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GEOPHYSICAL MONITORING OF ACTIVE HYDROLOGIC PROCESSES AS PART OF THE DYNAMIC UNDERGROUND STRIPPING PROJECT

R.L. Newmark
and
The Dynamic Underground Stripping
Project Monitoring Team

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R. L. Newmark and the Dynamic Underground Stripping Project
Monitoring Team*

*Contributors: D. Chesnut,[a] C. Chung,[b] W. Daily,[a] S. Jarpe,[a] D. LaBrecque,[d] S. Lu,[a] E. Majer,[c]
E. Owen, J. Peterson,[c] A. Ramirez,[a] C Schenkel,[a] M. J. Wilt,[c] J. J. Zucca[a]

Abstract

Lawrence Livermore National Laboratory, in collaboration with University of California at Berkeley and Lawrence Berkeley Laboratory, is conducting the Dynamic Underground Stripping Project (DUSP), an integrated project demonstrating the use of active thermal techniques to remove subsurface organic contamination. Complementary techniques address a number of environmental restoration problems: 1) steam flood strips organic contaminants from permeable zones, 2) electrical heating drives contaminants from less permeable zones into the more permeable zones from which they can be extracted, and 3) geophysical monitoring tracks and images the progress of the thermal fronts, providing feedback and control of the active processes[1].

The first DUSP phase involved combined steam injection and vapor extraction in a "clean" site in the Livermore Valley consisting of unconsolidated alluvial interbeds of clays, sands and gravels. Steam passed rapidly through a high-permeability gravel unit, where *in situ* temperatures reached 117°C. An integrated program of geophysical monitoring was carried out at the Clean Site. We performed electrical resistance tomography (ERT), seismic tomography (cross-borehole), induction tomography, passive seismic monitoring, a variety of different temperature measurement techniques and conventional geophysical well logging.

Introduction

Underground steam presents a detectable target for geophysical imaging through its thermal signature, changes in fluid-filled porosity, and its effect on fluid and soil chemistry. The primary objectives of the geophysical monitoring activities are to image and provide real-time feedback control and monitoring of the heating operations, and determine the nature and extent of the active subsurface processes and how they affect the formation. One of the reasons for fielding several similar techniques is to evaluate the relative strengths and weaknesses of each and determine those aspects that represent the tradeoffs between their application in terms of cost and utility.

As expected, the steam produced strong changes in some of the physical properties of the formation. We learned valuable lessons regarding instrument fielding, data management and processing. During the second DUSP phase, we will clean up an area contaminated by gasoline that leaked from an underground storage tank (the Gas Pad). The lessons learned during the Clean Site demonstration are being applied to the Gas Pad well design and measurement plans.

Multiple-Use Wells

One of the Project's challenges was to design multiple-use wells to decrease the total number of wells. Two designs were fielded for monitoring purposes; 1) 11 temperature-type wells and 2) three tomography-type wells (Figure 1). The temperature-type wells were cased with 1.5" diameter fiberglass sealed at the bottom and typically rigged with 8 ERT electrodes and four fixed thermocouples. The three tomography-type wells were cased with 6" diameter fiberglass sealed at the bottom, and two of these wells were rigged with 8 ERT electrodes. These wells were designed to accommodate the requirements of the seismic and electromagnetic induction tomographic techniques, as well as the larger-diameter commercial logging tools. As such, they were intended to be water-filled, for better coupling between the seismic sources and the formation.

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[a] *Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, California, 94550.*
[b] *College of Engineering, University of California, Berkeley, California, 94720.*
[c] *Lawrence Berkeley Laboratory, 1 Cyclotron Rd., Berkeley, California, 94720.*
[d] *University of Arizona, Department of Mining and Geological Engineering, Tucson, Arizona, 85721.*

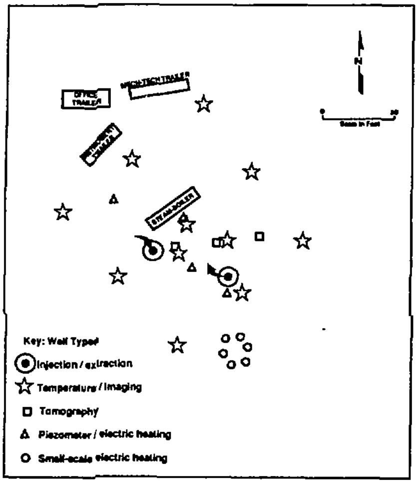

Figure 1. Site map, showing well locations.

Temperature Measurements

Temperature measurements made in the dedicated temperature monitoring wells provided the "ground truth" for describing the steam progress through the field. We made daily temperature measurements during and after steam injection in nearly every well[2]. Temperature readings were taken over the heated zones in all 11 temperature monitoring wells using a movable thermocouple probe. In addition, fixed thermocouples set in several of the wells were read and recorded, providing a reference for adjusting the measurements made using the thermocouple probe. Temperature measurements indicate strong lithologic control of the steam front (Figure 2). The relatively high permeability gravel zone shows the largest temperature rise, the caliche and clay-rich zones bordering the gravels show substantially smaller temperature rise.

Geophysical Logs

Geophysical logs were obtained at several stages during the Clean Site activities. Immediately after drilling and before completion, caliper and resistivity logs were run in the three tomography wells and in the extraction well. We ran induction logs in most of the temperature wells and the three tomography wells several times during steam injection. The induction logs clearly show changes in formation electrical properties as a response to steam injection (Figure 2). Electrical resistivity decreases in the steamed zone, an effect that can be largely explained as being due to thermal effects[3,4]. However, changes in the electrical properties as seen in the induction logs and other electrical techniques are often of broader extent than the zones of increased temperatures, suggesting that other, more subtle effects such as changing fluid saturation around the heated zones or changes in groundwater chemistry are occurring. Temperature measurements and induction logs obtained in the temperature monitoring wells are essential for correlating and interpreting the anomalies seen in the tomographic images.

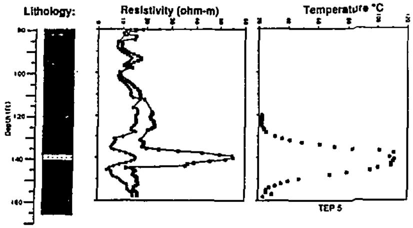

Figure 2. Relationship between lithology, electrical resistivity and temperature during steaming (see lithology key on Figure 3).

There are three principal predicted effects due to steam injection: 1) heating of the pore fluid should decrease electrical resistivity, 2) displacement of pore water by steam should cause an increase in electrical resistivity, and 3) heating of the pore fluid should increase the exchange cation mobility in the clay minerals, decreasing electrical resistivity. Other effects include changes in pore water chemistry due to salinity differences between the groundwater and steam condensate.

Simple corrections for changes in the fluid resistivity due to thermal effects result in good agreement with the observed resistivity profiles[4]. Models suggesting that the dominant electrical conductivity arises from the double layer associated with the clay minerals adequately predict the resistivity changes observed in the steam zone[3,4]. Using simple corrections for temperature and salinity differences in the gravel zone, we are able to estimate the fluid saturation during steaming. By this method, we estimate the fluid saturation during steam injection drops to about 60% from the initial fully saturated conditions in the gravel zone[4].

Commercial neutron porosity, gamma-gamma density and induction logs were run in the three tomography wells before and once during the steam injection phase. These logs were run to evaluate anticipated changes in the porosity and density of the formation. Of these, the most useful are the neutron logs, which indicate a decrease in neutron porosity in the steamed gravel unit by 2 - 4%[5].

Electrical Resistance Tomography (ERT)

Electrical Resistance Tomography (ERT) proved the most successful technique for providing near real-time imaging of the active processes between wells. ERT data were collected before, several times during, and after steam injection. The baseline ERT images provided information regarding the continuity of lithologic units across image planes[4]. ERT images clearly show the progress of the steam front across the image planes as a zone of lower resistivity (Figure 3). The shallow electrical resistance anomalies probably reflect fluid infiltration and subsequent dryout from the surface use of fresh water during final well completion activities. Our ability to collect, process and analyze the data improved substantially during the Clean Site test, so that images that took nearly a week to generate now take a matter of hours. This improvement in processing capability brings us near to our goal of near real-time feedback for the principal monitoring techniques.

Seismic Tomography

Seismic cross-hole tomography data were collected three times during steam injection[6]. Hydrophones were found to be better than accelerometers for detecting the airgun signal, at least for the rays traveling horizontally. An automatic picking system for picking these data was developed. The data are noisy, and the vadose zone data are particularly difficult to analyze. For that reason, we have focused on the data below 25 m. Baseline images reveal increased slowness (decreased velocity) in the vicinity of the water table, reflecting partial liquid saturation (Figure 4). Steam passing through the target gravel zone produced a velocity decrease of about 5%. Part of this change can be explained in terms of temperature and pore pressure increases from the introduction of the steam; the rest can be explained in terms of a change in the fluid saturation from completely saturated to partially saturated conditions. Other anomalies may result from fluid infiltration and subsequent dryout.

Passive Seismic Tomography

The passive seismic monitoring system did not detect any events unambiguously associated with steam injection. The array detected numerous small events during the airgun firing; these were successfully located in the vicinity of the source well[7]. However, the absence of events clearly associated with steam injection suggests that either steam injection at the Clean Site did not produce any acoustic signals or that the acoustic emissions resulting from the movement of steam were

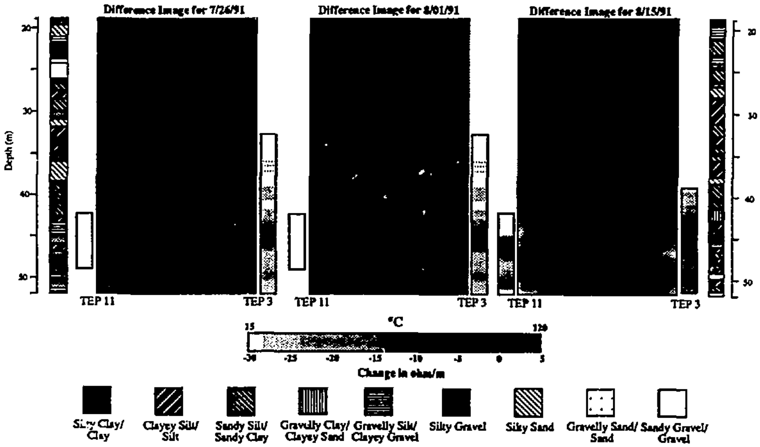

Figure 3. Electrical resistance tomography views of the steam zone. Each panel depicts the difference between the resistivity distribution measured in the image plane and the baseline values measured before steam injection. These difference images are constructed from data obtained 3, 9 and 23 days after start of steam injection. Lithology and temperature profiles logged in each of the bordering wells on the same days are shown to the right and left of each image. The steam plume moves across the plane as a zone of decreased electrical resistivity centered on the silty gravel layer. Development of the lower steam layer by the end of the test is seen in the 8/15 image.

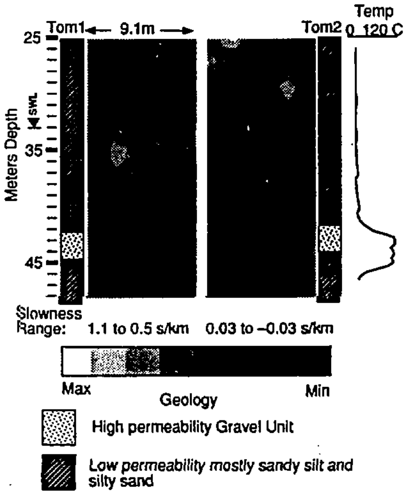

Figure 4. Seismic tomographic images from the Clean Site: (A) Baseline image. Slowness increases in the vicinity of the water table. (B) Difference image comparing travel times obtained after a week of steam injection with initial baseline travel times. The steam zone is revealed as a band of increased slowness corresponding to the high-permeability gravel unit.

too small to be detected by the surface array we fielded. A downhole array might be fielded to resolve the threshold question in a future test.

Induction Tomography

Cross-borehole electromagnetic (EM) induction tomography is in an earlier stage of development than ERT. The EM data indicate that the resistivity within the steam-swept gravel decreased by almost a factor of 10. Simple layered models resulting from inversion of the data show close agreement with induction logs run in the tomography wells at about the same time. The data show that the steam zone thickens and intensifies with time during the injection phase[8]. The increasing thickness occurs mostly in the downward direction, and the magnitude of the anomaly increases (resistivity decreases). Layered models are particularly appropriate for these data, as the steam front had already passed the monitoring plane (tomography plane) by the time the later datasets were obtained. Three-dimensional forward models suggest that EM measurements should be capable of resolving the edge of the steam front if the data are collected when the steam front is passing across the imaging plane.

Summary of Key Monitoring Results:

1. Induction logging can provide good predictions of steam movement.
2. Electrical resistance tomography provides detailed images of steam movement between imaging wells.
3. Seismic cross-hole tomography detects the steamed zone, but at lower resolution than ERT.
4. Electrical techniques reveal changes in electrical properties over a broader zone than the thermal disturbance; other possible factors include fluid movement and chemical changes.

Acknowledgments

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