0</td>
<td>195.0</td>
</tr>
<tr>
<td>Sand &amp; Gravel</td>
<td>3.0</td>
<td>198.0</td>
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<tr>
<td>Clay</td>
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<td>Gravel</td>
<td>14.0</td>
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Groundwater encountered at 91.0 ft.

Depth of well 220.0 ft.
**WELL DATA**

**LOCATION:** Test well 4S

<table>
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<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
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<tr>
<td>Fine Sand &amp; Gravel</td>
<td>35.0</td>
<td>35.0</td>
</tr>
<tr>
<td>Fine Sand &amp; Gravel w/Cobbles</td>
<td>31.0</td>
<td>66.0</td>
</tr>
<tr>
<td>Sand &amp; Gravel</td>
<td>9.0</td>
<td>75.0</td>
</tr>
</tbody>
</table>

Groundwater encountered at 55.0 ft.

Depth of well 75.0 ft.
**WELL DATA**

**LOCATION:** Test well 4D

<table>
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<tr>
<th>FORMATION DESCRIPTION</th>
<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Fine Sand</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Fine Sand w/occas. Cobble</td>
<td>4.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Coarse-Fine Sand &amp; Gravel</td>
<td>32.5</td>
<td>40.5</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>0.5</td>
<td>41.0</td>
</tr>
<tr>
<td>Coarse-Fine Sand &amp; Fine Gravel</td>
<td>45.0</td>
<td>86.0</td>
</tr>
<tr>
<td>Medium Fine Sand</td>
<td>27.0</td>
<td>113.0</td>
</tr>
<tr>
<td>Medium-Fine Sand w/occas. Gravel</td>
<td>9.5</td>
<td>122.5</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>0.5</td>
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</tr>
<tr>
<td>Coarse-Fine Sand &amp; Gravel</td>
<td>2.0</td>
<td>125.0</td>
</tr>
</tbody>
</table>

Groundwater encountered at 55.0 ft.

Depth of well 125.0 ft.
**WELL DATA**

**LOCATION:** Test well #5

<table>
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<th>THICKNESS OF STRATUM (ft)</th>
<th>DEPTH TO BOTTOM OF STRATUM (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine Sand w/Gravel &amp; Cobbles</td>
<td>35.0</td>
<td>35.0</td>
</tr>
<tr>
<td>Fine Sand &amp; Gravel</td>
<td>10.0</td>
<td>45.0</td>
</tr>
<tr>
<td>Fine Sand &amp; Gravel w/Cobbles</td>
<td>30.0</td>
<td>75.0</td>
</tr>
</tbody>
</table>

Groundwater encountered at 58.0 ft.

Depth of well 75.0 ft.
Appendix D

Resistivity Modeling Curves
Schlumberger array two-layer curves (from Orellana and Mooney, 1966).
Auxiliary curves for a bowl-type sequence (from Orellana and Mooney, 1966).
Auxiliary curves for a bell-type sequence (from Orellana and Mooney, 1966).
Auxiliary curves for an ascending-type sequence (from Orellana and Mooney, 1966).
Auxiliary curves for a descending-type sequence (from Orellana and Mooney, 1966).
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ELEVATION (feet)

SEISMIC CROSS-SECTION

DISTANCE (feet) FROM LANDFILL - WEST

LAYER 1 VELOCITY = 1412 ft/s
LAYER 2 VELOCITY = 4479 ft/s
LAYER 3 VELOCITY = 7692 ft/s
PLATE II

ELEVATION
( feet)

SEISMIC CROSS-SECTION

LAYER 1 VELOCITY = 1412 ft/s
LAYER 2 VELOCITY = 4479 ft/s
LAYER 3 VELOCITY = 7692 ft/s

DISTANCE (feet) FROM LANDFILL - WEST

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PLATE II

SEISMIC CROSS-SECTION

HORIZONTAL SCALE: 1 inch = 125 feet
VERTICAL SCALE: 1 inch = 60 feet

DISTANCE (feet) FROM LANDFILL - WEST

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PLATE III
SEISMIC CROSS-SI

ELEVATION
( feet)

860 -
800 -
740 -
680 -
620 -
560 -
500 -

Layer 1 Velocity = 1412 ft/s
Layer 2 Velocity = 4479 ft/s
Layer 3 Velocity = 7692 ft/s

DISTANCE (feet) FROM LANDFILL

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PLATE IV

SEISMIC CROSS-SECTION

ELEVATION
(feet)

860 -
800 -
740 -
680 -
620 -
560 -
500 -
440 -
380 -
320 -
260 -
200 -
140 -
80 -
0 -

LAYER 1 VELOCITY = 1412 ft/s
LAYER 2 VELOCITY = 4479 ft/s
LAYER 3 VELOCITY = 7692 ft/s

HORIZONTAL SCALE : 1 inch = 1

DISTANCE (feet) FROM LANDFILL - SOUTH

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PLATE V
GEOELECTRIC CROSS-S

ELEVATION (feet)

RESISTIVITIES IN OHM-FT

HORIZONTAL SCALE: 1 inch = 125 feet
VERTICAL SCALE: 1 inch = 60 feet
PLATE V

ELECTRIC CROSS-SECTION

ELEVATION
(feet)

RESISTIVITY ZONES

ZONE I: 2501 - ∞ OHM-FT
ZONE II: 501 - 2500 OHM-FT
ZONE III: 50 - 500 OHM-FT

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PLATE VI

GEOELECTRIC CROSS-SI

ELEVATION (feet)

RESISTIVITIES IN OHM-FT

HORIZONTAL SCALE : 1 inch = 125 feet

VERTICAL SCALE : 1 inch = 60 feet

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PLATE VI
GEOELECTRIC CROSS-SECTION

ELEVATION (feet)

RESISTIVITY ZONES
ZONE I : 2501 - ∞ OHM-FT
ZONE II : 501 - 2500 OHM-FT
ZONE III : 50 - 500 OHM-FT

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PLATE VII
GEOELECTRIC CROSS

ELEVATION (feet)

RESISTIVITIES IN OHM-FT

HORIZONTAL SCALE: 1 inch = 125 feet

VERTICAL SCALE: 1 inch = 60 feet

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PLATE VII

EOELECTRIC CROSS-SECTION

ELEVATION
(feet)

RESISTIVITY ZONES

ZONE I : 2501 - ∞ OHM-FT
ZONE II : 500 - 2500 OHM-FT
ZONE III : 50 - 500 OHM-FT
RESISTIVITIES IN OM-FT

HORIZONTAL SCALE: 1 inch = 125 feet

VERTICAL SCALE: 1 inch = 60 feet

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PLATE VIII
ELECTRIC CROSS-SECTION

RESISTIVITY ZONES
ZONE I : 2501 - ∞ OHM-FT
ZONE II : 501 - 2500 OHM-FT
ZONE III : 50 - 500 OHM-FT

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PLATE IX
GEOLOGIC CROSS-SECTION

ELEVATION (feet)

860 -
800 -
740 -
680 -
620 -
560 -
500 -
400 -
340 -
280 -
220 -
160 -
100 -
40 -
0 -

HORIZONTAL SCALE: 1 inch = 125 feet
VERTICAL SCALE: 1 inch = 60 feet

DISTANCE (feet) FROM LANDFILL - WEST

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PLATE IX
GEOLOGIC CROSS-SECTION

LANDFILL

WW4

CLAY LAYER

CONTAMINATED ZONE

DISTANCE (feet) INSIDE LANDFILL - EAST

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PLATE XI
GEOLOGIC CROSS

ELEVATION (feet)

HORIZONTAL SCALE: 1 inch = 125 feet
VERTICAL SCALE: 1 inch = 60 feet

DISTANCE (feet) FROM LANDFILL

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PLATE XI
GEOLOGIC CROSS-SECTION

ELEVATION
(Feet)

-860
-800
-740
-680
-620
-560
-500

YMW6
SB3

CLAY LAYER
CONTAMINATED ZONE

30 2750 2500 2250

2E (feet) FROM LANDFILL - WEST

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ELEVATION (feet)

VEERTICAL SCALE : 1 inch = 60 feet

HORIZONTAL SCALE : 1 inch = 125 feet

DISTANCE (feet) INSIDE LANDFILL - NORTH