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Detecting Leaks from Waste Storage Ponds using Electrical Tomographic Methods

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Abstract *– Methods for detecting and locating leaks in lined waste disposal ponds have been established based on injecting electrical current through the liner into the surrounding soil and then, with the aid of an under-liner array of electrodes, mapping electrical potential. High potential gradients then reveal likely location of leak spots within the liner. The approach is very expensive and is clearly not applicable in existing sites, where retrofitting is not an option. A tomographic variant of this electrical leak location method has been developed whereby electrical potentials are collected around the perimeter of the site and then with suitable data processing the locations of a leak within the pond is computed. Applications on a controlled laboratory scaled model and a field scale test site have shown promising results.*

Keywords: leak location, electrical imaging

1. INTRODUCTION

Large quantities of solid and liquid wastes are stored in ponds and lagoons world-wide. In many cases synthetic liners are used to protect 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 public water supply. Since these man-made liners will degrade eventually with time naturally and are prone to damage throughout the working life of the waste facility it is essential that techniques are available to assess the integrity of liners and locate possible leaks. In some cases, such leaks may be small in terms of flow rate but significant in terms of mass flux of contaminants.

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 [1], [2]. 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 'before plume' data. Leaks from barriers may also be relatively small in 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.

Relatively new leak location methods have been established based on injecting electrical current through the liner into the surrounding soil and then, with the aid of an under-liner array of electrodes, mapping electrical potential. The methods are based on the original work of [3] and [4]. High potential gradients reveal likely location of leak spots within the liner. Example recent applications include [5] and [6]. The approach is very expensive to implement and is clearly not applicable in existing sites, where retrofitting is not an option. A tomographic variant of this electrical leak location method was first proposed by [7]. In this new approach electrical potentials are collected around the perimeter of the site and then with suitable inverse methods the locations of leaks within the pond are computed. Figure 1 illustrates the general procedure.

To date applications of this method has employed reasonably complex inversion methods to determine the leak locations. In an attempt to derive more robust, hence practical data processing techniques we report here on recent experiments using this method of determining the location of leaks in waste storage ponds using only boundary measured data.

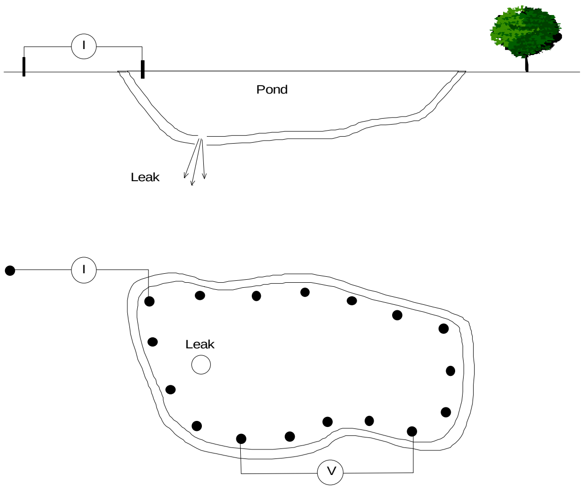


Figure 1: Schematic of measurement procedure. Electrodes (shown as solid circles) may be also located outside the pond.

2. METHODOLOGY

The distribution of electrical potential (*v*) within the system shown in figure 1 can be represented by:

$$\frac{\partial}{\partial x}\left(s\,\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(s\,\frac{\partial v}{\partial y}\right)-l^2 vs = -Id(x)d(y) \qquad (1)$$

Here λ is the Fourier transformation variable, x and y are co-ordinates, σ is the electrical conductivity (assumed variable), I is the current applied and d is the Kronecker delta. This differential equation may be solved using the finite element method for given boundary conditions. Inverse Fourier transform and appropriate superposition of the calculated potentials yields the voltages of an arbitrary electrode configuration in the considered plane.

The inverse solution of (1) for the problem here requires the determination of the distribution of current (I) given the conductivities (s) and voltages (v). In practice, transfer resistances are measured and thus the task of an inverse solution is the determination of the distribution of unit current.

If the region of interest is discretised into node points for solution of the forward problem any number of these node points may be selected as possible current source nodes. The inverse solution may then be considered as 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 (as in the case of inverse methods for resistivity tomography). Such regularisation may be so such that significant over-smoothing of the final result occurs.

Alternatives to gradient methods are the increasing range of 'global optimum' methods based on controlled Monte Carlo sampling within the parameter space. Method 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 experiences with this type of approach was encouraging (see [7]) 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 indicate some degree of 'trust' associated with the result. Incorrect assessment of leak locations have severe financial 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 inversion parameters and the consequence of inappropriate choice of such factors.

In addition, the distribution of electrical conductivity within the region is unlikely to be known. Waste disposal ponds will often contain a wide range of materials and thus be highly heterogeneous in electrical properties. The spatial distribution of waste depths has the same influence as variation in waste type. Depths may be estimated but will often be poorly know. Inverse methods which rely on accurate knowledge of these factors are unlikely to have practical value in industry.

Given these constraints our aims are to determine what useful and reliable information may be derived from electrical leak location surveys using only boundary data. Our approach here is to adopt simple robust data processing techniques in an attempt to assess their viability in practical situations, rather than more elaborate inverse methods suitable only for research sites.

Rather than approach the measure of misfit between the model and the data in terms of a least squares fit, the correlation of data to model may be used. The product-moment correlation is expressed here as:

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

where D_i is the i^{th} measured transfer resistance and $F_i(I_k)$ is the i^{th} transfer resistance computed due to unit current at location *k.* For *M* possible current source nodes the value of r_k may then me 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 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 (2) is inappropriate since only one 'optimum' will be apparent. It is therefore essential that the reliability of the correlation function, produced in this way, can be made. Calculation of the correlation function is not computationally demanding once the forward solutions have been determined for the *M* possible source nodes. It is, therefore relatively trivial to carry out a search using pairs of source nodes to assess the improvement in correlation in comparison to using only one source node. The search must contain all possible pairs due to possible non-uniqueness, as explained earlier. The magnitude of current in each of the two possible sources may differ and so the search must also account for this by sampling various permutations of the same source pair.

The implementation of such a search is trivial. By selecting a sufficient number of combinations of source node pairs and a sufficient number of permutations in their relative current strengths it is possible, with very little computational effort, to assess which combinations resulted in improvement over using one single source node. By simply displaying the distribution of the number of occurrences that each source node, when combined with another, improved the correlation with the data, it is possible to reveal the level of unreliability in the location of optimum correlation from one source node alone. High reliability will be shown by a distinct peak in this count function, centred on the peak of the correlation function. Low reliability will be revealed by more than one possible source node showing high counts. This will be illustrate by two examples, one using a controlled laboratory test, the other using measurements at a field scale test site.

3. APPLICATION TO A SCALED MODEL

3.1 Experimental setup

A scale model was designed as follows. Twenty stainless steel electrodes were located around the perimeter of a shallow plastic container, 90cm by 42cm in plan, filled with mains water. Figure 2 shows the basic setup. To represent a leak, another stainless steel electrode was located at sites A, B and C in figure 2. Combinations of these sites were also considered using two electrodes simultaneously. The electrode sites A, B and C thus represent ideal leaks in the container (equivalent to a current source placed outside the tank).

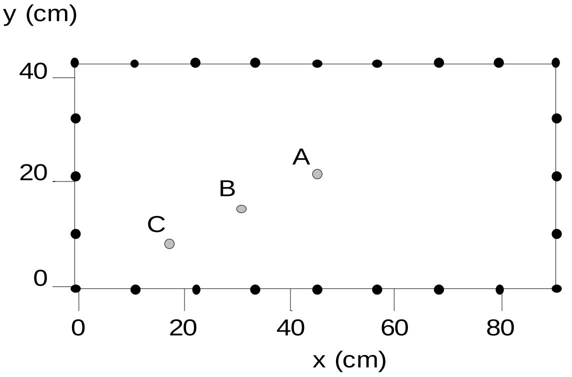


Figure 2: Experimental setup for laboratory leak tests (solid dots show electrode sites)

To model the system a finite element mesh containing 640 elements, 693 node points was used. To represent possible current source locations 135 of these finite element nodes were used as shown in figure 3.

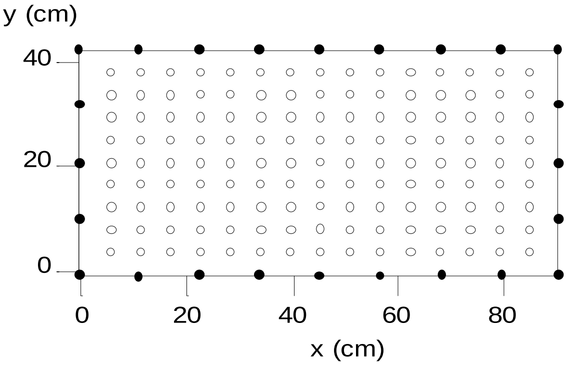


Figure 3: Distribution of possible source nodes used for laboratory experiment.

For each of the three possible 'leak' sources plus a number of combinations of sources, transfer resistances were collected by using the source(s) as one current electrode and one of the boundary electrodes as the other current electrode. Resistances were then measured between various pairs of other boundary electrodes. The procedure was repeated by using each boundary electrode in turn as a current electrode. In total 360 measurements were collected for each possible 'leak' source. The injected waveform used was a switched DC type, 4Hz frequency, typical of geophysical applications. Current magnitudes varied but were typically approximately 1mA.

3.2 Results

Figure 4 shows the correlation function in (2) plotted for two of the cases considered. Since correlation shows a reasonably flat surface the response has been exaggerated by plotting r_k^{10} rather than r_k. In figure 4a the correlation function is shown for a single 'leak' at point B (see figure 2). For this case the optimum goodness of fit clearly matches the actual source location. For a combination of two sources (at A and C in figure 2) figure 4b shows that the correlation is poorly suited, as would be expected.

For cases with one major source location (one dominating leak) simply plotting the correlation may then be a robust solution. A measure of reliability is required, as discussed earlier. Figure 5 illustrates one possible way of addressing this by plotting the number of occasions each of the possible 135 sources nodes, when used with any other, improves the correlation with the data, when compared to the optimum from using one single source node. For reference the search consisted of approximately 200,000 combination of source node pairs.

Also shown in figure 5 is the location of the source node(s) for optimum goodness of fit (defined by maximum correlation), observed during search. For the single source node case in figure 5a the reliability measure shows a distinct peak close to the location of the single leak. This can then be interpreted as confirmation that the correlation function in figure 4a does in fact locate the leak well and confirms that the signal is dominated by a single source. For the dual source in figure 5b the response is significantly different. Here, although a maximum can be seen, the important feature is that a large number of source nodes can be used in combination with each other and result in an improvement over a single source node. Note that here no significance is placed on the extent of that improvement.

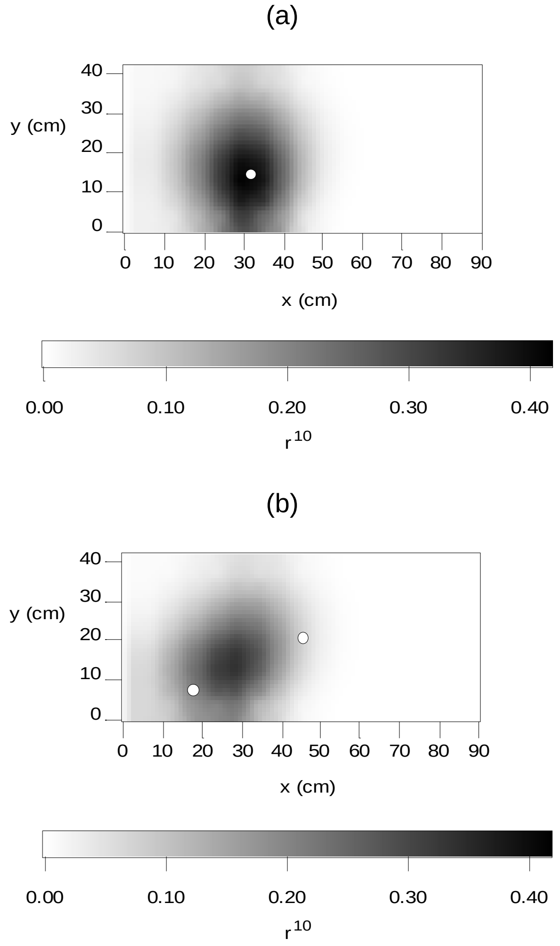
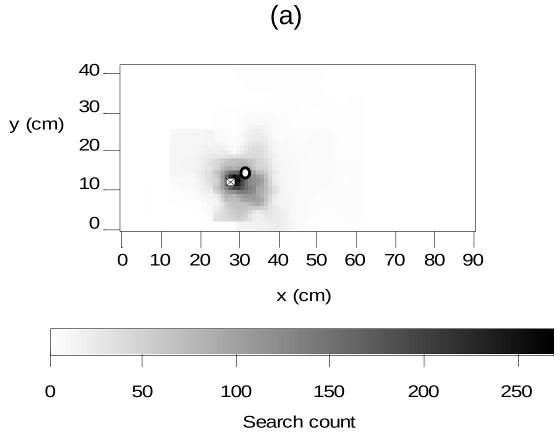


Figure 4: Example results of laboratory experiments showing correlation function plotted for two cases: (a) single leak, (b) dual leak. Circles indicate actual source location.



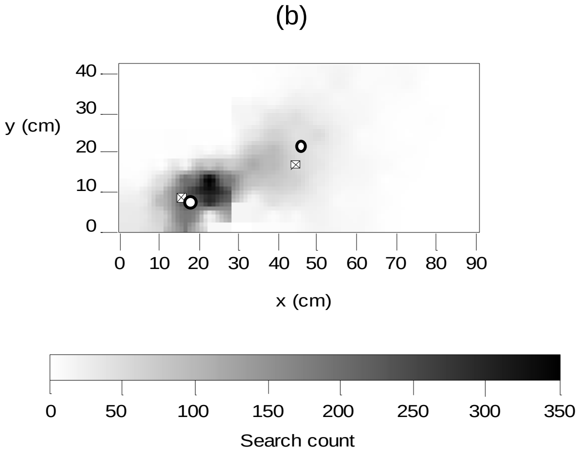


Figure 5: Reliability measured plotted for the two cases in figure 4: (a) single leak, (b) dual leak. Circles indicate actual source location, crossed square shows optimum source node combination resulting from the search.

Since it is possible to select the optimum pair of source nodes (defined as those producing the maximum correlation with the data) encountered during the search, their locations are shown in figure 5a and 5b for the two cases. Even for the dual source case in figure 5b the optimum solution corresponds well with the true location of the sources.

4. FIELD SCALE DEMONSTRATION

4.1 Experimental setup

Field scale experiments were conducted during summer, 1998 at a storage pond in Livermore, CA, USA. The application permitted tests to be performed under more realistic conditions. Besides the obvious issue of scale other factors are relevant: the electrical conductivity is likely to be highly variable within the pond due to the liquid stored and variability in depth; the pond has an irregular boundary making modelling errors more significant.

An array of 36 electrodes was installed just within the perimeter of the pond, as shown in figure 6. Measurements of resistance were made using a similar arrangement to that used in the laboratory scale experiment. The magnitude of current applied was typically 200mA. Two source locations were selected, as shown in figure 6.

In order to model the response the region was discretised into 2880 finite elements, 2997 nodes. 106 of these nodes were used as possible source nodes.

4.1 Results

Figure 7 shows sample results from the experimental programme. In figure 7a the correlation function in (2) is plotted for the single 'leak' case. In figure 7b, correlation between model and data for each possible source node is shown for the dual 'leak' case.

The results are consistent with the findings of the laboratory scale pond: for the single source case the correlation function works well but clearly is inappropriate for more than one leak.

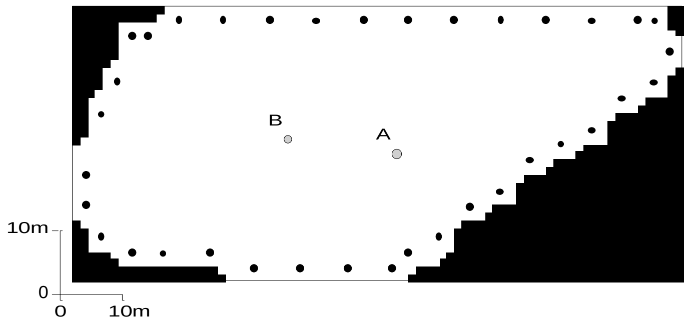


Figure 6: Experimental setup for field scale leak tests.
Solid dots show electrode sites, A and B indicate locations of current sources.

As in the small scale test searches were performed to investigate the reliability of the result from using only the correlation function. Figure 8 illustrates the result of this search for the two cases. In figure 8a a well peaked response indicates good reliability, whereas in figure 8b the unreliability of the correlation function result in figure 7b is clearly shown by a much wider peak.

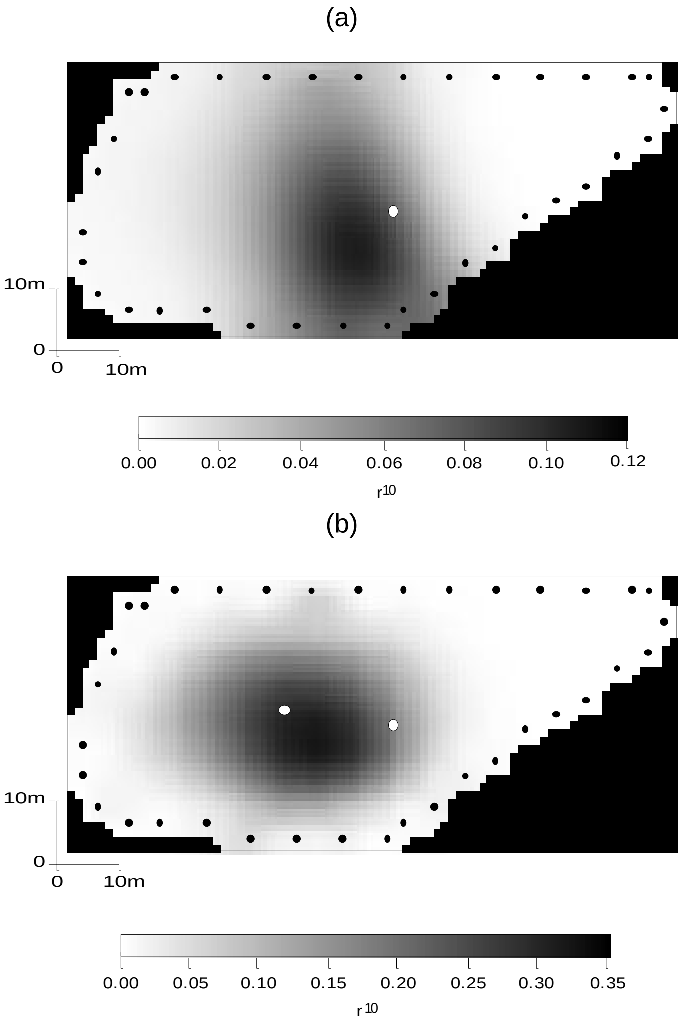


Figure 7: Correlation maps for field scale leak tests (a) single leak, (b) dual leak. White circles show locations of current sources.

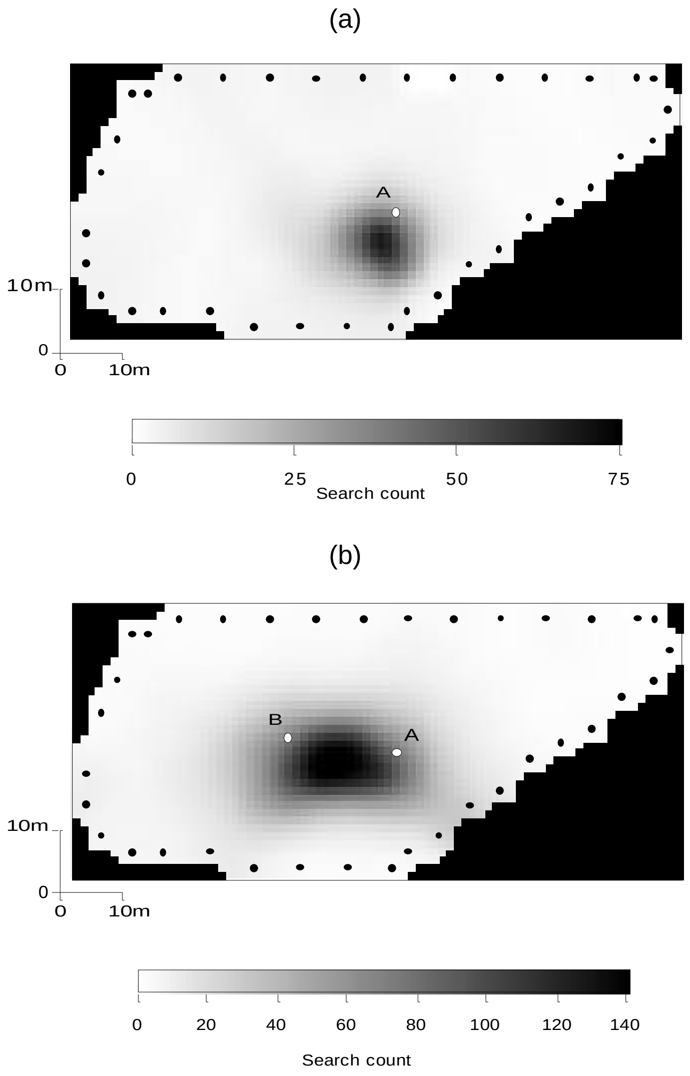


Figure 8: Search counts showing reliability for field scale leak tests (a) single leak, (b) dual leak. White circles show locations of current sources.

5. CONCULSIONS

To our knowledge the experiments reported here are the first attempts to determine leak locations in storage ponds using measurements obtained from electrodes located within the perimeter of a storage pond. The results indicate that it is possible to derive information about the location of a major electrical (and hence fluid) leak through electrically insulating liners without resorting to complex inversion methods. By displaying maps of the correlation between data and the response of a numerical model using a number of possible source locations the location of a single leak can be estimated with accuracy.

The reliability of the leak location implied by the correlation function can be easily assessed by an extensive search of combinations of two or more source locations. Since the forward model is only computed once the computation cost of the procedure is minimal and certainly possible on site immediately following data collection. Such tools may then be used to help locate not the exact location of a leak but reasonably small areas of suspected damage to the environmental barrier, the exact location being determined by more thorough investigations within such areas.

Non-robust inversion methods have little practical value for detecting leaks from the many waste disposal sites world-wide. Data processing tools must assess levels of reliability or uncertainty in the final response due to the financial implications of false assessments. We anticipate more investigations into simplistic approaches, such as the type utilised here.

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