Modeling of Electrical Resistivity Data in the Presence of Electrically Conductive Well Casings and Waste Storage Tanks – 14609

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ABSTRACT

Electrical geophysical methods are used at the Hanford Site to delineate subsurface contamination, monitor both natural and engineered subsurface processes, and monitor for leaks from buried single shell high-level waste tanks. However, buried conductive infrastructure in many locations degrades the utility of electrical methods, often exerting a confounding influence on resistivity data. In this paper we demonstrate how modeling conductive infrastructure can limit the deleterious effects conductive wells and tanks by simulating the response of resistivity-based ex-situ tank leak detection technology currently deployed at the Hanford Site. The modeling reveals that it may be possible to significantly improve leak detection sensitivity, enough to design systems that would enable low volume chronic leak detection within the Hanford tank farms.

INTRODUCTION

Electrical resistivity tomography (ERT) has proven useful for monitoring subsurface processes and imaging the distribution of vadose zone contamination at the Hanford Site[1-6]. The method uses electrodes placed at the surface and/or within boreholes to collect data that is numerically processed to produce an image of the bulk electrical conductivity of the subsurface. Contaminants released into the vadose at the Hanford Site were typically highly saline and relatively conductive, presenting an excellent target for ERT imaging within the native low conductivity sands and gravels comprising the Hanford vadose zone. In addition, time-series of electrical resistivity data are currently being used to monitor for tank leaks during high-level nuclear waste retrieval operations at the Hanford Site C Tank Farm [7, 8], and have been proposed for low-volume chronic leak detection at other Hanford Site tank farms awaiting retrieval.

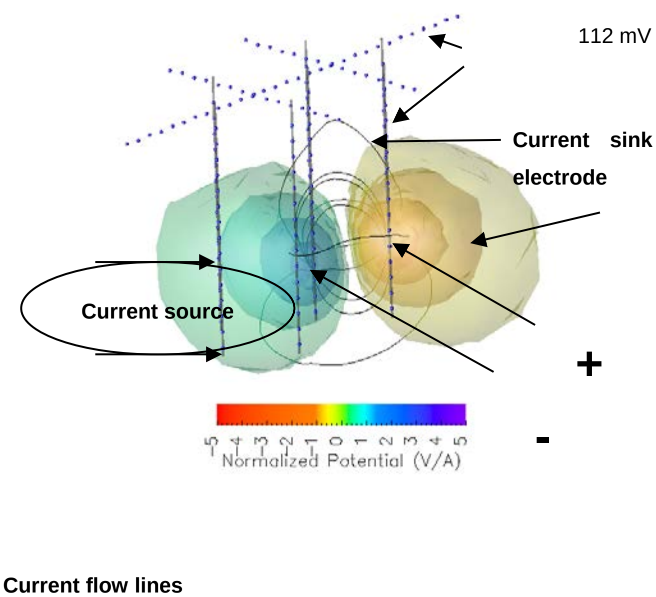
By providing the capability to non-invasively image and monitor contaminated regions of the vadose zone, ERT has the potential to significantly reduce cost of closure by reducing uncertainty concerning contaminant distribution, and by eliminating the necessity to be near contaminated zones for detection. However, at Hanford and many other DOE sites, contaminants originate from electrically conductive infrastructure such as pipes, wells, and waste storage tanks. Being highly conductive, these features tend to channel electrical current and dominate resistivity data, masking the distribution of soil contamination. This masking effect has reduced the sensitivity of ERT imaging in areas with dense subsurface infrastructure such as the tank farms. Unfortunately, these areas are often where significant vadose zone contamination exists, where borehole access is expensive, and where ERT imaging would otherwise be more effective. Conductive tanks and pipes also significantly reduce the sensitivity of resistivity data to leaks that originate from those structures.

Although metallic infrastructure degrades the ability of ERT to image contaminated regions, the locations and dimensions of the metallic features are often well known. This provides the opportunity to model conductive inclusions within the ERT imaging algorithm, enabling the algorithm to simulate the effects of infrastructure and better resolve contaminant distributions.

However, due to the large contrast in conductivity between native soils and metallic infrastructure (approximately 10 orders of magnitude), infrastructure effects cannot be accurately modeled using standard ERT algorithms[8]. We have implemented an algorithm that addresses this condition by decoupling the metallic and non-metallic parts of the subsurface domain using specialized boundary conditions [9] and a geometrically flexible unstructured tetrahedral mesh [10]. In this paper, we demonstrate the accuracy of the approach using analytic solutions, and the utility of accurate infrastructure modeling for resistivity applications at the Hanford Site. We provide a synthetic example demonstrating how the infrastructure modeling capability can be used to simulate tank leak detection responses, providing the technical basis for designing electrode arrays and data collection sequences that provide optimal leak detection sensitivity. The synthetic example shows that detection sensitivity may be significantly improved using optimized measurement sequences and electrode configurations identified by the simulation results. Such modeling can be used to provide the technical basis for designing low volume, chronic leak detection systems for monitoring single shell high-level waste storage tanks at tank farms awaiting retrieval at the Hanford Site.

ERT BACKGROUND

ERT is a method of remotely imaging the interior electrical conductivity structure of the subsurface [11, 12]. A single datum is collected using two electrodes (source and sink) to inject current into the subsurface, and two separate electrodes (positive and negative) to measure the resulting electrical potential arising from the current injection (figure 1). Many such measurements are collected in strategic configurations using an array of electrodes to produce an ERT data set, which is then analyzed using a computationally intensive tomographic algorithm to reconstruct the electrical conductivity structure of the subsurface. Surface based electrode arrays are typically comprised of metallic rods driven six to twelve inches into the subsurface. Borehole electrodes are typically comprised of short (2-8 inches long) metallic tubes attached to a multi-conductor cable, each insulated conductor being attached to an electrode and rising to the



surface for connection to survey instrumentation. Each electrode makes contact with the subsurface when the borehole is backfilled, or by groundwater when the electrode is below the water table. It is also possible to use existing well casings and tanks as ERT electrodes. Well casings and tank electrodes are currently used in the tank leak detection system deployed during high-level waste retrieval operations in the Hanford Site C Tank Farm.

The relationship between current flow and electrical potential within the subsurface, and the basis of the ERT method is described by the Poisson equation,

$$\nabla \bullet \sigma(\mathbf{r}) \nabla \phi(\mathbf{r}) = I(\mathbf{r}),$$ eq. (1)

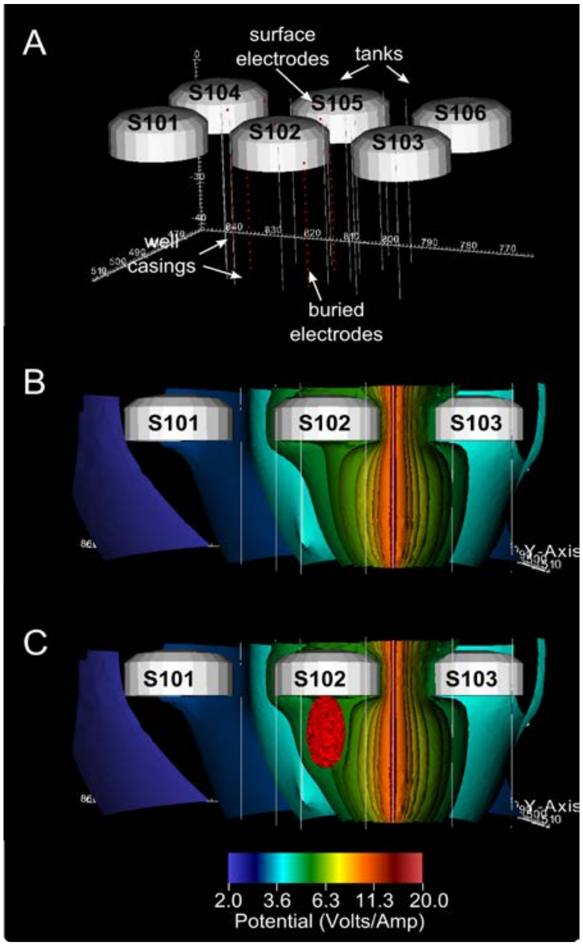
where $\mathbf{r}$ is a vector representing the position in space, $\sigma(\mathbf{r})$ (S/m) represents the subsurface electrical conductivity distribution, $\phi(\mathbf{r})$ (V) represents subsurface electrical potential distribution, and $I(\mathbf{r})$ (A/m^3) represents the subsurface current density. To model equation 1 numerically, conductivity is specified on a discretized computational mesh and current density is specified at the source and sink locations, resulting in a matrix of equations that is solved to produce the corresponding subsurface potential distribution. In the case where metallic materials are buried in the subsurface, electrical conductivity can vary from eight to twelve orders of magnitude. The resulting set of matrix equations cannot be adequately represented at machine precision, making accurate solutions to equation 1 infeasible using standard numerical approaches. We solve this problem using immersed interface boundary conditions, whereby the effects of the metallic structures are solved at the metal boundaries using the potential and current flux boundary conditions that must exist in reality. We use an unstructured tetrahedral mesh to represent the subsurface, providing the capability to efficiently and accurately model abstract shapes, and to accurately model subsurface potentials generated in the presence of conductive infrastructure.

HANFORD SITE RESISTIVITY BASED TANK LEAK DETECTION

Electrical resistivity based ex-situ tank leak detection is currently the primary technology being used to monitor for emerging leaks during high-level nuclear waste retrieval from single shell tanks at Hanford's C Tank Farm. The approach is based on the assumption that the high conductivity waste leaking from a tank will change the bulk electrical conductivity of the soil, thereby altering the potential (e.g. the voltage) measured during an ERT survey using available electrodes, included well casings and tanks. The technology was developed by Hanford Site contractors in the mid 2000's, and tested using field experiments aimed at reproducing tank leak conditions and tank farm electrode configurations to the extent possible. Although field testing provided valuable data concerning detection sensitivity, the testing was inherently limited. For example, once a single leak was simulated at a particular site, the original pre-leak condition could not be recovered for further testing of an emerging leak. In addition, it was not possible to test a leak originating from an actual buried tank, so a controlled wellbore injection was used to simulate a tank leak. Due to the limited nature of the field testing, some uncertainty exists concerning the sensitivity of resistivity based leak detection monitoring, particularly concerning application to low volume chronic leaks in single shell tank farms. The capability to accurately model subsurface potentials during in the presence of tanks and wells enables the leak detection sensitivity to be investigated under any given field condition, which could provide the technical basis for implementing effective resistivity based low volume leak detection systems in single shell tank farms currently awaiting retrieval.

SYNTHETIC LEAK DETECTION SENSITIVITY ANALYSIS AT THE HANFORD S TANK FARM

Initial field testing of resistivity based leak detection technology was conducted at the Hanford Site S Tank Farm by site contractors. We reconstructed the S Farm configuration of tanks, wells, and surface electrodes used during the field testing within the computational mesh to synthetically investigate detection sensitivity from a growing contaminated mass originating from a leak at the center of tank S102 (figure 2). The objective of the study was to investigate detection capability of the currently deployed technology in relation to alternate measurement configurations that might provide improved sensitivity. Responses for all possible measurement configurations were generated for three cases. First were pole-pole measurements, whereby one of the current electrodes and one of the potential electrodes are placed far from the tank farms. In this case only tanks and wells were used as electrodes in order to simulate the currently deployed technology, which uses a pole-pole configuration with tank and well electrodes. Second, we simulated dipole-dipole measurements, whereby all electrodes used are within the tank farms. In this case surface electrodes are also used. Third, dipole-dipole measurements were simulated using an array of borehole electrodes surrounding a tank (figure 2A).



Surface and borehole electrodes

Figures 2B and 2C show example simulation results for a no leak and large leak condition respectively, originating from the center of S102. In each case, current is injected along a wellbore casing located near S102, and extracted on an electrode far from the tank farm (i.e. a pole-pole injection). The colored isosurfaces in each figure show the subsurface potential distribution generated by the current injection in volts per ampere of current injected. Note the slight distortion of the potential field caused by the leak. In order to detect the leak, the change in potential from the no leak to leak condition must be measureable between any available electrode pair. For the pole-pole measurements, which represent the currently deployed technology, the largest relative change in potential occurs between tank S102 and a remote electrode far from the tank farm (i.e. a pole-pole measurement), which is consistent with field testing observations. The second and third simulation cases described above are not shown graphically, but are summarized in the results section.

RESULTS

All possible measurement configurations were tested for simulation cases one, two, and three as described above, resulting in 53,493 simulated measurement of each of 40 logarithmically spaced leak volumes. Results were analyzed in terms of the percentage change in simulated voltage caused by a given leak volume. Measurements that did not exceed reasonable noise thresholds expected under field conditions were removed from consideration, and the most sensitive measurements from the remaining pool were chosen for each simulation case. The most sensitive measurements for each simulation case are shown in figure 3.

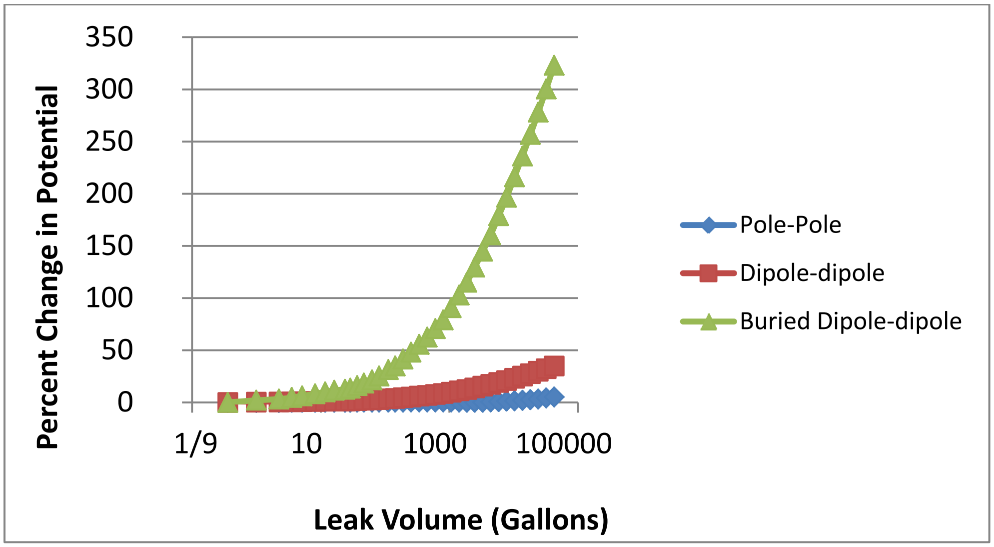


Figure 3. Most sensitive leak detection responses for pole-pole measurements using tanks, wells, and surface electrodes (blue), dipole-dipole measurements using tanks, wells, and surface electrodes (red), and dipole-dipole measurements using buried electrodes (green).

DISCUSSION

The S102 leak scenario modeled in this study suggests that it may be possible to significantly improve ex-situ tank leak detection capabilities by collecting dipole-dipole measurements instead of pole-pole measurements. The simulated pole-pole measurements, which represent the current protocol used at the C Tank Farm, provide the least sensitive detection in this case. Using surface electrodes with tank and well electrodes to collect dipole-dipole measurements significantly improves sensitivity. Using buried electrode arrays with dipole-dipole measurements provides a dramatic improvement. For example, results from the S102 field test suggested a leak of approximately 2000 gallons could be detected using the pole-pole technology deployed for that test. A similar response is detected at less than 100 gallons using buried electrodes with dipole-dipole measurements.

CONCLUSIONS

Electrical geophysical methods are used at the Hanford Site to delineate regions of subsurface contamination, understand subsurface processes, and monitor high level waste tanks for leaks. Understanding the deleterious effects of metallic infrastructure on electrical geophysical data is critical for assessing leak detection sensitivity. Modeling the effects of metallic infrastructure enables detection sensitivity to be assessed, and detection systems to optimized in the absence of expensive and complicated field testing results that must accurately reproduce actual tank leak conditions. We have demonstrated through synthetic modeling that leak detection capability can likely be significantly improved using optimized electrode arrays and measurement configurations. Such modeling provides the technical basis for understanding and validating systems designed to detect low volume chronic leaks from buried pipes and tanks at the Hanford Site, or at other industrial sites where subsurface leak detection capabilities are needed.

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