BURIED LANDFILL DELINEATION WITH INDUCED POLARIZATION: PROGRESS AND PROBLEMS*

Norman R. Carlson, Jennifer L. Hare, and Kenneth L. Zonge
Zonge Engineering & Research Organization, Inc., Tucson, AZ

In Proceedings of the 2001 Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Denver, Colorado, March 4-7, 2001

Abstract

In recent years, the use of induced polarization (IP) data for delineating buried landfills has increased significantly, due to technological advances that have made this method faster and less expensive, and therefore more applicable to the environmental industry. As the database of IP information grows to include information over waste of differing composition and in differing environments, interpretation has improved significantly. Problems and limitations still exist, of course, but the IP method has become an efficient and economic tool in evaluating waste sites. We discuss here progress in interpretation, including methods to process large amounts of data rapidly in order to decrease costs, and we discuss problems that still exist, such as electrode stability, which still limit the field survey speed.

Introduction

IP and resistivity information both add significantly to the more traditional landfill mapping tools, such as conductivity or magnetics, since they can provide substantially more vertical information than most conductivity systems, and unlike magnetics, they are capable of detecting non-metallic waste. Vertical information is vital in estimating the volume of waste, which is an important factor in determining the cost of remediation or in planning for future use of the landfill site. Since waste is often segregated in landfills (green waste, construction waste, household waste, etc.) magnetic surveys often show only the footprint of areas that contain substantial amounts of metal; IP and resistivity often detect non-metallic landfill areas that are not detectable with magnetic surveys. These benefits of the IP and resistivity methods have made it an extremely valuable tool in our environmental work in general and in our landfill studies specifically.

In the past, resistivity methods have already been shown to be useful in delineating some landfills, and it is possible to acquire these data rapidly and economically. If there is a resistivity contrast between the landfill and the background material, resistivity methods are often an adequate mapping tool. In areas where background is moderate or low resistivity, however, typical landfill material may be similar in resistivity to background, and therefore indistinguishable from background. Even in some higher resistivity backgrounds, lower resistivity landfill material is easily confused with back-filled excavations. Since many old landfills were previously excavation sites (such as gravel operations, or quarries), it is common to find landfills in close proximity to old, back-filled excavations. Both a landfill and a back-filled excavation will show a resistivity contrast with the native background, and are therefore easily confused. As a result, and as we have found frequently in our work, resistivity (and therefore conductivity) are often not sufficient data sets for waste delineation.

In 1974, Angoran, Fitterman, and Marshall (1) showed a measurable IP response over a landfill, and since that time numerous studies have confirmed this effect. IP has not been used extensively, however, because it is more difficult and costly to acquire than resistivity data. During the last few years, we have applied advances in receiver and computer technology toward decreasing the cost of IP data acquisition by increasing the survey speed. Significant progress has been made; we are currently able to acquire IP data approximately 30 to 40 times faster than five years ago, and now have a large database of IP data over numerous landfills, including many high resolution grids (rather than just single test lines). In order to become more cost-effective, we have had to develop faster interpretation aids in order to handle these large data sets. Even with the increase in field speed, however, some problems still exist.

Problems

Electrode Stability

As is the case in many tomography surveys, when we initially began applying a computer-controlled mulitplexer system to IP surveys, we attempted to minimize the data acquisition and multiplexer switching time by optimizing the schedule of transmission locations. In addition, the same electrodes were used for transmitter and receiver positions at different times while reading a given spread of electrodes, unlike most of our mineral exploration surveys in which transmitter and receiver electrodes are physically different materials (usually steel or aluminum stakes and non-polarizable porous pots, respectively). We calculated the sequence and location of transmitter dipoles that would provide full coverage of the spread with the least number of transmissions and multiplexer switching. This was done to maximize the speed of the survey, in order to make it cost-effective for local governments or land developers.

We immediately found that the result was noisy, non-repeatable IP measurements for many data points when an electrode was part of a receiver dipole shortly after having been part of a transmitter dipole. Resistivity measurements were repeatable, since that part of the measurement is made during the time when the current is on, during peak voltage, and is therefore less susceptible to noise.

In order to determine whether this noise was unique to, or just exacerbated by, the electrodes in use, we did a comparison of five different electrode material types. In this comparison, data were acquired on the same 30-electrode dipole-dipole spread. Our standard field equipment in a typical configuration was used, including a 30-channel multiplexer and 13-channel receiver, measuring 12 receiver dipoles simultaneously while one channel monitors the transmitter output. The electrode materials that were compared were stainless steel stakes, aluminum conduit stakes, copper grounding braids (2 inches by 12 inches), lead plates (2 inches by 12 inches), and non-polarizable copper-copper sulphate porous pots. A 50% duty cycle, time domain signal was used with a repetition rate of 0.5 Hz, and 13 windows (or gates) along the decay curve were measured. Each measurement (or data block) consisted of four cycles stacked and averaged, and each measurement was then repeated.

Figure 1 shows the results of this comparison. As a measure of noise, we simply show the repeatability of the chargeability between the two data blocks (one acquired immediately after the other) in milliseconds for each measurement versus the time in minutes since the receiver dipole was used as a transmitter dipole. As is clearly evident, in general, repeatability improves substantially with increased time since transmission. For example, at 3.5 minutes after transmission, a large number of data points do not repeat within 1 millisecond, and some do not repeat even repeat within 10 milliseconds. After 10 minutes, however, most data points repeat within 1 millisecond. We assume that the instability of the electrodes is also a function of the local soil conditions, but have not completed testing this assumption yet. In Figure 1, note that a large number of data points show very good repeatability of 0.1 milliseconds or less, regardless of electrode type or time-since-transmission, and these are primarily small n-spacing positions in the spread, where signal strength is high compared to the noise.

The relative "noisiness" of each electrode type is consistent with our general field experience. The porous pot electrodes were generally the most quiet; 3.5 minutes after transmission, repeatability was approximately 2.5 milliseconds, and repeatability improved with time. In contrast, some measurements with conduit stakes did not even agree within 25 milliseconds at 3.5 minutes after transmission. Since the IP anomalies we have measured at some landfills is very small (2 to 4 milliseconds at asbestos disposal sites, up to several 10s of milliseconds in areas of high metal content), repeatability of less than 1 millisecond is important in these surveys.

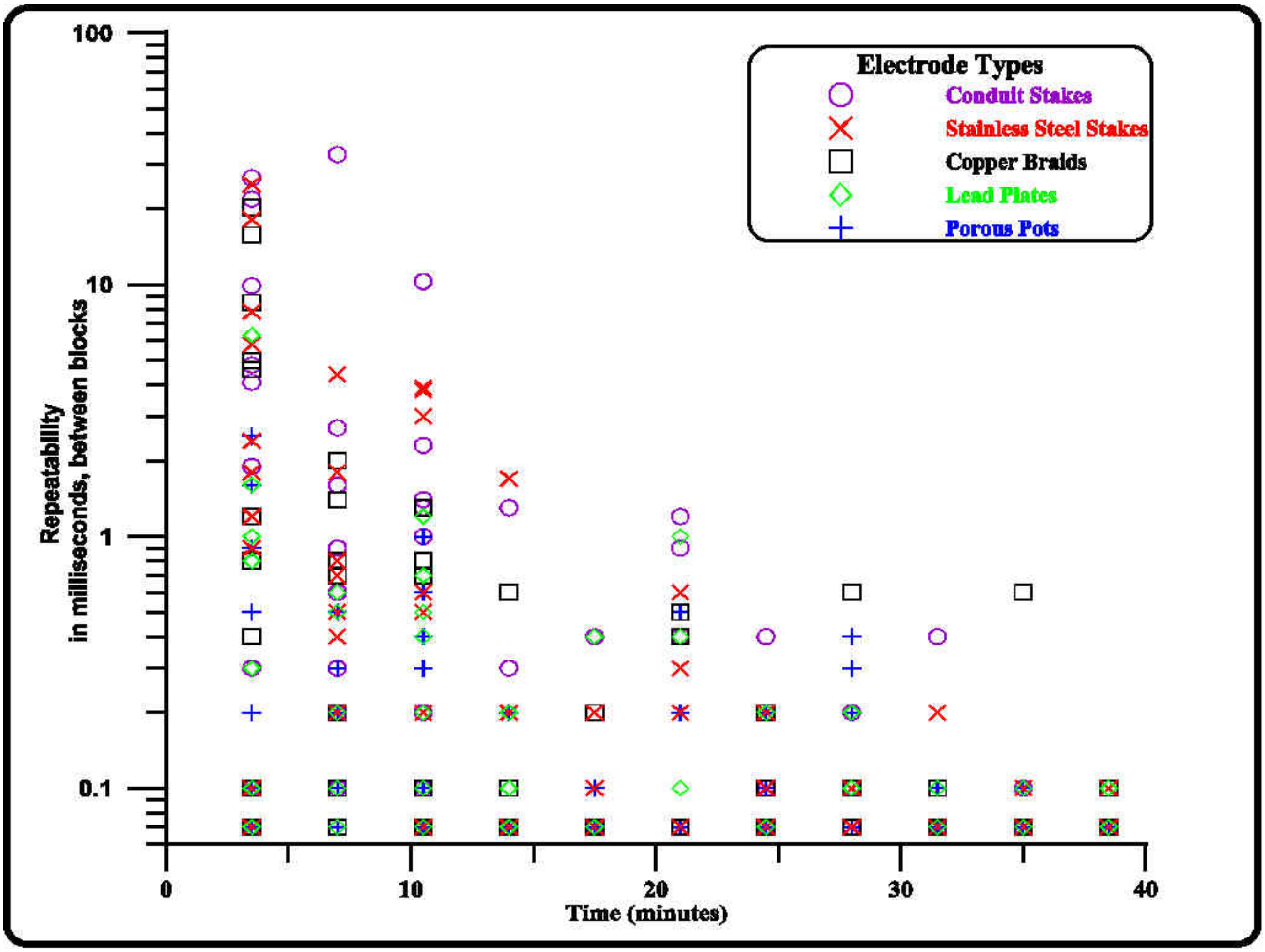

Figure 1. Repeatability between consecutive blocks of the chargeability measurement in milliseconds versus time since the receiver electrodes were used as transmitter electrodes. Five common electrode materials were compared at the same location using the same transmitter, receiver, and cables.

In this comparison, conduit stakes were the most noisy, followed by stainless steel stakes (a common electrode for many rapid resistivity systems geared for environmental/engineering applications), then copper braids (the electrode we use for our landfill IP surveys), followed by lead plates, and finally non-polarizable porous pots, which were the quietest. We continue to use copper braid electrodes in our IP surveys; braids are quieter than aluminum and stainless steel stakes, but they are substantially less expensive than porous pots and lead plates. Logistically, braids are also easier and faster for the crew to use than pots, and much more durable.

We are continuing to research this noise situation, but at the present, our solution is a logistical one. For all surveys in which IP data are required, the survey acquisition is in a linear roll-along fashion, with the transmitter dipole following the receiver dipoles down line, such that any given electrode position is not used as a receiver after it is used as a transmitter. This is not the most efficient sequence time-wise, but good IP data can be acquired relatively rapidly. When the electrode noise problem is corrected and we can optimize the schedule for each spread, we expect a 10% to 20% increase in efficiency, and corresponding decrease in survey costs.

Progress

Interpretation

Improved presentation of the survey results to non-geophysicists, and often non-scientists, has been an important factor in our processing and modeling decisions. For example, one common configuration for IP data acquisition is the dipole-dipole array. Since the dipole-dipole array is not a vertical sounding method, a buried IP responder can affect measurements that are not directly over the responder, making the interpretation of source location, size, and depth very difficult. We use a 2-D smooth-model inversion method that includes topographic effects for generation of cross sections, rather than relying on traditional pseudosections for presentation of the data. The results of our smooth-model inversion are intentionally gradational, rather that showing abrupt subsurface changes. This is because inversion of any geophysical data is inherently non-unique; that is, an infinite number of earth models may yield identical observed data. Our IP inversion program attempts to mathematically optimize the unavoidable trade-off between model resolution and variance, or noise. Recent experience modeling numerous landfill IP and similar data sets, where we also have ground-truth information, has illuminated the extreme significance of inversion control parameters on model accuracy.

Once an IP model has been generated, (and we stress that the modeling is actually an iterative process), the final interpretation step is to delineate and identify the source if possible. IP anomalies tend to delineate most buried waste materials better than resistivity anomalies. This is in part because background IP is generally extremely uniform and near zero in magnitude, except in some rare cases where certain types of polarizable clay is present. Background resistivity, however, is often quite variable due to changes in geology and water saturation, and thus obscures or confuses the expected resistivity contrast signature from the buried waste. The resistivity of waste materials is also much more variable. It can range from relatively high resistivities for some materials (such as construction waste), to very low for others, especially those containing metallic material. Where ground-truth data are not available for calibrating the earth's electrical response, our experience with environmental IP data suggests that it is best to use IP anomalies to delineate "where the waste is", and to use both the IP and apparent resistivity amplitudes to estimate "what the waste is".

As an example, Figure 2 shows the inversion model IP results from field data at a military refuse site where Automobile Shredder Residue (ASR) is thought to have been buried over many years spanning the WWI and WWII eras. Although the exact composition of the suspected material is not yet known, a general estimate of modern ASR is 27% plastic, 7 % rubber, 17 % Fiber, 49 % other (glass, metals, dirt). Some of the old ASR material is exposed on the surface near the base of the slope shown on Figure 2. The surface IP response is moderate, in the 5 to 7 msec range. The anomaly is well defined and extends from about station 30 to 250 on this line. IP values of up to 20 msec are observed between stations 80 to 150. Here, the ASR may contain a higher portion of metallic debris.

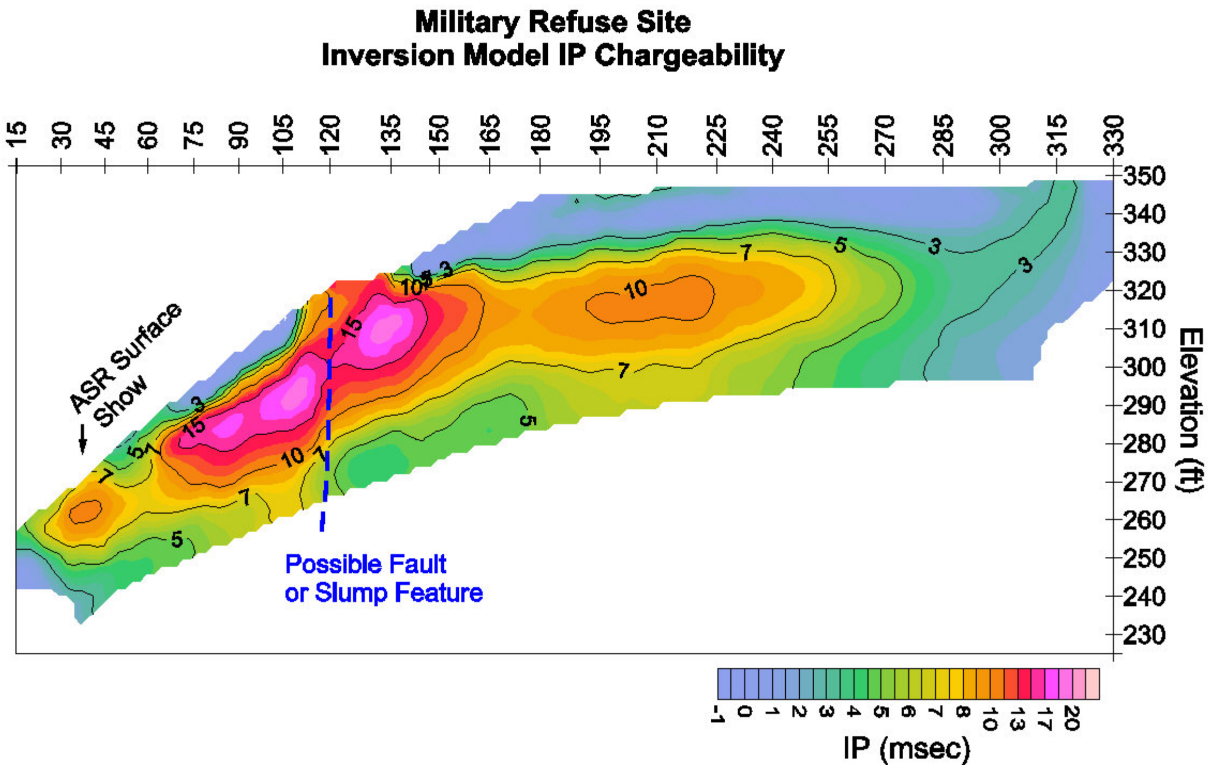

Figure 2. Inversion IP anomaly from a military refuse site. Data are 0.5 hertz, 15-foot dipole-dipole array data. (Station numbers are in feet).

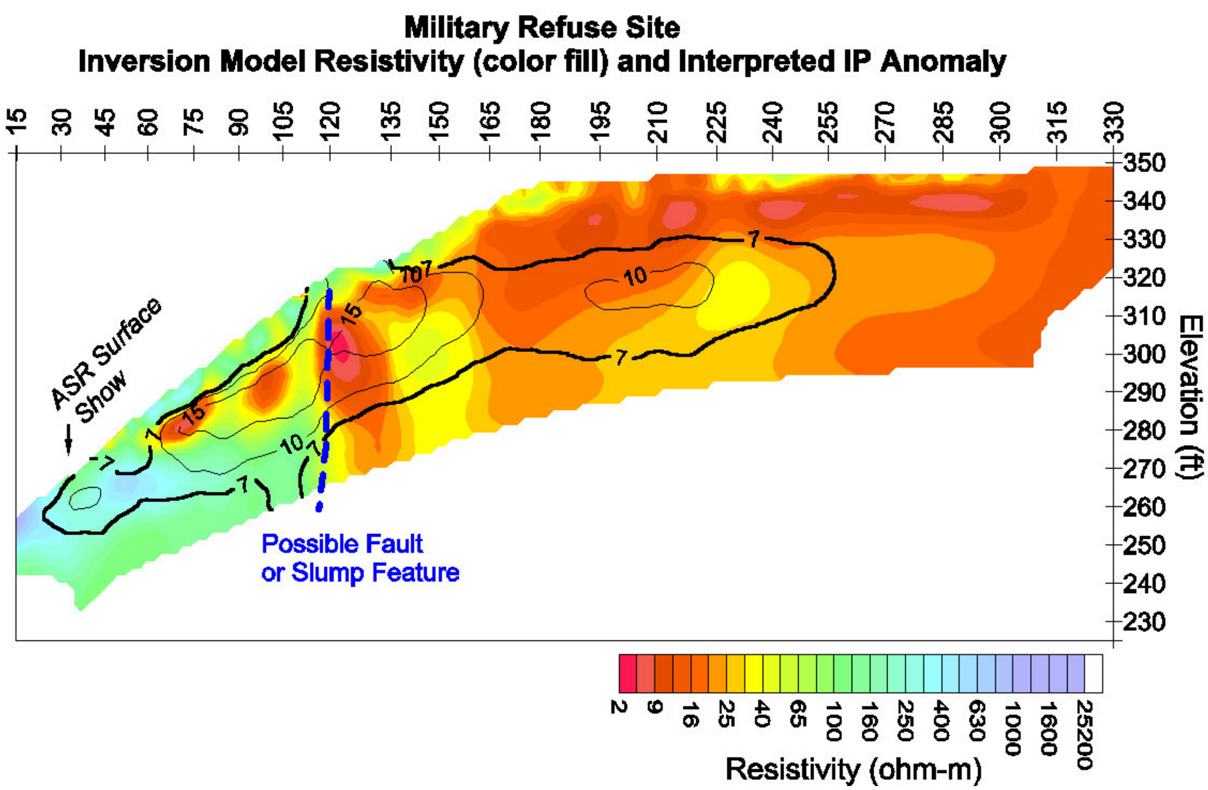

Figure 3. Resistivity (color-fill) and IP anomaly (black contours) from a military refuse site. Data are 0.5 hertz, 15-foot dipole-dipole array data. (Station numbers are in feet).

The apparent resistivity model is shown for the same line in Figure 3, along with an outline of the IP anomaly for comparison. The ASR surface show has relatively high resistivity, in the 200 to 600 ohm-meter range. The resistivity picture (Figure 3) here is complex, and interpretation of the resistivity alone would be difficult. Moderately high IP levels (7 to 15 msec) near the surface are generally correlated with high resistivity values (likely low to moderate metallic content ASR). Very high IP values (>15 msec) correlate well with isolated low resistivities (likely high metallic content ASR). Note that from about station 120 to the end, extremely low resistivities (2 to 30 ohm-meters) are most likely due to highly saturated ground. This section of the line is a heavily watered, grassy area at the site.

This particular example highlights the difference in information provided by IP and resistivity. The two data sets show two very different pictures; had we used only resistivity (or a conductivity system), we may have correlated the ASR surface show with increased resistivities, resulting in an incorrect interpretation that there is little or no ASR up-slope from the surface show. Similarly, had we relied only on IP data, we would have been unaware of the fault/slump feature, and the apparent presence of substantial moisture up-slope from the fault**.**

Interpretation of Large Data Sets

Delineating source material geometry from an IP anomaly can be complicated by source anomaly interference, limited resolution and decreasing resolution with depth, and variable amplitude IP response due to depth or differing source materials. In environmental work, an IP survey is often conducted before any excavation is performed. Lacking ground control, one problem is that the location of the actual trench or landfill, for example, is rather subjective. Interpretation of source extent can be made using several methods, including picking anomaly peaks or troughs, steepest gradients, or simply based on some amplitude threshold. An interpreter intuitively uses some form of these methods when interpreting model sections by hand. He may also use corroborating data to constrain the interpretation in particular locations, and calibrate his interpretation method for areas with no constraints.

Interpretation of a large grid from a high-resolution, environmental IP survey is time-consuming on a line-by-line basis, and due to the subjectivity, can be inconsistently interpreted. A "first-pass", semi-automated method for interpreting models would be useful. To this end, we are developing a semi-automated interface interpretation method using threshold amplitudes and gradients that is useful for processing many model lines quickly. We have found that an interpretation of waste boundaries based on a particular IP value (the "threshold") is sometimes too simplistic. In some cases, a more accurate boundary can be interpreted based on the gradient of the IP data; in several cases, the maximum gradient of the IP has shown the best correlation with the boundary between waste and non-waste material.

By automating the process for choosing the depth in inversion model results where the data is at a threshold, or at a given gradient, waste boundaries and waste volumes are substantially easier to estimate for large IP grids. The technique eliminates some of the interpretation subjectivity, and surfaces can be evaluated in map view for a quick analysis of site trends. Ground-truthing is necessary to determine whether the appropriate interpretation criteria were used. As illustrated by the seismic industry, automatic interpretation methods are, at best, to be used only as an aid to the interpreter.

Some simulations were conducted in order to evaluate which interpretation criteria work best for various simple earth models. The models were given similar parameters to actual environmental sites we have recently investigated. Figure 4 shows the inversion model IP anomaly from a simple two-layer, asymmetric trench with a true IP value of 12 msec. The forward model was generated by simulating 0.5 hertz, 15-foot dipole-dipole data. The best interpretation of the trench base is determined by using a threshold IP amplitude of about 5 msec. In general, for simple homogeneous bodies, using a threshold amplitude value works well.

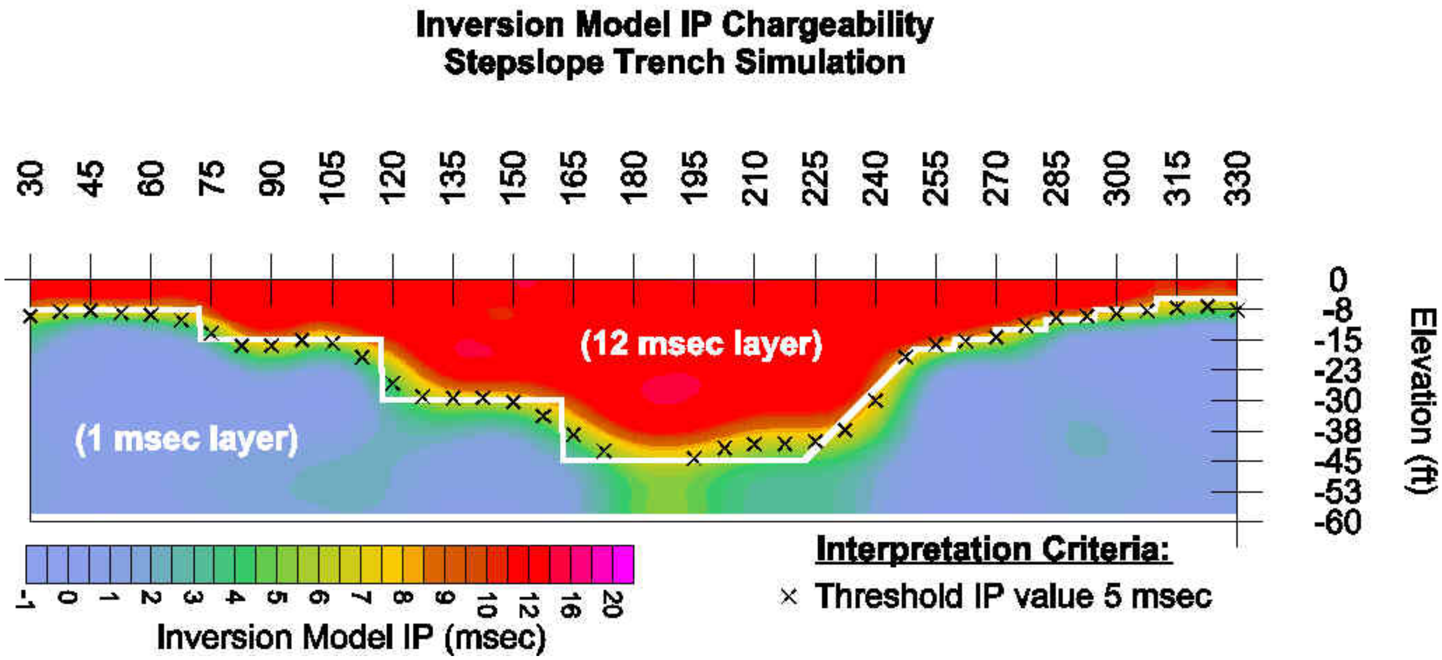

Figure 4. **Simulated simple trench-like body. The input for the forward model is shown in white, inversion model by color-filled contours, and trench base interpretation in black. Simulated data are 0.5 hertz, 15-foot dipole-dipole array data. Horizontal scale = vertical scale.**

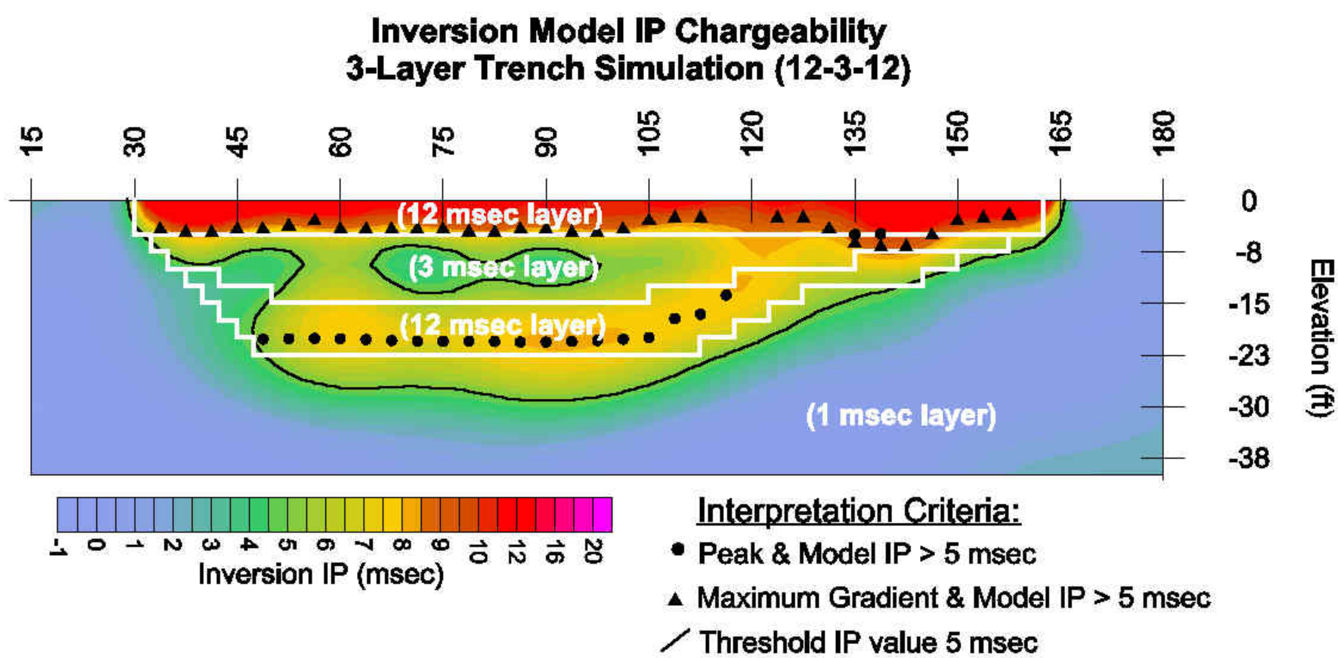

Figure 5. **Simulated three-layer trench-like body. The input for the forward model is shown in white, inversion model by color-filled contours, and trench base interpretation in black. Simulated data are 0.5 hertz, 15-foot dipole-dipole array data. Horizontal scale = vertical scale.**

For distinct bodies with different IP responses, or vertically inhomogeneous bodies, such as the simulated trench shown in Figure 5, then using a simple amplitude threshold for interpretation is not always optimum. Figure 5 shows the inversion model generated from an asymmetric, three-layer trench with a 3 msec layer in between two 12 msec layers. The results from three interpretation criteria are shown. In this case, the trench base depth is best picked by using the first IP peak located by searching upward from the bottom of the model results. This scenario has been observed by us on field data from a high-resolution IP survey over a landfill which had drilling data for corroboration. Note that the IP maximum gradient criteria picks the base of the upper layer quite well, while the IP peak closely fits the base of the bottom layer. A boundary pick based on a simple threshold value would be incorrect in this situation (shown by the solid black line in Figure 5). Our interpretation software allows selection of absolute values, "peak" or "trough" values (searching vertically either upward or downward), or gradients; in each case, the selection can be further refined by limits on the IP or depth values.

Summary

Although the IP method has been in use for decades, primarily by the minerals industry, significant improvements have been necessary before applying it economically in the environmental industry. Survey speed has improved, resulting in the need for improved interpretation techniques. Of particular importance is the need to accurately delineate horizontal and vertical boundaries of waste in order to assist in estimating cleanup costs or for site-use planning. Programs that allow rapid boundary interpretation of large data sets are being developed, and have already proved useful. In the field, research is continuing into how to increase data acquisition speed, in order to decrease field costs. One lingering problem is the stability of electrodes, which is certainly one of the factors that have limited the use of IP in these types of surveys in the past. By correcting this problem logistically, survey grid costs have decreased to around $1,000.00 US per acre; an additional 10% to 20% cost reduction may be possible if a truly stable, but inexpensive, electrode system can be developed.

Acknowledgments

We would like to acknowledge the help and assistance received from the City of Tucson's Office of Environmental Management and the Department of Solid Waste Management; Richard Byrd, Fran LaSala, Karen Masbruch, Chris Leverenz, and David Bell have been especially helpful in development of our IP work. John Patskan of the U.S. Navy Public Works Center provided useful background information, and has allowed us to discuss some of the data presented here.

References

1. Angoran, Yed E., Fitterman, David V., and Marshall, Donald J., 1974, "Induced Polarization: A Geophysical Method for Locating Cultural Metallic Refuse", *Science*, 21 June, vol. 184, pp. 1287-1288.

2. Carlson, Norman R., Mayerle, Cris M., Zonge, Kenneth L., 1999, "Extremely Fast IP Used to Delineate Buried Landfills", in Proceedings of the 5th Meeting of the Environmental and Engineering Geophysical Society European Section, Budapest, Hungary.