The Performance of Electrical Methods for Assessing the Integrity of Geomembrane Liners in Landfill Caps and Waste Storage Ponds

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ABSTRACT

Geomembrane leak location methods have been established based on injecting electrical current through the liner into the surrounding soil and then, using pairs of electrodes above the liner, high potential gradients associated with current leakage may be identified. Recently, permanent electrode arrays have been installed at a number of sites as a means of long term monitoring of the integrity of a landfill liner. There has, however, been no scientific study to date which addresses the performance of such systems. Here, we utilise a physical scale model of a landfill liner/cap and investigate the usefulness of grid based and boundary electrode arrays for detecting multiple leaks in a landfill liner or cap. We compare the two electrode geometries under a series of controlled electrical leak experiments and demonstrate how both these arrangements can detect and locate leaks in a geomembrane. We also demonstrate some of the limitations of the method. For example, present data processing schemes can give misleading results when there are multiple leaks. The influence of variation in resistivity of the soil above or below the liner and also boundary current leakage on the performance of the technique is also studied. The results suggest that these two factors, unless they are accounted for, can have a significant impact on the results and subsequently affect the practical value of electrical leak detection systems.

Introduction

Large quantities of solid and liquid wastes are stored in ponds and lagoons world-wide. In many cases synthetic liners are used to prevent the waste from leaking out of the storage facilities and entering the environment, which could have devastating affects on the quality of local groundwater and thus the public water supply. Since these man-made liners will degrade eventually with time, and naturally are prone to damage throughout the working life of the waste facility, it is essential that techniques are available to periodically assess the integrity of liners and locate possible leaks. Giroud and Bonaparte (1989) estimate leakage rates through common defects in a typical landfill liner, as shown in Table 1. The potential for high mass flux of contaminants into aquifers is clearly significant and reliable methods are required to assess damage to liners during the working life of a landfill and also post-closure. In addition, there is a need to be able to assess the performance of geomembranes used for landfill caps (barriers to prevent vertical flow into a completed landfill).

Since many stored wastes have a high electrical conductivity contrast with soil water, resistivity imaging has been used in a number of studies to reveal leakage from surface and subsurface storage facilities; see for example Van *et al.* (1992) and Ramirez *et al.* (1996). These methods rely on assessing changes in the subsurface resistivity to monitor contaminant plumes. In most cases an assessment of the integrity of an environmental barrier is required over a short term period, without a leak ("before plume" data). Without such data it is often difficult to detect the plume. Leaks from barriers may also be from a relatively small discharge, making resistivity contrasts undetectable, but still significant from the potential pollution threat. In addition, there has been relatively recent interest in leakage from water storage facilities and pipelines; in many such cases resistivity imaging will not provide conclusive results, again due to the minor changes likely to result in the bulk resistivity of the subsurface.

Geomembrane leak location methods have been established based on injecting electrical current through the liner into the surrounding soil and then, using pairs of electrodes above the liner, high potential gradients associated with current leakage may be identified. The methods are based on the original work of Para (1988) and mobile systems are now used routinely for quality assurance testing following liner installation (see for example, Laine, 1991). These methods have also been used during the active life of landfill systems (for example, Laine *et al.*, 1997; Colucci *et al.*, 1999). Figure 1 illustrates the electrical leak detection concept for both landfill liner and cap systems.

More recently, permanent under-liner electrode arrays have been installed at a number of landfill sites to allow long term monitoring of leakage. Frangos (1992, 1997)

Table 1. Leakage rates (in litres ha^{-1} day^{-1}) through a 1 mm HDPE geomembrane (after Giroud and Bonarparte, 1989)

	Water depth above geomembrane (m)				
Flow path	**0.003**	**0.03**	**0.3**	**3**	**30**
Permeation	0.0001	0.01	1	100	300
Pinhole	0.01	0.1	1	10	100
Small hole	100	300	1,000	3,000	10,000
Large hole	3,000	10,000	30,000	100,000	300,000

documented the earliest demonstration of such an approach. Others, for example, Nosko (1996) and White and Barker (1997) have reported similar studies.

The permanent approach can be expensive to implement and is clearly not applicable in existing sites, where retrofitting is not an option. However, a permanent system has several advantages. First, because such a system can be easily automated to run autonomously or controlled remotely, it is not necessary for regular deployment (with attendant costs) of a liner inspection crew. Second, an automated system would not require an inspection crew to be exposed to toxic materials in a storage facility. Third, an automated system would allow nearly continuous monitoring instead of occasional inspection. The electrical leak detection and location methods discussed herein are especially suited for permanent monitoring systems for geomembranes used as liners in ponds, landfills and caps. A tomographic variant of traditional, permanently-installed, electrical leak location methods was first proposed by Binley *et al.* (1997). In this approach electrical potentials are collected around the perimeter of the site, either inside or outside the storage pond/landfill, and then, with suitable inverse methods, the locations of leaks in the geomembrane are computed that best satisfy the measured data. It is this method, with several variations, that will be studied herein.

Commissioned by the UK Environment Agency, Bishop (2002) recently compiled an extensive review of electrical leak location methods for testing geomembranes. From this report it is clear that little is understood about the reliability of permanent monitoring systems. Several applications have used single test leaks to demonstrate success without assessing how multiple leaks in the system may degrade the overall performance, how leakage of current through boundaries may limit the method and the impact of subsoil heterogeneity on the performance of leak location systems. More alarming perhaps is that no attempt appears to be made in any industrial systems to assess the uncertainty in leak location, *i.e.*, the reliability of the solution of the inversion algorithm. We address these issues here by comparing two electrode arrays in a laboratory scale physical model. The two arrays represent a permanent under-liner (or above cap) configuration and a boundary-only arrangement.

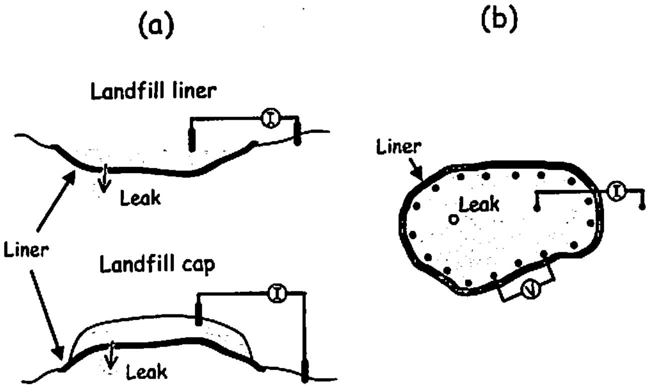

Figure 1. (a) Schematic of electrical leak imaging method for both landfill liner and cap testing. Electrical current is injected as shown. (b) Schematic of tomographic electrical leak imaging system proposed by Binley *et al.* (1997). Electrical potential gradients are measured on the electrodes inside the edge where the membrane is exposed (as is shown here) or just outside that boundary.

Methodology

Experimental Setup

A scale model was constructed as follows. Forty eight stainless steel electrodes were installed in a 1 cm deep plastic container, 0.9 m by 0.44 m in plan, partially filled with tap water. Twenty four of the electrodes were installed around the perimeter of the container and the remaining twenty four electrodes fitted internally, as shown in Fig. 2. The container was placed on the water surface of a large (3.5 m diameter, 3 m deep) water tank (representing a uniform half space around the model landfill).

To represent leaks from the container to the surrounding fluid, other stainless steel electrodes were located at sites A, B, C, D and E as shown in Fig. 2. Based on earlier calibrations of the system, a 200 kΩ resistor was fitted in series to each test leak electrode in order to represent equivalent electrical leakage to that through a 2 mm diameter hole.

The system was designed to represent the two cases: (1) a leaking landfill liner and (2) a leaking landfill cap. For a leaking landfill liner, the internal electrodes model a permanent under-liner system. For the leaking landfill cap, the internal electrodes represent a grid of electrodes placed above a landfill cap liner. The boundary electrodes represent a retrofit solution for an existing landfill cap or a retrofit solution for a landfill/pond liner.

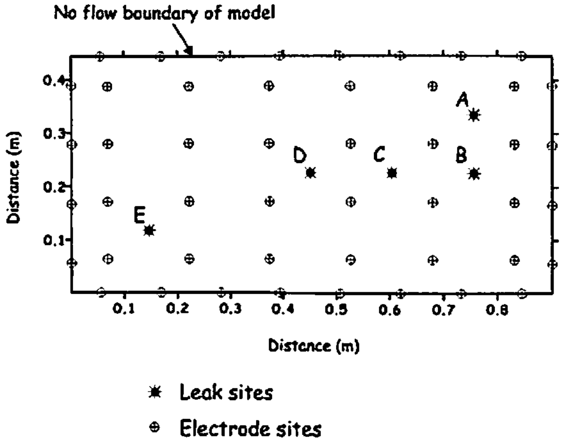

Figure 2. Experimental set-up for laboratory leak tests.

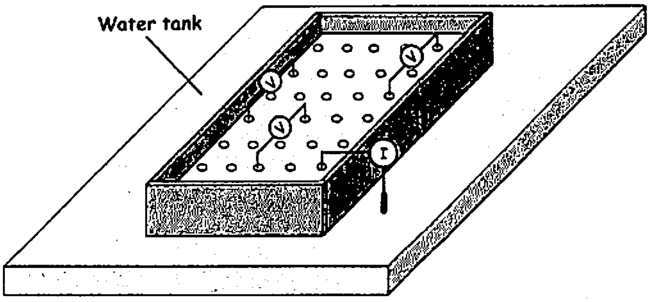

Figure 3. Illustration of measurements for internal electrode arrangement.

Using this arrangement, a series of experiments were conducted to assess:

(i) For a uniform resistive fill in the container, how accurately can we distinguish multiple leaks with the internal array or the perimeter array?

(ii) If the resistivity of the fill is spatially variable, does the performance of the leak location degrade?

(iii) If electric current leakage around the perimeter of the container occurs, how does this affect performance and, if so, how can we correct for this boundary leakage?

For each leak arrangement, transfer resistances were collected by using one of the internal (or boundary) electrodes as one current electrode and an electrode placed in the surrounding water as the other current electrode. Voltages were then measured between pairs of internal (or boundary) electrodes. The procedure was repeated by using each internal (or boundary) electrode in turn as a current electrode. The spacing of voltage measurement dipoles was two electrodes, as shown in Fig. 3 for the internal electrode arrangement. This resulted in 504 measurements for both internal and boundary electrode cases. The injected waveform used was a switched DC type, 2 Hz frequency. Using a constant voltage source (50 V) current magnitudes varied but were typically 0.2 mA.

Numerical Modelling

A finite element based forward model of 2-D current flow in a 2-D resistivity field was used to analyse potential fields in the container due to different current electrode positions. For each measurement the position of one current electrode was known, and the other current "electrode" was the leak or leaks in the container. By designating a fixed number of possible leak locations we computed the potential field for any combination of leaks (each with differing conductance) by using the principle of superposition. To model the system, a finite element mesh containing 2,176 elements and 2,077 node points was used. To represent possible current source locations, 136 of these finite element nodes were used as shown in Fig. 4 for the internal electrode grid. Note that the assumption of 2-D variation in resistivity is valid for the physical model used here but in a real environment 3-D variation will exist.

The inverse problem here is the determination of the magnitude of current at all of these possible source nodes. Various approaches to the inverse problem may be taken. Conventional gradient-based least squares techniques may appear appropriate, however, they require constraints within the inversion since the current magnitude must be positive. In addition the solution must be stabilised in some manner, such as through regularisation.

Alternatives to gradient methods are the increasing range of "global optimum" methods based on controlled Monte Carlo sampling within the parameter space. Methods such as Simulated Annealing and Genetic algorithms may be considered within this class of techniques. These methods are reasonably straightforward to apply and ideally suited to constrained problems such as the one posed here. Our initial experience with this type of approach was encouraging (see Binley *et al.*, 1997) however continued experimentation with a range of inverse methods revealed a small number of cases where apparently optimum results were inconsistent with known leak locations. The cause of this is believed to be the non-uniqueness of the solution coupled with inevitable, yet poorly assessed, data errors. In other words, the solution of the inverse method may indeed fit the data well, but many other solutions (including those representing the real case) which have been rejected by the inversion procedure may fit the data equally well.

For successful industrial application of this method the imaging procedure must produce a degree of trust in the result. Incorrect assessment of leak locations has severe financial and environmental implications, in particular when waste material (solid or liquid) has to be removed temporarily in order to repair the liner material. In addition, data processing must not require expert knowledge of

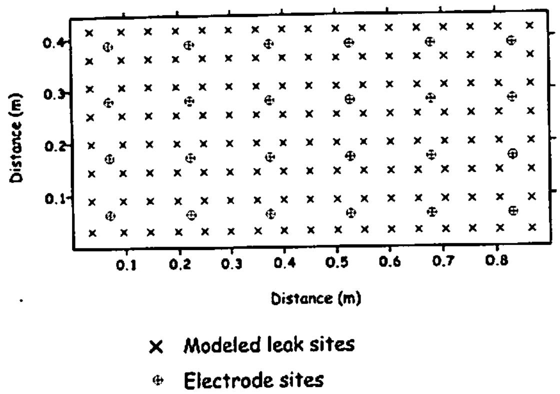

Figure 4. Distribution of possible leak source nodes used for modelling, also shown is the internal electrode layout.

inversion parameters and the consequence of inappropriate choice of such factors.

Given these constraints, an approach was devised to sample the parameter space (different leak locations, each of different magnitude) and assess the likelihood of an electrical current source at each of the possible leak sites. If only one leak exists in the system, determining its location is trivial (as shown later), the problem becomes much more complex, however, if multiple leaks occur. The possibility of multiple leaks has been somewhat overlooked in a number of previous studies where the performance of permanent electrode systems has been assessed based on the ability to locate only one test leak.

For each possible combination of leak sources a measure of misfit between the model and the data is required. Here, the product-moment correlation of data to model is used; this is expressed as:

$$r_k = \frac{\sum_i (D_i - \bar{D})(F_i(I_k) - \bar{F}(I_k))}{\sqrt{\sum_i (D_i - \bar{D})^2 \sum_i (F_i(I_k) - \bar{F}(I_k))^2}} \qquad (1)$$

where D_i is the i^{th} measured transfer resistance and $F_i(I_k)$ is the i^{th} transfer resistance due to unit current at location k computed using the forward model, $\bar{D}$ and $\bar{F}$ are the mean measured and computed transfer resistances, respectively. For M possible current source nodes the value of r_k may then be computed. We therefore expect that, for the case of a single leak, the highest positive correlation will be associated with the source node closest to the location of the leak. A map of the spatial pattern of the correlation function should then reveal the leak location.

For cases where more than one leak occurs a map of the correlation function in (1) is inappropriate since only one "optimum" will be apparent. It is therefore essential that the correlation function, produced in this way, can be made reliable. Note that calculation of the correlation function is not computationally demanding once the forward solutions have been determined for the M possible source nodes.

The approach adopted here consists of carrying out a search of the goodness of fit between the data and a model for different leak combinations and different leak magnitudes. Once this search is considered complete we do not determine the "optimum" solution but rather how frequent each possible leak location occurs in the top ranking models. The procedure is as follows:

(i) Generate a correlation map for single leak sources, as described above. This will be used to assist sampling combinations of possible leak sites.

(ii) Generate a large number of realizations of leak combinations and leak magnitudes. The minimum number of leaks is 2, and here we set a maximum number of leaks to be 10 (since we assume that it is unlikely that more will exist in the system). The number of leaks N for each realisation is selected randomly. The correlation map in step (i) is used to create a pseudo prior probability for each source location. We assign $0.5 \times (1 + r_k)$ (*i.e.*, with a range 0 to 1) to this probability. For each of the N sources we randomly select a source node from the set of M possible sources. We then assess the viability of using each of these source nodes in turn by generating a uniform random number U in the range 0 to 1. If U exceeds the prior probability for this source location then this source node is not used, otherwise a current strength of U is assigned. This means that all source nodes with a low prior probability will be used relatively less than those with a high prior probability, and when they are used they are more likely to be assigned a low current. For all cases considered here the total number of Monte Carlo realizations used for each case is 10^8. This number was selected on the basis of preliminary trials. With 10^7 realizations and above, little difference was seen in the results.

(iii) For the given set of N source nodes the current is rescaled so that the total current is unity. The goodness of fit between this model and the data is then computed through superposition of the M forward models used in step (i).

(iv) Steps (ii) and (iii) are repeated for all realizations.

(v) For the set of top ranking realizations (here we consider the best 10^4 in terms of their goodness of fit) we then examine each of the M source nodes in turn and build a histogram of current strength. This is illustrated in Fig. 5, for a single leak test using internal electrodes. In Fig. 5 histograms of current magnitude are shown for two sites. At one of these sites there is clearly a high likelihood of significant current leakage.

(vi) The final stage of the procedure consists of determining, at each of the modelled source locations, the proportion of the 10^4 realizations that carry a significant current (here we used 10% of the total applied current). This then permits a map to be formed which will reveal a high probability of significant current leakage.

Results

Internal Electrode Array

Figure 6 shows the correlation function in (1) plotted for two of the cases. In Fig. 6a the correlation function is shown for a single leak at site A (see Fig. 2). For this case the optimum goodness of fit clearly matches the actual source location. For a combination of multiple sources (at A, B, C and D in Fig. 2) Fig. 6b shows that the correlation is poorly suited for leak location, as would be expected. For cases with one major source location (one dominating leak) simply plotting the correlation may then be a robust solution. However, in most practical realistic field applications the number of leaks will not be known, in addition, the relative (electrical current) magnitude of each leak will also not be known.

Applying the Monte Carlo search procedure outlined in the previous section to single and multiple leak cases, we may assess the ability to resolve the individual leak source locations. Fig. 6c; d and e shows the results for one, two and four leak cases using the internal electrode array. In Fig. 6c the search reveals a single area, which covers the true leak site, of likely current leakage. In Fig. 6d, for the dual leak case, a single zone again results but the position is shifted to overlap the two leak sites. From this result it is clear that there is insufficient signal to permit differentiation of the two leaks and emphasises the caution that must be used when analysing electrical leak data with optimum search algorithms.

For the four leak case (see Fig. 6e) we are able to differentiate three leak zones which fall well within the areas of applied current leakage. Note that the differentiation of leak zones along the long axis of the model landfill is much better than along the short axis. We attribute this to the alignment of voltage dipoles used for the internal array (see Fig. 3) and would expect some improvement if an additional set of dipole measurements were taken oriented along the shorter axis.

Boundary Electrode Array

Figure 7 shows the correlation function in Eq. 1 plotted for two of the cases considered using an array of electrodes located around the perimeter of the model landfill. As in the previous case the function works well to identify a single leak case (Fig. 7a) but is clearly inappropriate for the multiple leak case (Fig. 7b). Figure 7c, d and e shows the Monte Carlo search results, which should be compared with those for the internal electrode array in Fig. 6. For the boundary array in Fig. 7 there is a marked difference between the responses for one and two leak cases but insufficient signal to be able to confidently identify two leak zones. In Fig. 7e, for the four leak case, the entire region of leakage is mapped well but individual areas of leakage would clearly be falsely predicted by an optimum search algorithm.

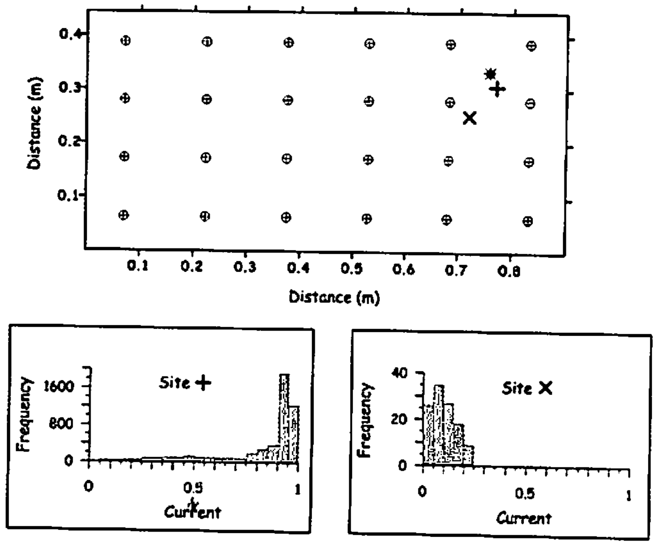

Figure 5. **Illustration of current magnitude histograms for two locations for single leak case using internal electrode array. Symbol ✱ indicates true leak location.**

Although these results highlight weaknesses in a procedure based solely on perimeter measurements our findings do suggest that broad areas of suspect leakage may be adequately identified, even for multiple leaks. Such measurements may then be more appropriate for reconnaissance surveys which serve to identify areas requiring more detailed investigation using mobile electrical surveys deployed within the landfill.

The Effect of Non-Uniform Resistivity

The spatial variability of resistivity within a landfill or above a landfill cap is inevitable and yet the impact of such variability appears to have been neglected in previous studies of electrical leak location methods. In many cases we would expect significant variability in resistivity, particularly above a landfill cap where differences in thickness and water saturation levels are likely to exist. Fortunately, it should be possible to utilise the electrodes installed for electrical leak location to assess the variability in resistivity and then incorporate that within the forward model for leak location. So far, however, previous studies have only used electrode arrays to provide additional information about possible leaks from a landfill, say by mapping leachate plumes, rather than using the results to improve the detection capabilities.

To investigate the effect of non-uniform resistivity on the response of the landfill model we carried out experiments

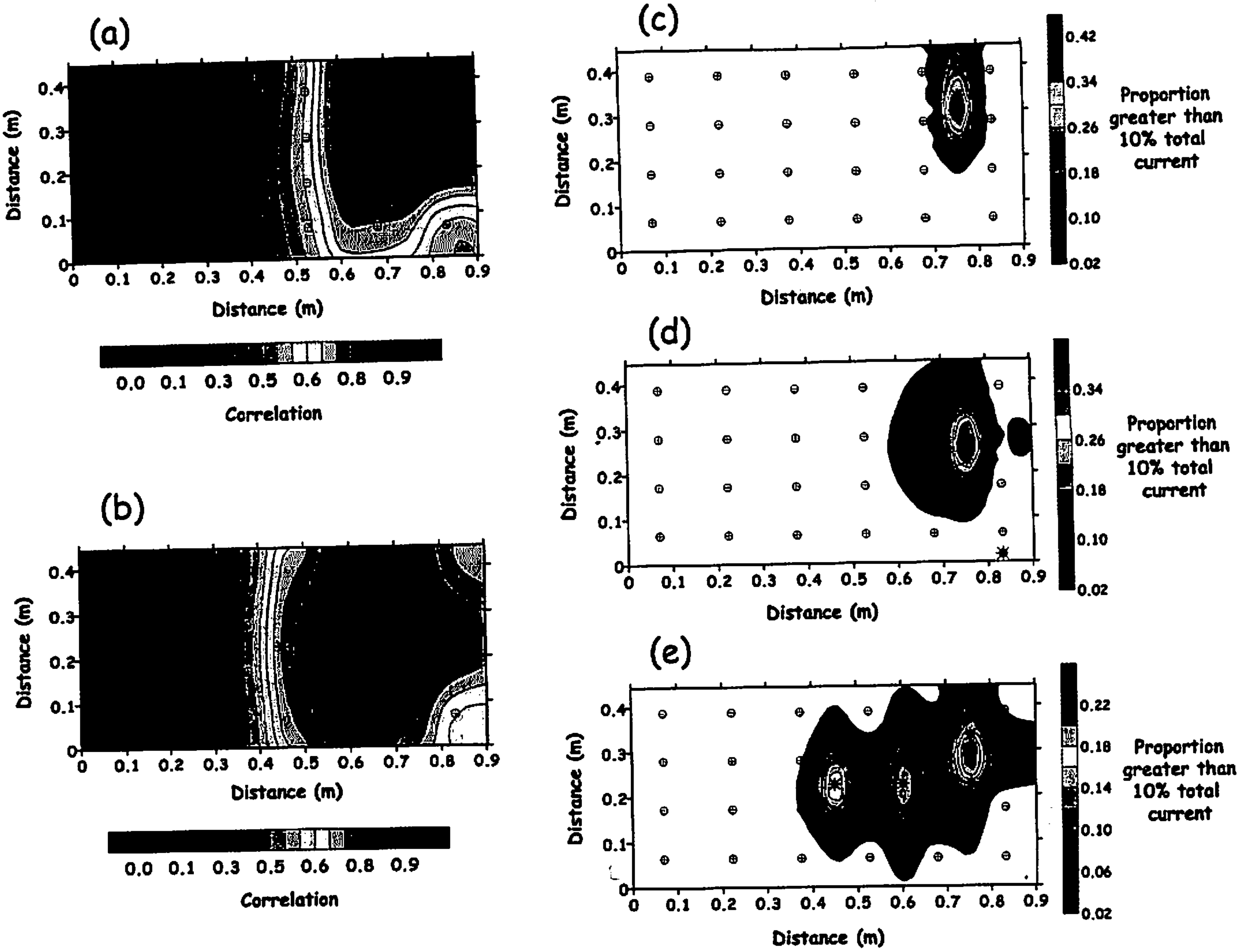

Figure 6. Internal electrode array results. (a) Correlation function for one leak case, (b) correlation function for four leak case, (c) Monte Carlo search results for one leak case, (d) Monte Carlo search results for two leak case and (e) Monte Carlo search results for four leak case. Symbol ✱ indicates true leak locations.

identical to those reported in the previous two sections, but with an arrangement of plastic blocks inserted in the water filled container. Figure 8a shows the arrangement used. To determine the resistivity distribution within the water/plastic filled vessel, electrical resistance tomography (for example Daily *et al.*, 2003) was used with all twenty four boundary electrodes, adopting a dipole-dipole measurement scheme with a dipole length twice the distance between pairs of electrodes. Figure 8b shows the resulting 2-D resistivity image. The image identifies three regions of relatively high resistivity caused by the large plastic blocks, but fails to resolve the smaller blocks. In addition, a resistive zone in the lower left region of the container is evident and a conductive region along the rightmost boundary. We attribute these two features to water level variation in the vessel. It was difficult to maintain the vessel level during the experiment.

With this variable resistivity arrangement, and using the same boundary electrodes, electrical leak data were collected for a one leak and a four leak case. Figure 9a and 9b shows the results of the Monte Carlo search assuming a uniform resistivity. Comparing Fig. 9a with Fig. 7c and Fig. 9b with Fig. 7e there is little effect of the non-uniform resistivity on the results. In the one leak case (Fig. 9a) the leak detection is in fact improved due to the effect the non-uniform resistivity. However, the resolution of leaks is weaker in the four leak case as only two local optima are resolved (see Fig. 9b), in comparison to three optima in Fig. 7e. Similar findings were observed using the internal electrode array.

To address this potential degradation in the ability to resolve leaks under conditions of non-uniform resistivity the electrodes may be utilized for resistivity imaging and

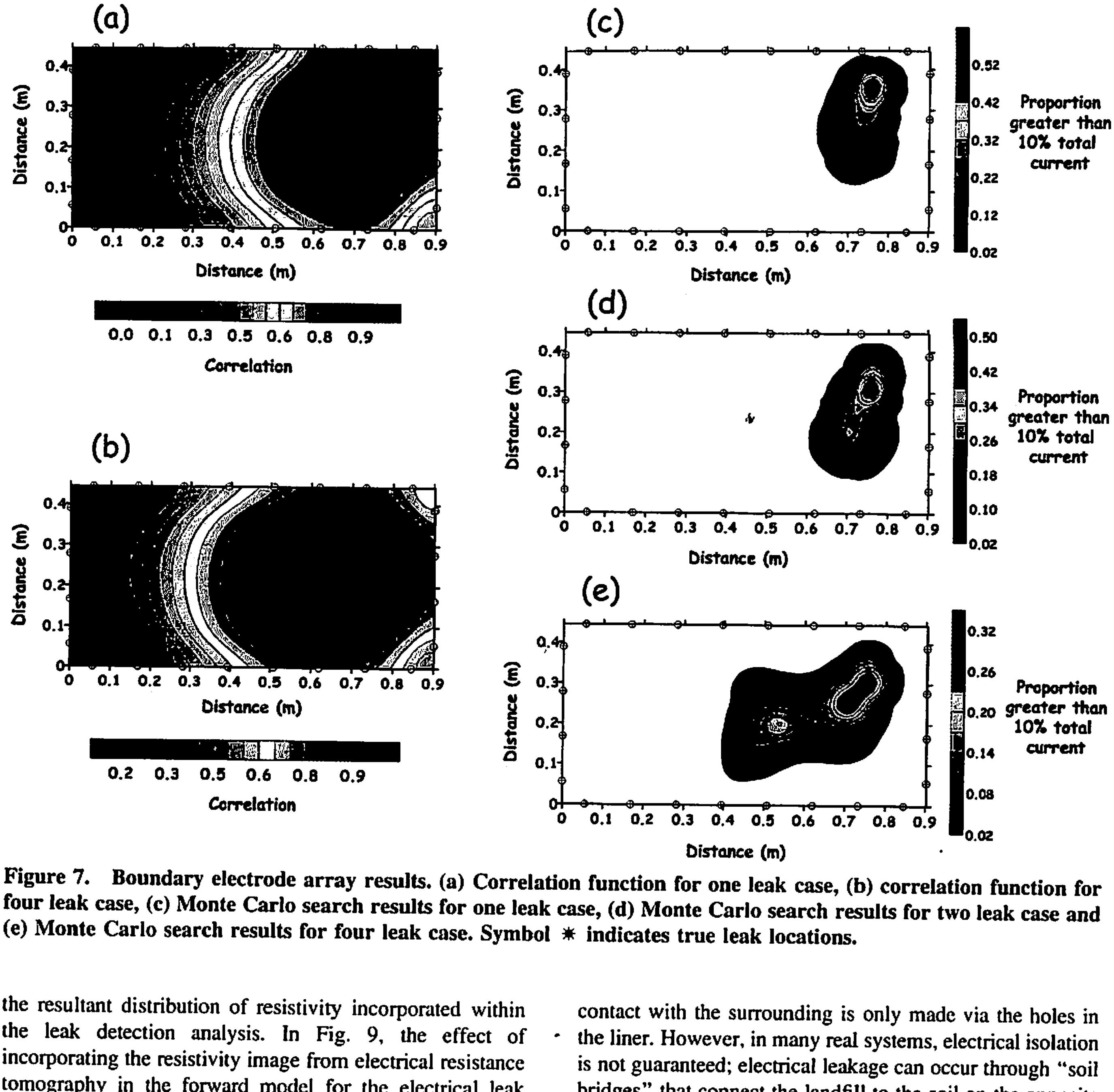

Figure 7. Boundary electrode array results. (a) Correlation function for one leak case, (b) correlation function for four leak case, (c) Monte Carlo search results for one leak case, (d) Monte Carlo search results for two leak case and (e) Monte Carlo search results for four leak case. Symbol ✱ indicates true leak locations.

the resultant distribution of resistivity incorporated within the leak detection analysis. In Fig. 9, the effect of incorporating the resistivity image from electrical resistance tomography in the forward model for the electrical leak problem can be seen. Comparing Fig. 9a with Fig. 9c and Fig. 9b with Fig. 9d minimal improvement is seen for both single and multiple leak cases. We therefore may conclude that the spatial variability of resistivity may alter the performance of the leak location system and, at least for the case considered here, incorporating knowledge of the resistivity distribution does not significantly improve the success of the method.

The Effect of Boundary Leakage

So far it has been assumed that the boundary of the model landfill is a perfect insulator and thus electrical contact with the surrounding is only made via the holes in the liner. However, in many real systems, electrical isolation is not guaranteed; electrical leakage can occur through "soil bridges" that connect the landfill to the soil on the opposite side of the liner. These bridges are due to movement of soil which previously covered the cap or deliberate placing of soil over the liner edge to secure the membrane along the periphery. We illustrate the bridging effect here with a single leak located at site E (see Fig. 2) using internal electrode data. Boundary leakage was created by raising the level of fluid within the landfill model to that in the surrounding water tank.

The correlation function in Eq. 1 is shown for this case in Fig. 10. A relatively constant and low correlation is seen for all possible source locations. Resolving any leaks internally is clearly unachievable. While this is an extreme

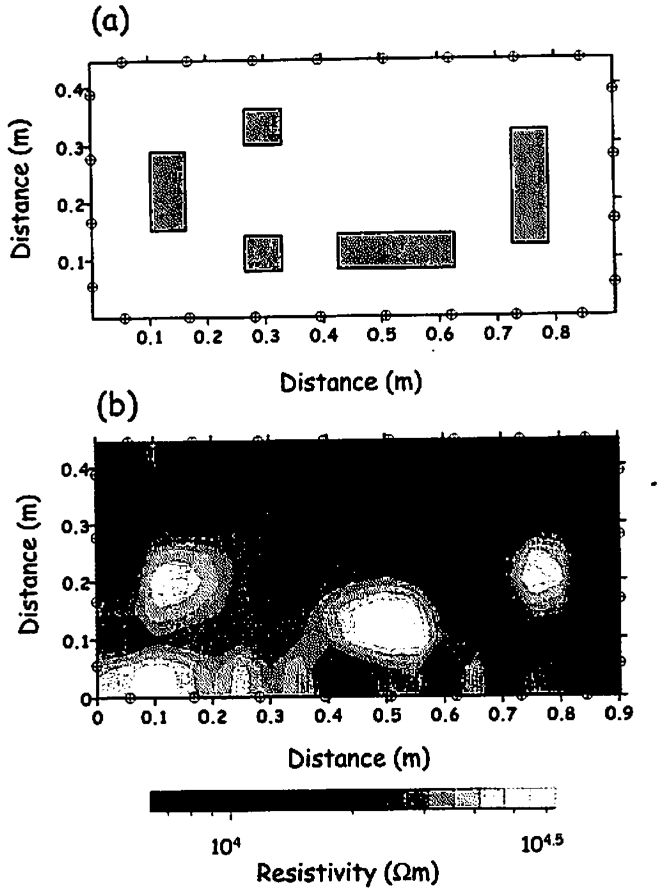

Figure 8. Non-uniform resistivity experiment: (a) arrangement of plastic blocks and (b) resistivity distribution determined from boundary electrode measurements.

case (since in many real cases boundary leakage will probably be isolated to sections of the perimeter) it does illustrate a potential weakness in the electrical leak location method. If the boundary leakage current (and distribution) were known then it would be possible to incorporate this within the forward model. Unfortunately current flowing across the boundary is not easily measured. However, if the electrical potential along the perimeter is raised to a known level by installation of a continuous electrode around the perimeter, then this could be incorporated easily within the model.

To investigate this approach measurements were retaken with the same physical set-up but with an additional wire electrode around the perimeter just at the water's surface and kept at the same potential as the (moving) current electrode placed inside the vessel in the water tank (see Fig. 3). With this arrangement the boundary of the landfill model is raised to the same electrical potential as the internal current electrode and the boundary electrode acts as a guard electrode for current flowing across the boundary. The effect of such a modification is shown in Fig. 10b, which except for the boundary leakage and boundary guard electrode, corresponds to the same physical arrangement in Fig. 6a. The correlation plot now clearly identifies a maximum near the location of the true leak even though the vessel has a non-insulating boundary. The response is much poorer than the true isolated case (Fig. 6a) but nevertheless shows significant improvement over the non-isolated case in Fig. 10a.

Discussion and Conclusions

A series of electrical leak location experiments, using a laboratory scale physical model of a landfill liner or cap, has produced a number of important results which, we believe, will impact further development of this technique for practical application.

Single leak problems are simple to solve for a reliable and accurate location and for such cases boundary electrode arrays perform as well as internal arrays. Using single leak cases as test problems for a leak detection system has some value for real systems since often one leak will dominate so that leaks can be located sequentially. The first survey would locate the dominant leak. After this leak is repaired, another survey is used to locate the dominant leak of those remaining. This process is continued until all of the detectable leaks are located and repaired. However, to best exercise a leak detection and location system more elaborate tests should be made to demonstrate the suitability of the system for multiple leaks.

As expected, an array of electrodes installed internally is far superior for detecting multiple leaks in a landfill liner or cap, compared to electrodes installed along the perimeter. However, care must be taken in applying optimal search inverse methods to such systems. Our Monte Carlo search approach permits a comparison of the goodness of fit for different solutions, using different measures, and from such a comparison there is clear non-uniqueness in the solution. Many different combinations of leak sources and strengths can produce virtually identical measures of goodness of fit. If such optimal search methods are to be used, the operator must be satisfied (and be able to demonstrate) that the solution found is a global optimum. If this is not possible then we recommend Monte Carlo methods, modified to constrain the parameter space search. These should not be used to find an optimum but rather to assess a range of model responses that are consistent with the data.

Boundary electrode arrays, for the cases considered here, can be used to map zones of potential leakage but are unlikely to resolve the location of multiple leaks. Such an approach does have potential, however, as a reconnaissance method prior to more detailed, possibly invasive, investigation in localised regions of a landfill. As leaks become

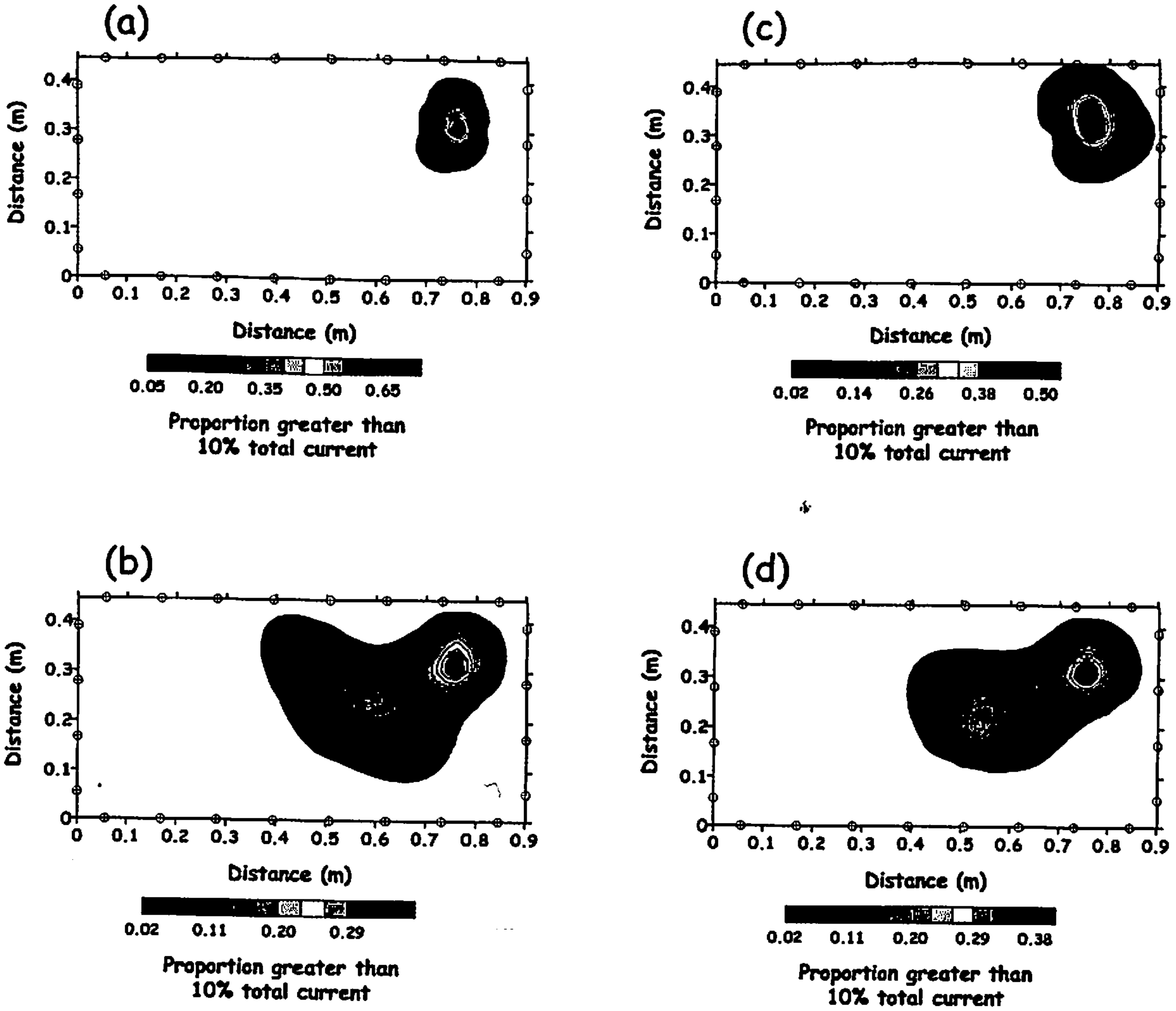

Figure 9. Monte Carlo search results with non-uniform resistivity due to plastic blocks in Fig. 8a. (a) One leak case and using boundary electrode array and assuming uniform resistivity, (b) four leak case using boundary electrode array and assuming uniform resistivity, (c) one leak case and using boundary electrode array and assuming resistivity distribution in Fig. 8b, (b) four leak case using boundary electrode array assuming resistivity distribution in Fig. 8b. Symbol ✱ indicates true leak locations.

identified in this way, they may then be repaired and/or electrically isolated and the survey repeated to improve sensitivity to remaining leaks. In some cases, installing electrodes under a liner is not viable due to cost or the fact that the landfill has already been constructed. Boundary arrays may also be used for waste pond problems in cases where access within the region of potential leakage is not possible because electrodes cannot be safely installed in very toxic waste.

It is reasonable to expect that electrical leak detection methods are sensitive to the variation in resistivity of soil surrounding the electrodes. Electrical resistivity imaging techniques may be used to assess such variation and then incorporated within the leak location analysis. Such attempts here show limited value of such an approach. However, we studied only a single example and we believe that making the same conclusion for all cases would be dangerous. More significant is the effect of non-isolating boundaries on leak location sensitivity. Our trials have shown how such sensitivity is reduced for a relatively simple arrangement. To overcome such problems we propose the use of a guard electrode installed around the perimeter of the landfill. Initial trials with such an arrangement applied to our laboratory scale model have proved successful, although we recognise that field scale tests must now be performed.

Mobile electrical leak location techniques are recognised as standard tools for periodically determining the performance of electrically insulating barriers, such as those used in landfills, ponds and caps (Bishop, 2002).

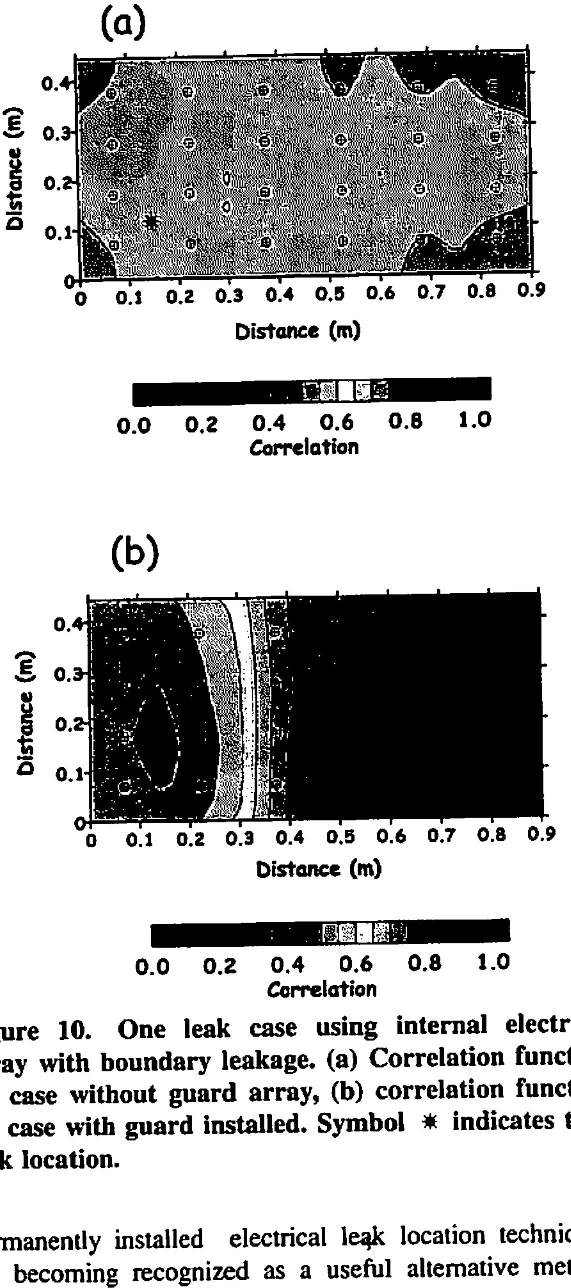

Figure 10. One leak case using internal electrode array with boundary leakage. (a) Correlation function for case without guard array, (b) correlation function for case with guard installed. Symbol ✱ indicates true leak location.

Permanently installed electrical leak location techniques are becoming recognized as a useful alternative method because they are more suited for long term monitoring of performance. Electrical leak location systems can be especially valuable because they can be easily automated and controlled remotely. A data acquisition system may be permanently installed at the site and connected by standard telephone lines to some central computer. We have recently used such a system for monitoring leaks in an underground storage tank and expect to see many more applications in the near future.

Given such advances in technology and the apparent success of a few recent studies, we have no doubt that permanent electrical leak detection systems will become even more widely used. However, our results suggest that the identification of multiple leaks in a complex heterogeneous environment is not a trivial task. There is a danger that such methods will be accepted in industry before a full scientific evaluation has been made of their limitations and detective capabilities. We strongly urge others to carry out further evaluation of these methods.

Acknowledgments

This work was performed under the Earth and Environmental Sciences Directorate at Lawrence Livermore National Laboratory for DOE grant SF-20-SS01, Mike Serrato, Subsurface Contaminants Focus Area, Project Manager. The work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48. We are grateful to Abe Ramirez for useful contributions that improved the manuscript.

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