Near Real-Time Two and Three-Dimensional Electrical Geophysical Monitoring of Natural and Engineered Processes Associated with Subsurface Remediation – 16052

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ABSTRACT

Legacy soil and groundwater contamination associated with nuclear weapons production is projected to be one of the largest cleanup liabilities to the U.S. Department of Energy for the foreseeable future. Remediation of subsurface contaminants is complicated by the combined effects of geochemical heterogeneity, geological heterogeneity, and the difficulty and expense of adequate borehole access. Each of these complications contributes to uncertainty in the distribution of contaminants and the performance of in situ treatments, which increases risk to human health and the environment and cost to closure in general.

Electrical resistivity tomography (ERT) is a method of remotely imaging the electrical properties of the subsurface, which are governed by both geochemical and geological structure, thereby providing useful proxies for understanding contaminant distribution and the behavior in situ remediation processes. Recent advancements in both data collection and data processing capabilities are enabling ERT monitoring to be executed and provided to site operators in near real-time. To summarize the process, ERT surveys are rapidly and continuously collected during a time-sensitive operation such as an amendment injection. At the completion of each survey, data are transferred by wireless internet to offsite supercomputing resources for parallel tomographic inversion. Inversion results are then transferred back to onsite operators and/or other locations for visualization. In this paper, we demonstrate the utility of time-lapse ERT for monitoring fluid transport (both gas and liquid phase). We then demonstrate two real-time imaging applications for monitoring both natural and engineered processes at the Hanford Site within the vadose and the saturated zones. We expect this new capability for autonomous real-time imaging to enable ERT to be used as a cost-effective, short-term rapid feedback mechanism for guiding subsurface remediation injections, in addition to longer term monitoring of post-injection performance and environmental impact, all using the same electrode array and instrumentation.

INTRODUCTION

Electrical resistivity tomography (ERT) uses an array of electrodes to remotely image the electrical conductivity of the subsurface [4, 5]. During a measurement, current is injected across one pair of electrodes, and the resulting potential is measured across another pair. Many such measurements are strategically collected to create a data set that is processed using a tomographic inversion algorithm to recover the subsurface electrical conductivity distribution that gave rise to the measurements. Electrical conductivity is a useful metric for understanding subsurface structure because it is governed by porosity, saturation, pore fluid conductivity, and soil textural properties [6]. When one or more of these properties changes with time, time-lapse ERT can be used to monitor those changes in space and time. In time-lapse imaging, static influences are removed from the image, revealing only what has changed in time, and thereby enabling ERT to monitor very subtle changes in the subsurface. Fig. 1 shows several examples of static ERT imaging for characterization and time-lapse imaging for process monitoring.

A typical time-lapse imaging campaign involves collecting ERT surveys on a repeating cycle during some subsurface process of interest. Data are then taken from the field and analyzed to reveal the evolution of the process. One useful application of time-lapse ERT is to monitor the migration of some amendment injected to remediate a contaminated subsurface region. In this case, remediation performance depends critically on amendment delivery. Time-lapse ERT can remotely image amendment distribution throughout the treatment zone, providing a powerful

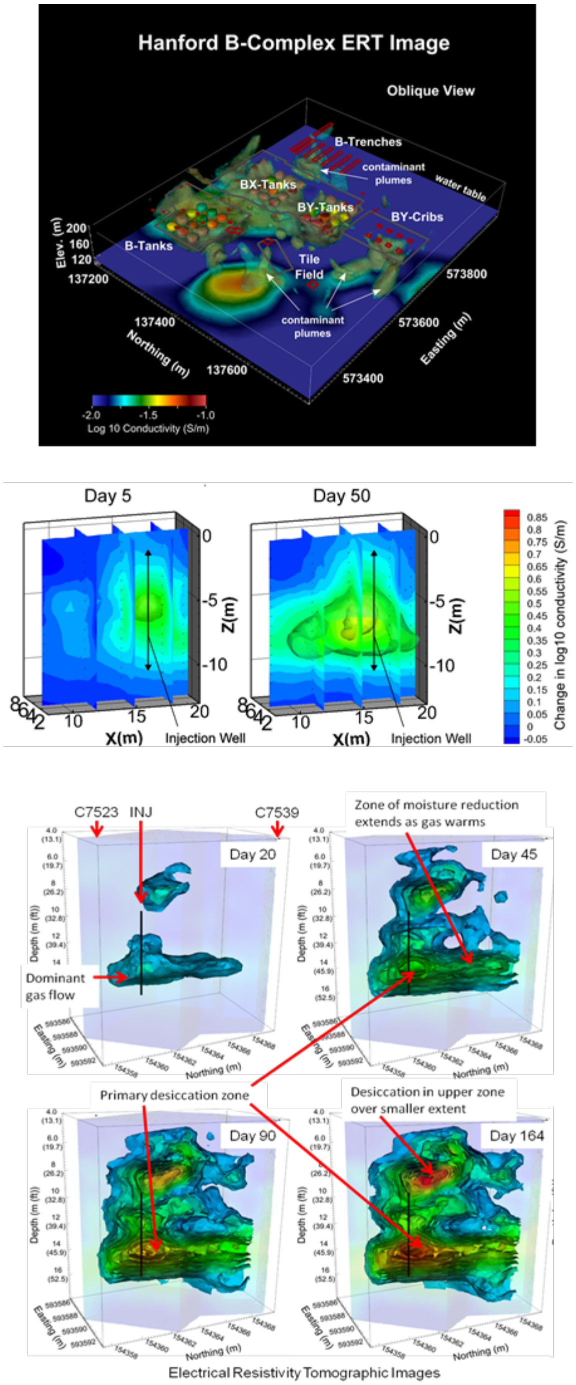

Fig. 1. (Top) Static 3D image of vadose zone contaminant plumes at the Hanford Site [1]. (Mid) Time-lapse ERT images of bio-amendment distribution at a bio-remediation site [2]. (Bot) Time-lapse ERT images of engineered desiccation in the Hanford Site vadose zone [3].

remediation performance assessment tool. However, time-lapse images are generally only available long after the process of interest has occurred, eliminating the opportunity to understand the process in real time. In the following text, we discuss recent advancements that enable time-lapse ERT images to be delivered to field operators and stakeholders in near real time. In the forthcoming sections, we present a flow diagram showing the operation of real-time ERT imaging. We then provide two examples from the Hanford Site. In the first example, we autonomously monitor the three-dimensional evolution of stage-driven river water intrusion into the Hanford 300 Area. In the second example, we monitor remedial amendment transport as it migrates through a shallow contaminated vadose zone, also at the Hanford 300 Area.

REAL-TIME ERT IMAGING FLOW SUMMARY

Fig. 2 shows the primary components of the real-time ERT imaging system. ERT data collection hardware is controlled by a field computer, which is internet accessible through a wireless internet link. When a time-lapse data set is completed, the field computer filters and preprocesses the data set into the format required by the inversion software operating on an offsite supercomputer. The supercomputer has resources dedicated to the ERT monitoring, which wait for each successive data set to arrive from the field computer. The supercomputer and field system communicate through a secure link over the wireless internet connection. When a data set arrives at the supercomputer from the field system, it is processed and returned for onsite visualization. Results can also be transferred from the field system to an offsite computer for website delivery, enabling offsite stakeholders to observe the process in near real time.

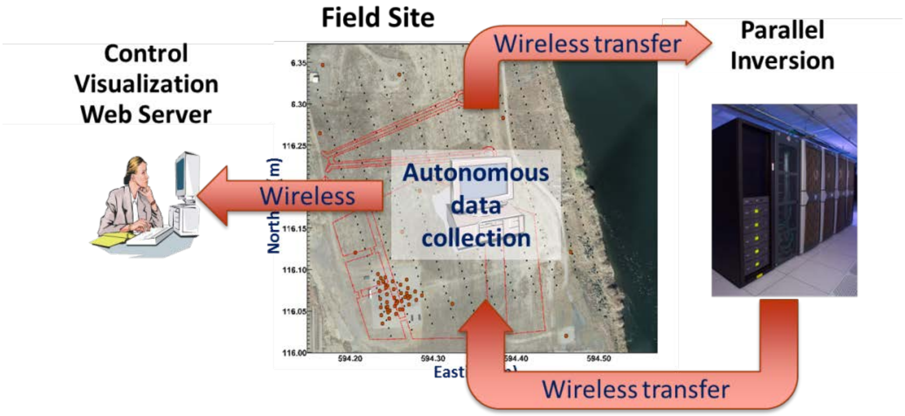

Fig. 2. Real-time ERT imaging system components.

EXAMPLE 1: COLUMBIA RIVER WATER INTRUSION IMAGING

The Hanford 300 Area is located adjacent to the Columbia River, approximately 5 km north of Richland WA. During its operational years, the 300 Area was the site of research operations and uranium fuel rod production facilities. Large amounts of uranium and other contaminants were released into large infiltration galleries (ponds and trenches), resulting in persistent uranium contamination that is the primary contamination of concern today [8]. Uranium mobilization and transport within the 300 Area is governed in large part by stage-driven river water intrusion, and corresponding changes in water table elevation [9-11]. Hence, understanding river water intrusion into the 300 Area is critical for understanding uranium transport to the Columbia River.

Groundwater-specific conductance within the 300 Area is approximately twice the river water specific conductance [12]. Thus, as river stage rises and river water begins to flow into the 300 Area, the electrical conductivity of the subsurface decreases where river water is present. With this in mind, a large 352 ERT electrode array (~350 m by 350 m) was installed within the 300 Area to image river water intrusion patterns during a high-stage spring runoff event in 2013, which lasted from April through September. Approximately four full data sets (~40,000 measurements) were collected per

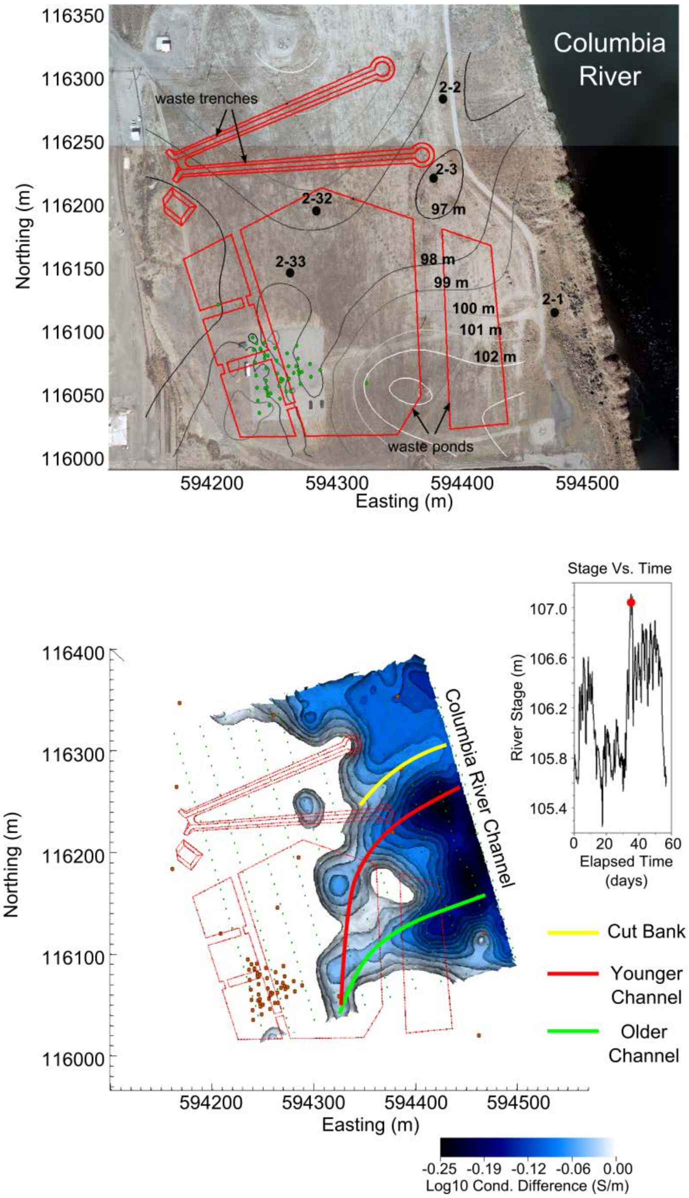

Fig. 3. (Top) Satellite image of Hanford 300 South Pond Area. Red lines indicate former infiltration gallery boundaries. Contours denote interpolated elevation of lower confining unit. (Bot) Maximum stage time lapse ERT image of river water intrusion, revealing preferred flow through a system of high permeability paleochannels [7].

day. Each data set was autonomously processed and inverted using 353 processors on a supercomputer housed at Pacific Northwest National Laboratory, requiring 1 to 4 hours for each data set.

Fig. 3 (top) shows an aerial image of the ERT imaging zone within the 300 Area, including outlines of the former infiltration pond and trench boundaries. Noting that the surface elevation in the area is typically about 115 m with little variability, the contour lines show the elevation of the lower bounding unit of the aquifer as inferred via well bore contact interpolation. Fig. 3 (bottom) shows one time-lapse ERT image taken from the full sequence (~400 images), which was taken at peak stage during the monitoring. The image shows river water advancing over 200 m inland of the shoreline for a stage rise of approximately 1.3 m from baseline conditions. The image also shows inland flow to be governed by high permeability preferred flowpaths, which are likely to be northward progressing paleochannel structures [7].

EXAMPLE 2: MONITORING AMMENDMENT TRANSPORT IN THE VADOSE ZONE

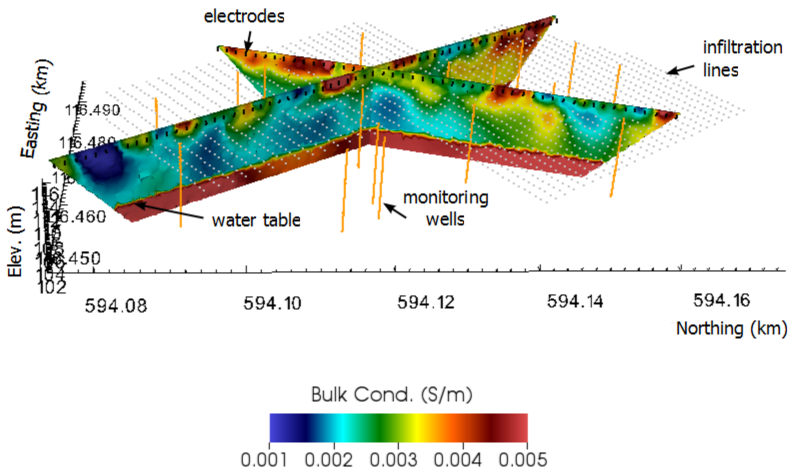

Fig. 4. Polyphosphate vadose zone infiltration layout superimposed on baseline ERT image along two transects. Zones of elevated conductivity within the vadose zone indicate elevated saturated due to moisture applied during infiltration system testing.

Former waste disposal activities within the 300 Area resulted in vadose zone contamination beneath former liquid waste disposal ponds and trenches. Vadose zone uranium contamination has been identified as the primary contributor to the persistent groundwater uranium plume. In 2015, implementation of the final remedy for groundwater contamination in the 300 area was initiated. Using a staged approach in situ treatment to immobilize uranium contamination in the vadose zone was conducted on a portion of the designated treatment area. The treatment involved saturating the vadose zone with a polyphosphate solution to create a calcium phosphate mineral (hydroxyapatite), which binds with uranium contaminated minerals in the vadose zone to produce a rind coating around the more soluble uranium carbonates, thereby immobilizing the uranium within the vadose zone. The polyphosphate solution was applied through injection wells, and through a series of near-surface infiltration lines that provided complete coverage of the treatment zone. As the solution infiltrated through the vadose zone, it increased both saturation and pore fluid electrical conductivity, which are two of the primary variables governing the bulk electrical conductivity of the subsurface. The subsequent increase in bulk conductivity caused by the polyphosphate solution provided a significant target for time-lapse ERT imaging. With this in mind, two ERT lines were installed within the treatment zone to enable time-lapse imaging. Fig. 4 shows the layout of the infiltration system, superimposed on an ERT image showing the vadose zone conductivity shortly after a pre-polyphosphate injection field test of the infiltration system. Increases in bulk conductivity near the infiltration lines are indicative of elevation saturation and/or pore water conductivity caused by moisture added during system testing. These results provided information concerning the operation of the infiltration system prior to the polyphosphate injection/infiltration.

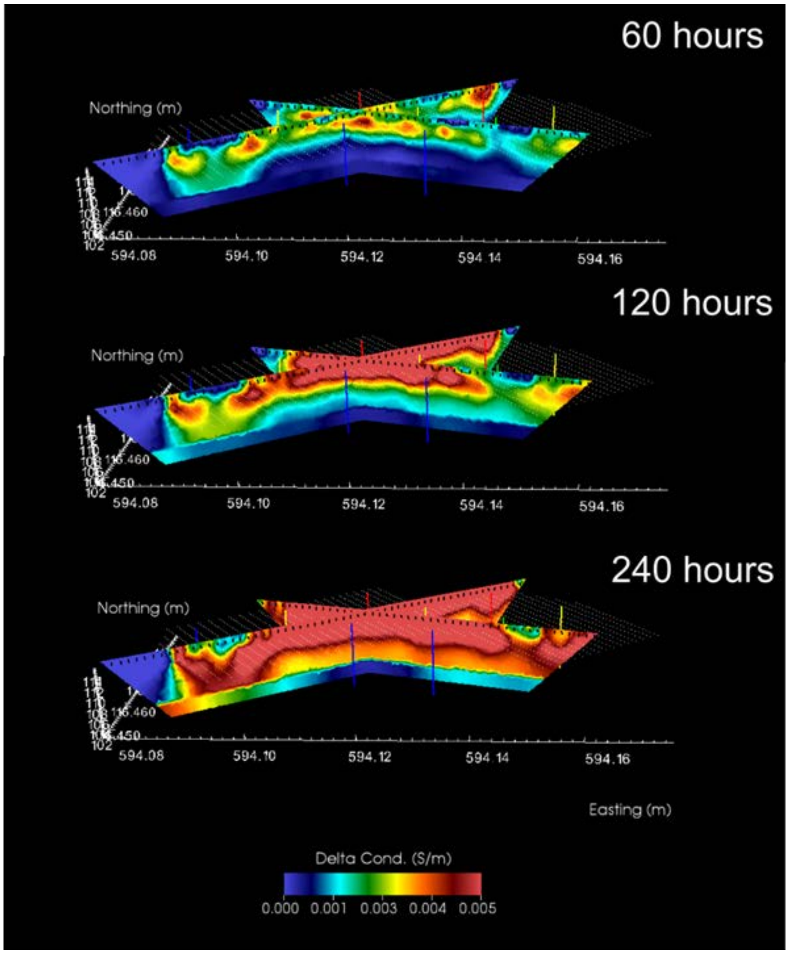

Fig. 5. Example ERT images of the advancing polyphosphate front at 60, 180, and 240 hours after initiation of infiltration.

During infiltration, ERT surveys were continuously collected on a 12-minute cycle. Autonomous data processing included filtering, transmission, inversion, and presentation to a website. The lag time required for imaging results to become available from the start of a survey was a minimum of approximately 14 minutes, with new images produced every 12 minutes.

The infiltration required approximately 2 weeks to complete. Over this time, the time-lapse images revealed the distribution of amendment along the two ERT transects, and provided site operators with valuable information concerning system operation and performance. Figure 5 shows the changes in subsurface bulk conductivity beneath each transect caused by the advancing polyphosphate front at 60, 120, and 180 hours after initiation of infiltration. Early breakthrough to the water table is evident at the western end of the infiltration zone. Overall, the ERT images suggest effective coverage of the treatment zone beneath the ERT transect.

CONCLUSIONS

We have demonstrated herein several examples of emerging capabilities in subsurface imaging, namely the capability to monitor subsurface processes in near real time. We expect this advancement to significantly enhance the utility of geophysical imaging for subsurface process monitoring by providing site remediation operators with valuable feedback concerning system performance, and enabling them to modify operations as required for performance optimization. In addition, the time-lapse images reduce uncertainty concerning process aspects that are difficult to completely assess using direct sampling, such as when and where an amendment reaches a particular point in the subsurface. By reducing uncertainty, subsurface remediation costs may be significantly reduced.

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