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Environmental Process Tomography in the United States

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ABSTRACT: As one consequence of economic growth over the past several decades, the citizens of the United States have inherited an unfortunate legacy of contaminated soil and ground water. Both the private and public sectors have contributed. From the private sector, has come the waste stream of the industrial revolution. A ubiquitous example is the corner gasoline station: we now acknowledge gasoline leaks from many of these underground storage tanks in the country. A major contribution from the public sector comes from the military establishment. Probably the most serious example here is 'mixed waste' resulting from nuclear weapon production: a mixture of toxic and radioactive wastes such as a hydrocarbon based solvent and uranium which contaminates soil at many government sites.

The clean up has begun but the early optimism has faded to the reality of a two-fold concern: the cost will be enormous using present techniques and, just as disturbing, some of the problems have no known solutions. Clearly, new approaches are needed. In response, the U.S. Government is supporting development of new technology and transfer of existing technology from other disciplines to apply to the problem. Part of this effort is development of geophysical tools used for underground imaging. These tools are closely related to many of those used in industrial process tomography.

Both seismic and electromagnetic methods are used for underground imaging. In either case, sensitivity and resolution are greatly improved by making measurements from boreholes instead of only from the surface. Seismic signals are usually more sensitive to subsurface structure such as lithologic boundaries, but recent work has also shown seismic tomography to be sensitive to the degree of saturation. Electrical methods can be useful for delineation of aquitards such as clay layers. Electrical tomography is shown to be particularly sensitive to movement of fluids such as steam. Examples of both seismic and electromagnetic process tomography will be discussed in relation to environmental remediation of soils and ground water in the United States.

1. INTRODUCTION

The citizens of the United States have a concern about environmental protection and cleanup of contaminated ground water and soil. Government agencies, aware of their civil duty, have responded to this concern. The U. S. Department of Energy, for example, has confessed to many past sins but simultaneously publicizes its desire to repent [U.S. Congress, Office of Technology Assessment, 1991]. The rhetoric has been supported by money appropriated to support the cleanup, which has already begun on many fronts. However, an important revelation came from the early efforts: the

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problem is larger than most politicians realized. Of course, the corollary is that the cost will be larger than their constituents can afford. After an appropriate period of indecision, politicians have concluded that new technology might ease the problem. The idea is that a modest investment by the government, in technology targeted at specific applications, will allow clean up to be done faster, safer and cheaper.

One of the areas of technology development supported by the U.S. Department of Energy is underground imaging--generating high resolution images, usually with the use of tomographic reconstruction techniques, of subsurface structure and process. Such information could be invaluable for *in situ* clean up. Site characterization, for example, is an important first step in site remediation. Done adequately, the result will help define how contaminants are distributed and what remediation strategy might be practical. Underground images are also useful for process monitoring. For example, it is a simple matter to inject surfactant into a formation to dissolve and flush a contaminant but quite another matter to know where that surfactant is actually going once it leaves the injection well. Good process monitoring is necessary for delineating how a clean up strategy is working--or not working.

What we want is high resolution images of subsurface structure and process. Seismic (compressional and shear wave acoustic) methods have traditionally been used for delineating underground structure. In fact, seismic reflection profiles have been very useful for finding the structural traps that define oil reservoirs. Electromagnetic methods are usually used for determining pore fluid content. Tomographic images of structure or fluids can be key elements to successful remediation of a contaminated site. In this paper we will review some of the underground imaging techniques that have been used recently in subsurface remedial efforts and then present in some detail a case history of one technique.

2. ELECTROMAGNETIC IMAGING

The principles of tomography were first introduced to the geophysical community in the mid 1970's by Jeff Lytle and coworkers of Lawrence Livermore National Laboratory (e.g., Dines and Lytle, 1979). They borrowed the reconstruction algorithms of x-ray tomography and used them to backproject the attenuation rate of high frequency electromagnetic (EM) radio waves transmitted along many different paths between two boreholes and produce an image of electrical conductivity or permittivity in the plane between the boreholes. The method is limited to imaging on a scale of a few meters to perhaps 20 meters (typical borehole separations) since radio waves are strongly attenuated underground. However, the technique, which can provide high resolution images, especially of moisture content, has been well developed over the years and has even been commercialized.

Sander *et al.*, (1992) report using this method of tomography to image a perchloroethylene (PCE) spill in an experiment to test various geophysical techniques for characterizing soil contaminated by hydrocarbons. They monitored the controlled release of PCE for 340 hours from cross borehole measurements at 160 MHz. The PCE with a relative dielectric permittivity of 2.3 provided a contrast with the water of permittivity 80. They report being able to delineate the vertical and lateral extent of the PCE plume as it was controlled by local heterogeneities in soil lithology.

Radio frequency tomography was also used by Borns *et al.*, (1992) to characterize stratigraphy beneath and define the conductive plume near a pit used to dispose of chromic acid at Sandia National Laboratory in New Mexico. Fifteen MHz signals were used to image between boreholes 30 m deep and 16m apart. At this frequency displacement currents govern wave propagation along approximately straight rays between the boreholes. They could detect various soil units as small as about 1 m scale by their conductivity contrasts. They also identified a conducting anomaly that may have been a portion of the chromic acid plume.

Cross borehole imaging has also been done at much lower frequencies (kilohertz to hundreds of kilohertz). In this regime, conduction currents dominate and the idea of waves is not appropriate. In this case a diffusion equation describes the physics and the inversion is much more complicated. However, Alumbaugh (1993) has recently reported successful two dimensional inversion of cross well field data and Wilt *et al.*, (1993) have used the technique for imaging a salt water plume. This technique shows promise for use in environmental process tomography.

James and Borns (1992) report a novel method for underground imaging which was used at the U. S. Government Waste Isolation Pilot Plant. The technique is not tomographic in the usual sense but is a process whereby the 2 dimensional subsurface current distribution is calculated from measurements of surface magnetic fields produced by currents induced when a large surface magnetic field is turned off. The subsurface conductivity is inferred from this current distribution. The work was used to delineate a conductive zone of high hydraulic transmissivity near the plant.

A novel generalization of single-source holography is reported by Bartel (1993). The target, in this case a shallow fuel oil spill, is illuminated by a down hole multifrequency source and the scattered field measured at an array of surface points. The reconstructed image yields an anomaly consistent with the presumed location of the plume but the spatial resolution is limited by the low frequencies used (below 4096 Hz).

3. SEISMIC IMAGING

Seismic tomography is usually performed similar to electromagnetic imaging: (compressional or shear) waves are transmitted along many different ray paths between boreholes and the signal attenuation or slowness is reconstructed using an iterative scheme. The method has limited environmental use because of the very high signal attenuation in unconsolidated soils (the typical environment of near surface contamination). However, several groups have shown it useful at some sites.

The U.S. Department of Energy sponsored an experiment of air stripping of TCE and PCE at the Savannah River Plant in South Carolina to test various technologies for *in situ* clean up of volatile organics from the vadose zone. Elbring (1992) reports using compressional and shear wave tomography to delineate moisture changes resulting from the air stripping, based on lab data suggesting a 40% change in velocity when saturation changed from 100% to 85%. He reports imaging low contrast wave speed anomalies which he interpreted as moisture content changes. Just as important, he reports that

the images were sensitive to structural features, such as a clay layer and interbedded sands and clays, that control gas movement underground.

Zucca *et al.* (1992) report use of cross borehole seismic tomography to monitor steam injection in soils. (This work was part of the Dynamic Underground Stripping Project which will be discussed in more detail when we describe electrical resistance tomography.) They reconstructed differences in wave slowness (inverse of wave speed) measured from before and during steam injection and found anomalies corresponding to the steam zone of about 0.8 s/km. Unfortunately, there were other features of similar and even greater magnitude in the images that could not be correlated to known processes.

4. ELECTRICAL RESISTANCE TOMOGRAPHY

Electrical resistance tomography (ERT) used in geophysics is a close relative to industrial process electrical tomography. In geophysics, however, the targets to be imaged can be very large--hundreds of meters or even kilometers in scale. This forces some differences between the two, especially in the instrumentation required to collect the data. However, the most fundamental difference is that geophysical ERT has been developed using a reconstruction algorithm based on an iterative scheme which fits a finite element forward model to the data. The advantage of this algorithm is the ability to reconstruct actual values of electrical resistivity without the need to make comparison images of changes in resistivity. The price is in computing time. The one step 'backprojection' type algorithms used in industrial process tomography (coupled with high frequency sources, e.g., Dickin *et al.*, 1993) are computationally very fast. For example, a demonstrated capability of 100 frames per second makes real time imaging possible in the hydrocyclone. The algorithm used in geophysics (LaBrecque *et al.*, 1993) is much more computationally intensive. We will discuss in this paper reconstruction times of 20 minutes--fast enough for most geologic processes but certainly not for the hydrocyclone!

Other differences between industrial and geophysical electrical tomography are less important. For example, in geophysics electrodes are usually grouted into boreholes so that the image plane is defined by two boreholes--their separation and depth. Also the data acquisition instrumentation will take a different form since it must be capable of handling much larger source voltages and currents (see Daily *et al.*, 1992). We now describe in detail the application of ERT to an *in situ* remediation project that involved the mapping of steam injected underground.

4.1. Electrical Resistance Tomography used to Monitor Steam Injection

The Dynamic Underground Stripping Project (DUSP) was undertaken by the Department of Energy (DOE) to demonstrate the remedial cleanup of volatile, organic compounds (VOC's) from saturated and unsaturated soil horizons at the Lawrence Livermore National Laboratory in California. The DUSP remediation concept combines subsurface steam injection and electrical ohmic heating to remove VOC's, in this case gasoline, from soil (Aines, 1991). The ohmic heating phase involves direct electrical heating by ohmic dissipation to increase the temperature of the least permeable layers (e.g., clays) where little or no injected steam would penetrate. This process heats the electrically conducting layers (silts and clays), evaporates the contaminant which moves down pressure gradient to the more permeable units (sands and gravels). The steam

injection phase involves injecting steam into the most permeable layers (sands and gravels) where the contaminant is swept to an extraction well and pumped to the surface for treatment. We used ERT to provide three dimensional images of the entire operation. These data were used to evaluate system performance and for real time process control. Because of a lack of space, we summarize some of the ERT results obtained during the steam injection phase of the demonstration.

Figure 1 shows a top view of the borehole layout. A steam injection well is near the plane defined by boreholes TEP-002 and TEP-009. We will abbreviate borehole names and refer to this plane as t2t9, with borehole t2 on the left side of the image and borehole t9 on the right. An extraction well is near the t2t3 plane. Each of the boreholes used for ERT measurements contained ten electrodes spaced every 3.66 m (12 ft.) between depths 15.85 m (52 ft.) and 48.77 m (160 ft.). The image plane width is determined by the borehole separations; the image planes ranged from 12.5 m (41 ft.) to 48.3 m (158 ft.) wide.

A key requirement placed on ERT was that results be available in near real-time because the data were used to make process control decisions each day. The ERT data collection and data processing systems were automated as much as possible in order to meet this requirement. During normal operations, a tomograph was produced within 20 minutes after the completion of data collection. The system required one full-time technician to operate the data collection system and transmit the data to a processing workstation; a part-time data analyst monitored the incoming data, identified any problems (e.g., problems caused by broken cables, voltages or currents outside the dynamic range of the instruments) and prepared the tomographs for final interpretation. From beginning of data acquisition to final image was about 90 minutes. We must be careful of boasting about this achievement at this conference where such time scales are measured in milliseconds. However, the comparison emphasizes the fundamentally different experimental problems (and solutions) in industrial and geophysical imaging.

The site of the demonstration is underlain by Pliocene to Holocene lacustrine and alluvial sedimentary deposits. The upper 52 m (170 ft.) of these sediments consist of approximately 60% fine grained sediments (clay and silt) and 40% coarse grained sediments (sand and gravel). Because of the complex interfingering of different sediment types that occur in an alluvial depositional environment, multiple sediment types exist at similar depth intervals in different boreholes. The upper part of the lithologic sequence consists of late Pleistocene to Holocene alluvial deposits consisting of complexly interbedded clay, silt, sand and gravel. Below this sequence, the Plio-Pleistocene Livermore Formation at the site is found starting between depths 24.5 m (80 ft.) to 35.5 m (116 ft.). The Upper member of the Livermore Formation is intersected by the monitoring boreholes; this unit consists of approximately equal amounts of sand, gravel, silt and clay.

4.1.1. Baseline Tomographs

Figure 2 shows the absolute images representing the (baseline) resistivity values prior to the start of ohmic heating. These images are compared with lithologic logs obtained for all of the ERT monitoring boreholes. The lithologic logs are based on visual inspections of soil core or drill cuttings. A common logarithmic scale is used to represent resistivity due to the wide range of values measured. The lighter grays depict regions of higher resistivity

Figure 1. Plan view of the site showing the steam injection wells, condensate extraction wells and the ERT wells.

Figure 2. Images of per-injection resistivity for 9 of the ERT planes. They are compared with lithologic logs from corresponding boreholes. Note that resistivity is depicted on a logarithmic scale.

whereas the darker grays depict regions of lower resistivity. Note that the resistive layers, close to the two side edges of each image, appear thicker than the same layers near the image center. This apparent thinning towards the middle of the images is an artifact of the decreases in sensitivity near the image center. Note also that the images do not show individual rectangular pixels but are spatially smoothed. Of course, this smoothing does not improve resolution which can not be better than one finite element pixel (about 2 m square for these images).

The ERT tomographs show two regions of high resistivity. The top of the lowest high resistivity region is between 34 m (112 ft.) and 39.6 m (130 ft.) depths; the thickness of this lower unit is typically between 2.1 - 5.8 m (7 - 19 ft.). This region of high resistivity extends throughout the whole site and correlates with a gravel layer identified in the lithologic logs; we will refer to this zone as the "lower steam zone" for this formation is one target of the steam injection. This zone represents a braided stream deposit which is relatively homogeneous and forms a laterally continuous sheet-like deposit; it is thought to exhibit good lateral hydraulic connectivity.

There is another region of relatively high resistivity, however, that appears to be intermittent throughout the site. We will refer to this region as the "upper steam zone". The top of this zone generally occurs between 23 - 29 m (75 - 95 ft.) and its thickness ranges from 0 - 9 m (0 - 30 ft.). This zone is a heterogeneous mixture of lens-shaped channel deposits containing high to lower permeability sandy to clayey gravels and silty sands. These deposits are hydraulically connected where overlying higher permeability units incise underlying channel deposits.

Between the upper and lower steam zones, there is a region of lower resistivity with a thickness ranging from 23 to 39 m (1.8 to 7.9 ft.). A sequence of clays and silts corresponds to this low resistivity region which acts as a confining layer hydraulically separating the upper and lower steam zones. Based on hydraulic testing, there seems to be no communication between the upper and lower steam zone, indicating that the intervening clays form a laterally continuous barrier.

4.1.2. Difference Tomographs

Electrical resistance tomographs were constructed before and during steam injection. From these data, difference tomographs were formed which represent changes in resistivity relative to initial conditions (i.e., the tomographs are generated by subtracting values of pixels in one tomograph from values of pixels in an earlier tomograph). These difference tomographs should show only those features that have changed between the time the two data sets were taken.

Figure 3 shows a time sequence of difference resistivity tomographs for planes in proximity to steam injection wells; the time sequence begins with the first day of the first steam pass (labeled day 1) and ends on the last day of the first steam pass cycle (day 36). The images are compared with formation lithologic logs obtained along the same boreholes where the ERT electrodes are located. For ease of comparison the gray scale representing resistivity change is the same for all images.

Figure 3. Difference ERT images in planes t10t6, t3t9 and t9t5 as a function of time during the entire steam injection history.

During the first few days of steam injection, all three time sequences in Figure 3 show anomalies of decreased resistivity that grow in size. The early part of the sequence also shows that the resistivity changes grow preferentially in one direction; for example, in the first 4 days the TEP10-TEP6 sequence shows that the changes towards TEP 10 are larger than those towards TEP 6 even though the injector is near the middle of the image. TEP 10 is located towards the extraction wells whereas TEP 6 is located away from the extraction wells. Similar observations can be made for the TEP 3 - TEP 9 and TEP 9 - TEP 5 sequences. These three sequences show that during the early part of the injection cycle the biggest resistivity differences generally occur towards the extraction wells rather than away from them. This pattern suggests that a larger fraction of the injected fluid moved preferentially towards the extraction well implying that the extraction system had some influence in the preferred direction of flow in both the vadose and saturated zones.

Figure 3 can also be used to evaluate the degree of hydraulic isolation between the lower and upper steam zones in the vicinity of the injector wells. The early part of the TEP 10 - TEP 6 sequence shows that the resistivity changes are mostly constrained to the lower zone at a depth of about 35 m (note the apparent thickening of the resistivity changes along the image edge is an artifact of the gradients in sensitivity). This behavior suggests that the lower steam zone appears to be well isolated from the upper steam zone during the time when only the lower steam zone was being treated. The TEP 3 - TEP 9 and TEP 9 - TEP 5 time sequences show contrasting behavior, i.e., resistivity changes are observed along a significantly wider depth range between 25 and 40 m. This behavior points to the presence of leakage from the lower steam zone to the upper zone when only the lower injectors are in use. The leakage may have been caused by failure of seals installed in the injection wells or by the presence of undiscovered fluid pathways in the confining layer between the upper and lower steam zone.

4.2. Summary

Electrical resistance tomography successfully monitored underground steam movement during the Dynamic Underground Stripping Project at Lawrence Livermore National Laboratory in California. The images presented here are only a small part of those used during the project. We have chosen to present these images to illustrate the capabilities and limitations of ERT for monitoring *in situ* processes.

One objective of the project was to evaluate the capabilities of this technique to provide images that could be used for process control. ERT was used to monitor a total of twenty-one planes over the seven-month period of the project. This large body of data was successfully used by site personnel to control steam injection as well as understand its impact on the overall remediation effort.

The U. S. Government can point to electrical resistance tomography as a successful investment in environmental technology: the method is currently being commercialized in the United States and within a few years the technique should be widely available to industry and government. It will be used not only for environmental process monitoring but also mining geophysics and it seems likely that other geotechnical applications will follow.

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