ELECTRICAL IMAGING OF PERMEABLE REACTIVE BARRIER (PRB) INTEGRITY

Lee Slater, Department of Geosciences, UMKC, Kansas City, MO
Joe Baker, Honeywell FM & T, Kansas City, MO
Andrew Binley, Dept. Environmental Science, Lancaster University, Lancaster, England
Danney Glaser, Department of Geosciences, UMKC, Kansas City, MO
Isaiah Utne, Department of Geosciences, UMKC, Kansas City, MO

Abstract

The permeable reactive barrier (PRB) is a promising in-situ technology for treatment of hydrocarbon contaminated groundwater. A PRB is typically composed of granular iron, which degrades chlorinated organics into potentially nontoxic dehalogenated organic compounds and inorganic chloride. Geophysical methods may assist assessment of in-situ barrier integrity and evaluate long term barrier performance. The highly conductive granular iron makes the PRB an excellent target for electrical imaging methods. Surface and cross-borehole electrical imaging was conducted at the PRB installed at the US Department of Energy Kansas City plant. The poor signal strength and insensitivity at depth, which results from current channeling in the highly conductive iron, limited surface imaging. Cross-borehole electrical measurements were highly effective at defining an accurate cross-sectional image of the barrier in-situ. Cross-borehole images obtained for seven panels along the barrier indicate significant variability in barrier integrity along the installation. In addition, the images suggest variability in the integrity of the contact between PRB and bedrock. This non-invasive, in-situ evaluation of barrier geometry has broad implications for the evaluation of PRB performance as a passive method for hydrocarbon treatment.

Introduction

The installation of a permeable reactive barrier (PRB) is a relatively new strategy for in-situ hydrocarbon removal from contaminated groundwater. A PRB is typically constructed of granular (zero valent) iron and strategically placed to capture hydrocarbon contaminated groundwater flow. As contaminated groundwater flows through the barrier, chlorinated organics come in contact with the reactive medium and are degraded into potentially nontoxic dehalogenated organic compounds and inorganic chloride (Gavaskar et al., 1998). The initial and long term performance of currently installed PRB's is uncertain. Gavaskar et al. (1998) highlight two key aspects of PRB evaluation that need immediate attention: **methods for non-invasive assessment of (1) PRB integrity following installation, and (2) long-term barrier degradation and performance.**

Monitoring of barrier integrity immediately following installation is required to evaluate the success of the installation procedure. Variability in the integrity of the barrier in situ may affect the performance of the barrier in hydrocarbon treatment. Deficiencies in the barrier (gaps, collapse structures, etc.) could seriously jeopardize groundwater quality down gradient from the barrier. Long-term monitoring strategies are required to record the deterioration in barrier performance that occurs as reactive iron is oxidized during hydrocarbon degradation. Gavaskar et al. (1998) note that the life cycle of the PRBs currently installed throughout the US is very uncertain. In this paper we evaluate the utility of electrical imaging for assessing the integrity of a PRB in situ. Unlike other methods of PRB assessment, electrical imaging offers a non-invasive solution to this evaluation problem.

Electrical imaging

The concepts of electrical imaging are now well described in the geophysical literature (see for example LaBrecque et al., 1996). Resistance measurements (the ratio of the voltage between an electrode pair to the current injected between another electrode pair) are made for a large number of sets of four electrodes placed in boreholes or at the surface. Given these measurements, it is possible to solve numerically for a conductivity distribution that results in a set of calculated resistance measurements which best fits with the measured response. The numerical solution typically applied in the inversion incorporates 2D or 3D finite element (FE) forward modeling and minimization of a weighted, regularized objective function. Recent environmental applications of electrical imaging include monitoring of leaks from underground storage tanks (Ramirez et al., 1996) detection of unexploded ordinance (Daily et al., 2000) and imaging hydraulic barriers (Daily and Ramirez, 2000). **The PRB is a unique environmental target for electrical imaging technology as the zero-valent reactive iron used in barrier construction is a highly conductive subsurface feature.**

Two important considerations in electrical imaging are (1) measurement errors, and (2) image resolution. LaBrecque et al. (1996) show that overestimation of data noise results in excessively smooth conductivity structure, whereas underestimation of data noise results in artificial image structure unrelated to the conductivity distribution. Noise estimation can be performed based on repeatability or reciprocity checks (Binley et al., 1995). Reciprocity is a better measure but is time intensive as the entire set of measurements must be repeated with the current and potential electrode pairs reversed. In this study, reciprocal measurements were obtained to characterize noise. A Gaussian noise distribution with a maximum relative error of 3-4% fitted the data and resulted in satisfactory inversion performance.

The spatial resolution of electrical imaging is not defined analytically as it is an unknown function of many factors including measurement error, electrode geometry, measurement schedule (number of independent measurements) and the conductivity distribution (Daily and Ramirez, 1995). The spacing between electrodes and distance from current sources exert a fundamental control on resolution. Recent numerical studies investigate the performance of established surface arrays in electrical imaging applications (e.g. Dahlin and Loke, 1998). The dipole-dipole array provides superior resolution when the signal-to-noise ratio is high (Dahlin and Bing, 2001). The geometry of the four electrode measurements comprising a cross-borehole dataset is equally important. Bing and Greenhalgh (2000) show that measurements maximizing the observed potential difference by splitting the current and voltage dipole pair between boreholes provide optimal resolution. This electrode geometry was utilized in this study. Further discussion of ERT resolution is given in LaBrecque et al. (1996) and Daily and Ramirez (1995).

Study site

A PRB was installed in April 1998 at the U.S. Department of Energy's Kansas City Plant in Kansas City, MO. This PRB was designed to remediate 1,2-dichloroethylene (1,2-DCE) and vinyl chloride (VC). PRB barrier design typically considers the hydraulic properties of the medium, regional hydraulic gradients, contaminant concentrations and iron-hydrocarbon reaction times (Gavaskar et al., 1998). Alluvial sediments underlie the site, primarily silty clay overlying basal gravel. These alluvial sediments are underlain by bedrock shale. The PRB was constructed as a continuous 130 ft long, 6 ft wide trench. The first 6 ft of the trench immediately above bedrock was filled with 100 % zero-valent granular iron. The remainder of the trench was filled with 2 ft of zero-valent iron and 4 ft of sand. The thicker lower unit was required to compensate for the higher flow-through velocities associated with the hydraulically conductive basal gravel. Clay backfill was used to cap the barrier. Figure 1 shows the cross-sectional geometry of the barrier and site geology. Superimposed is the position of electrodes and the finite element mesh used to reconstruct the conductivity distribution between wells. Note that the electrodes and mesh are shown for a nominal 10 ft borehole separation: The borehole separation for seven panels placed along the barrier varied from 9.5-11.5 ft. Further information on the barrier design, installation procedure and current performance is available from the Permeable Reactive Barriers Evaluation Team (http://www.rtdf.org/public/permbarr/prbsumms/default.cfm).

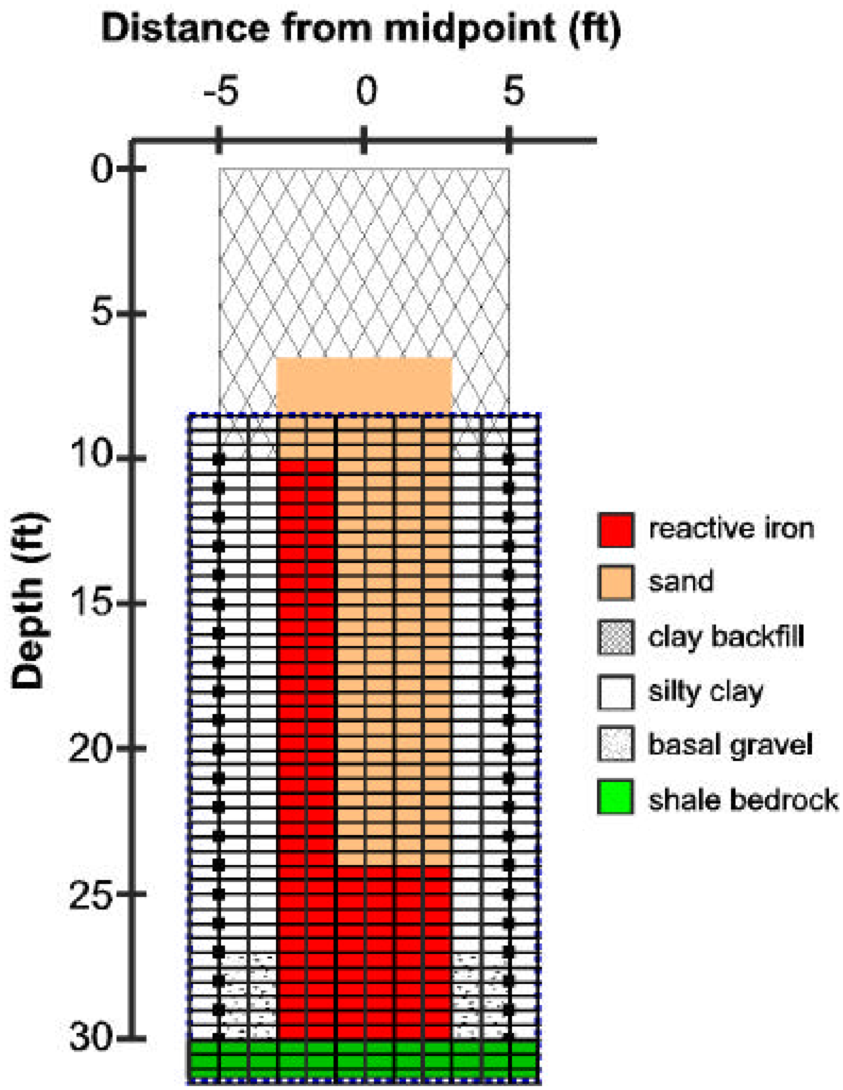

Figure 1: Idealized cross-sectional geometry of the PRB based on the design and installation effort

Figure 2 is a plan view of the site showing the position of 16 boreholes drilled to bedrock and installed with electrode arrays as per Fig. 1. Twenty-one electrodes were installed in each borehole at 1 ft intervals from the bedrock surface. Each borehole pair (e.g. 1-2) represents a 2D panel for imaging the cross-sectional electrical structure of the barrier at this position along (north-south) the wall. A 2D surface imaging survey was also conducted along the long-axis of the barrier (location shown in Fig. 2). The dipole-dipole array (n levels from 1 to 6) with multiple electrode spacing (1-4 m), provided 772 measurements. Reciprocal measurements were obtained and measurements with a relative reciprocal error (RE) greater than 5% removed. An error-weighted, regularized inversion algorithm, which accounts for topographic variability along the profile, was used to obtain a 2D model of the conductivity structure along the barrier axis.

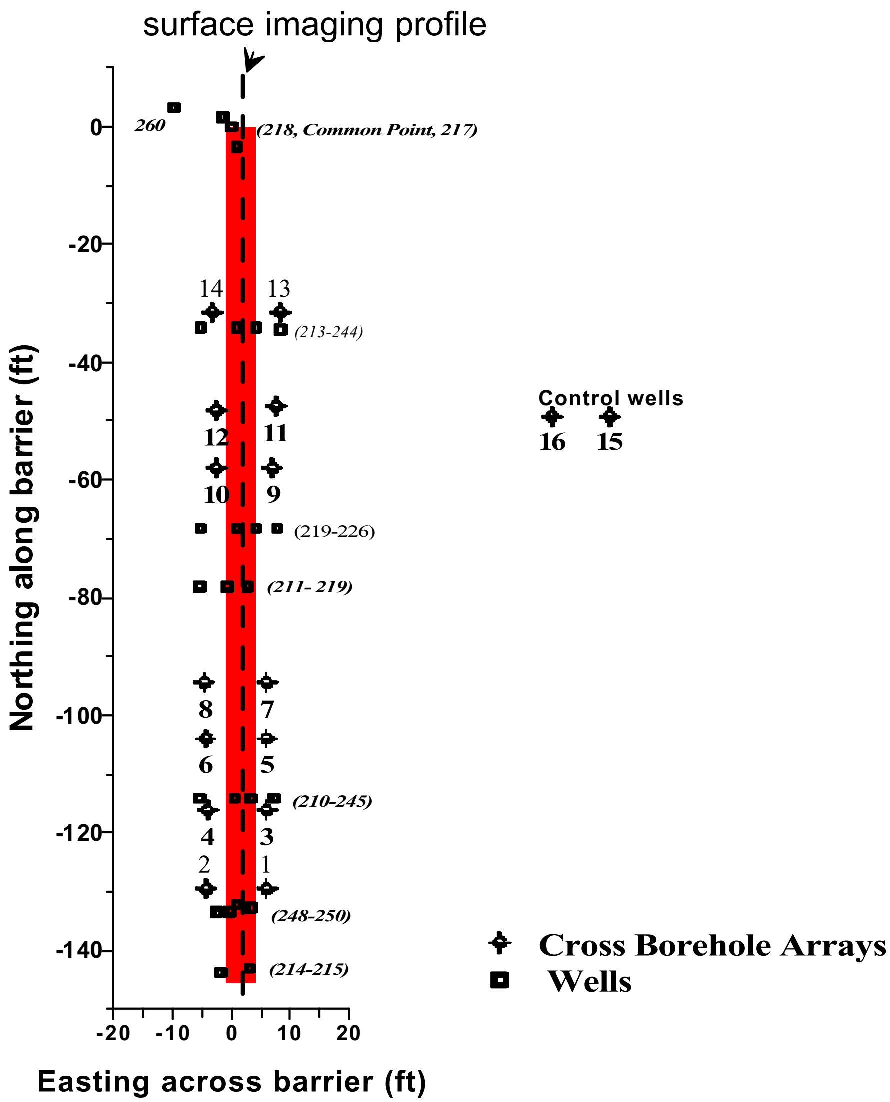

Figure 2: Plan view of PRB, location of cross borehole imaging arrays, surface array and monitoring wells.

The cross-borehole dataset incorporated 770 measurements in which the current and dipole pairs were split between boreholes. The resolving capability of this measurement sequence was numerically assessed by generating a synthetic dataset. A forward solution was obtained for the model structure shown in Figure 1. The conductivity of the individual units was varied and multiple solutions obtained. These forward solutions were primarily a function of the modeled major conductivity contrast between conductive granular iron and the in situ sediments. Synthetic datasets were generated by adding 3 % random errors to these forward solutions, and an image of the model structure obtained by inverting these datasets assuming a homogeneous medium as a starting model. An example image is shown in Fig 3. It illustrates the general suitability of the selected measurement sequence for imaging the PRB depicted in Fig. 1, assuming that the conductivity of the granular iron is much greater than the natural material.

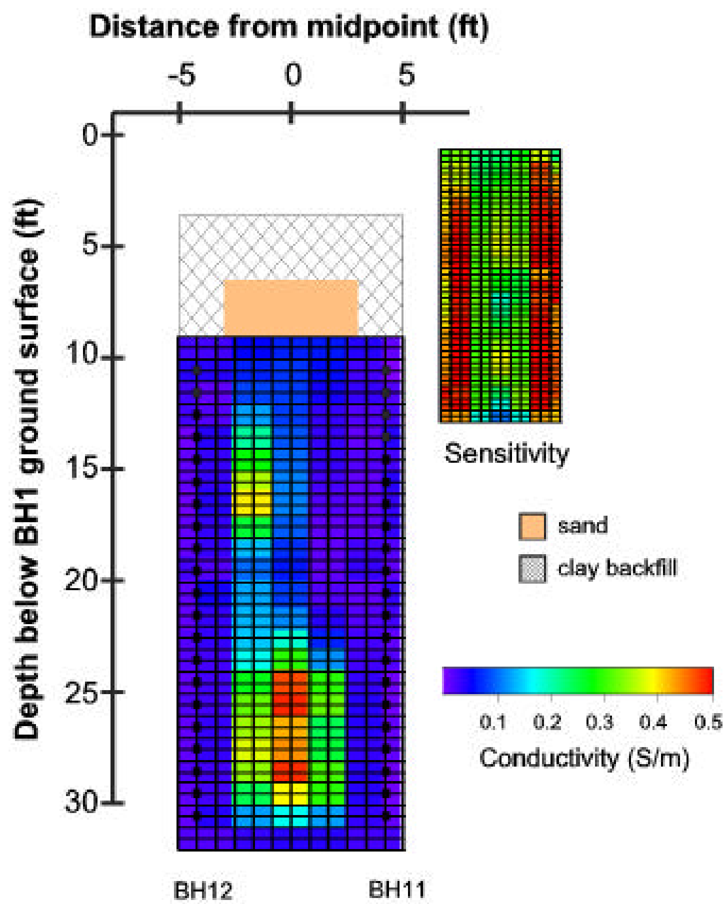

Figure 3: Synthetic image following inversion of a theoretical dataset created from a forward calculation for a model based on the design barrier geometry (Fig. 1) (PRB conductivity = 10^5 S/m in a 0.04-0.1 S/m background). The sensitivity image qualitatively depicts variability in image resolution on each plane (red is high sensitivity, blue is low sensitivity)

Field Results

Surface Imaging

The highly conductive PRB will channel current flow and hence limit the current penetration to depth achievable with surface imaging. This caused small voltage differences between potential electrodes at high n spacing, low signal to noise ratio and unacceptable reciprocal errors for approximately 25% of the measurements. These measurements were rejected prior to inversion. Figure 4 shows the 2D image of conductivity structure obtained from the surface survey. Summaries of drilling logs at three points along the barrier are shown for comparison. The imaging resolves a highly conductive subsurface feature, with lateral and vertical dimensions generally consistent with the PRB installation. However, due to the current channeling effect, definition of the basal boundary of the PRB is uncertain, and the apparent variability in the barrier thickness and conductivity is suspect. The imperfect correlation between the drill logs and resolved barrier geometry probably results from both image uncertainty and the very basic nature of the drilling record. These limitations, coupled with the fact that image resolution decreases with depth, suggests that surface imaging is only appropriate for defining the gross lateral and vertical extent of the barrier.

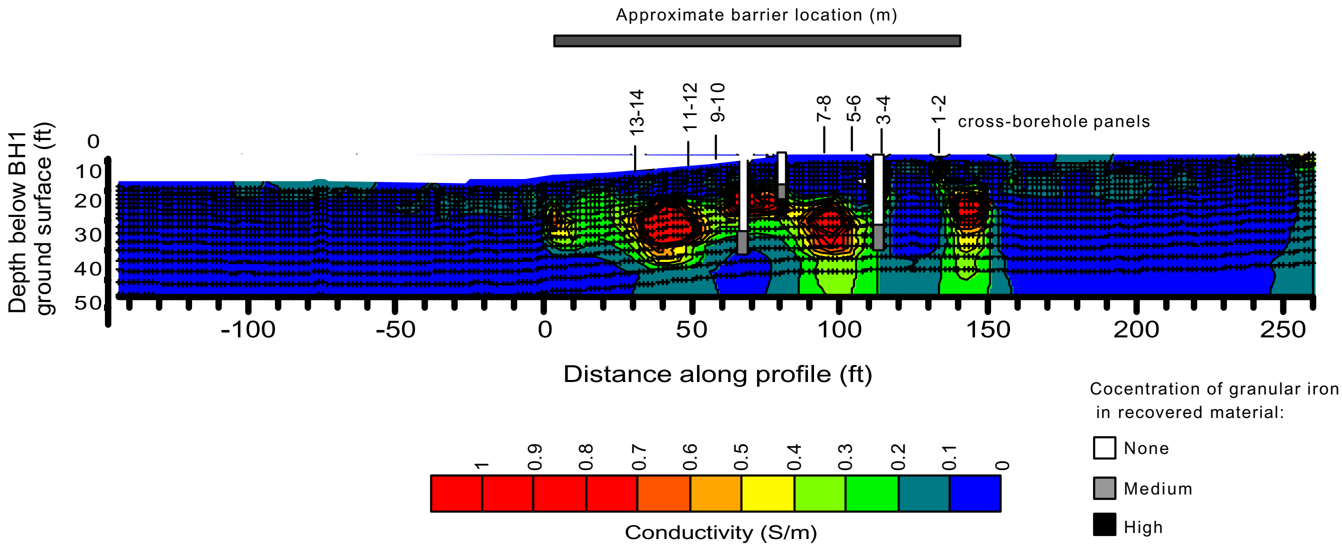

Figure 4: Conductivity structure obtained from surface electrical imaging along the long axis of the barrier (see Fig. 2 for line location). Estimated PRB location, drill log results and position of cross-borehole imaging panels also shown.

Cross-Borehole Imaging

Cross-borehole conductivity images for panels 1-2, 3-4, 5-6, 7-8, 9-10, 11-12,13-14 and 15-16 (a control panel away from the barrier) are shown in Fig. 5a and g. Image resolution is constant with depth. The general cross-sectional geometry of the barrier is well resolved by the inversion. The finite element mesh is superimposed on the images for comparison with Figs. 1 and 3. Assuming that Fig. 1 faithfully represents the cross-sectional barrier geometry along the PRB, the inversion precisely resolves the granular iron. The PRB is highly conductive: note that the resolved iron conductivity is greater than that predicted for the synthetic dataset based on a 10^{-5} Ohm m PRB.

The images show evidence for considerable variability in the integrity of the barrier along the long axis. Most apparent is the weak barrier response observed on panel 13-14. Synthetic modeling verified that this difference is not a function of the slightly greater between borehole spacing on this panel. This weak response most likely reflects a deficiency in barrier integrity during emplacement. Alternatively, it could conceivably reflect barrier degradation: the effectiveness of PRBs in hydrocarbon remediation is reduced with time as the reaction process converts the granular iron into iron oxides. However, although the lifespan of a PRB is unclear and dependent on numerous factors, appreciable deterioration is unlikely over only three years of operation. Panel 3-4 also exhibits evidence for reduced barrier integrity in the lower, thicker portion installed in the basal gravel.

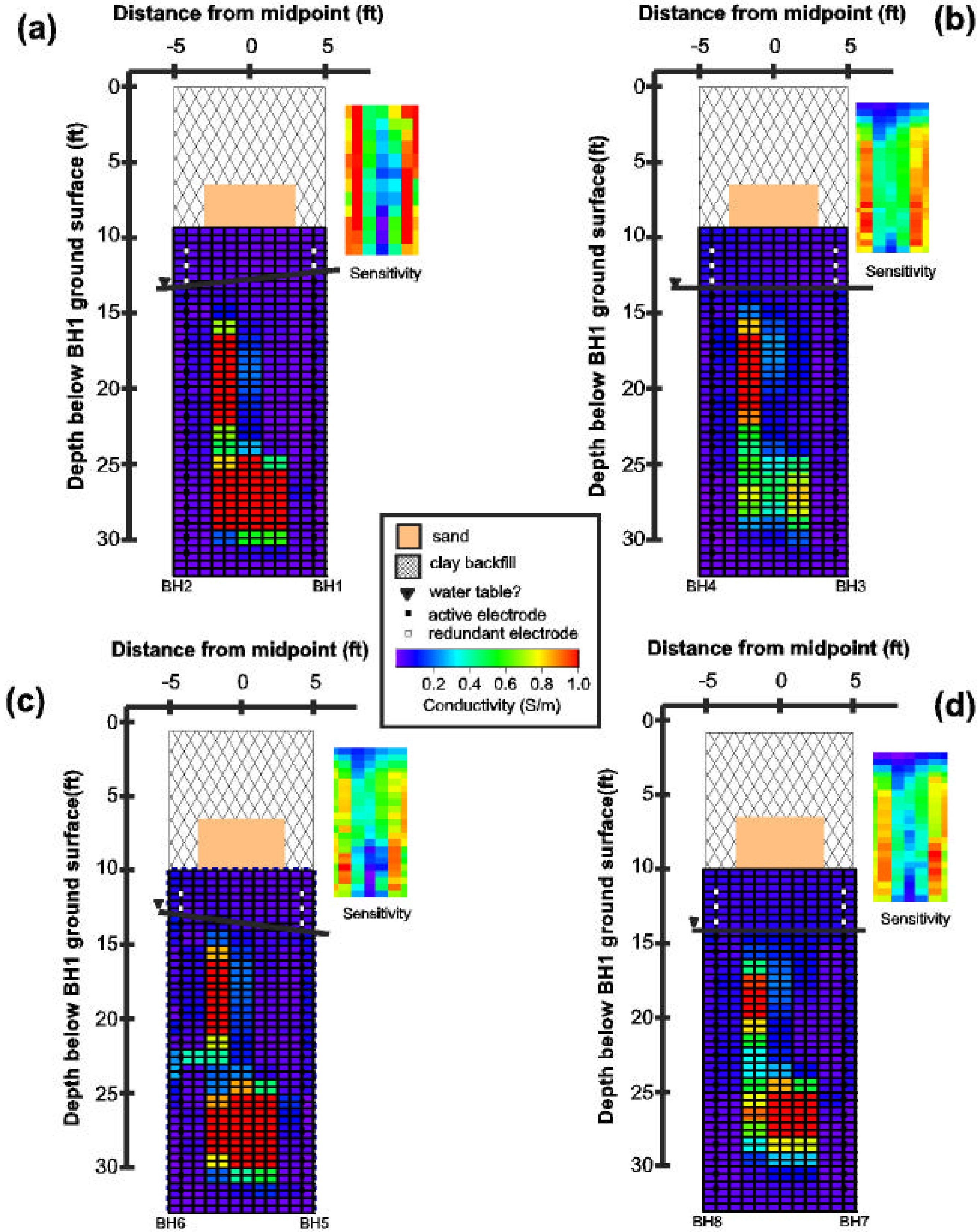

Figure 5: Cross-borehole electrical images of PRB integrity. The sensitivity image qualitatively depicts variability in image resolution on each plane (red is high sensitivity, blue is low sensitivity) (a) BH1-BH2 (b) BH3-BH4) (c) BH5-BH6 (d) BH7-BH8

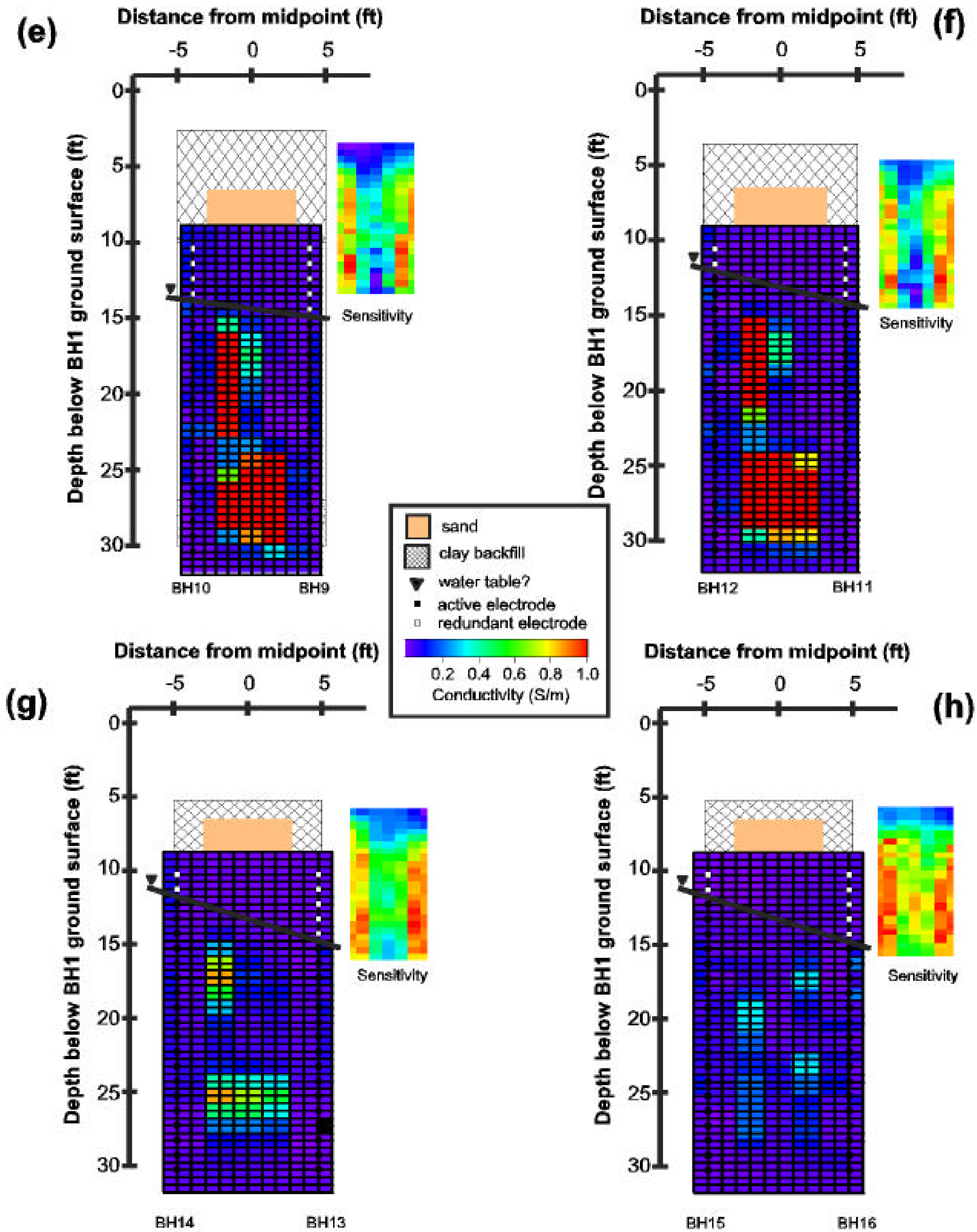

Figure 5 (continued): Cross-borehole electrical images of PRB integrity. The sensitivity image qualitatively depicts variability in image resolution on each plane (red is high sensitivity, blue is low sensitivity) (e) BH9-BH10 (f) BH11-BH12 (g) BH13-BH14 (h) BH15-BH16 (control)

One important aspect of PRB emplacement is whether good contact with the underlying bedrock is achieved. Gaps between the PRB base and bedrock may permit bypassing of contaminated groundwater. Fig. 5 illustrates considerable variation in electrical structure of the base of the PRB (the bedrock surface is at approximately 30 ft). However, the PRB emplacement procedure utilized here permitted visual verification of the bedrock contact and there is no evidence for seepage of contaminated water through the base of the PRB. Thus, the significance of this observed variability is uncertain and currently requires further investigation.

An additional interesting feature of these images is the consistently weak conductivity response where the upper (2 ft wide) and lower (6 ft wide) segments of the barrier join. This is most apparent in Fig. 5c, 5e, 5f and 5g. It might indicate a problem with barrier integrity resulting from emplacement of granular iron as the infill switched from 6 ft granular iron to 4 ft sand and 2 ft granular iron. However, inversion performance on a synthetic model of the barrier wall indicates that barrier definition is compromised at this locality: i.e. this feature results from a limitation in algorithm performance (Fig. 3). Consequently, the significance of the observed variability in iron resolution within this vicinity along the PRB length is unclear.

Summary

Electrical imaging is a very effective tool for in-situ verification of PRB integrity. The distinct geometry of the PRB at the DOE Kansas City Plant is well resolved from inversion of cross-borehole electrical measurements. This is a convincing demonstration of the utility of electrical imaging in engineering studies. The images provide evidence for variability in integrity of the iron along this PRB. Surface electrical imaging was of limited value, other than in defining the basic lateral and vertical extent of this PRB.

Elevated contaminant concentrations downgradient of this PRB have been observed at the southern end of the installation. Flaws in the barrier integrity and bypassing of contaminated water around the southern end of the barrier have both been invoked as explanations for this observation. The electrical imaging does not support a problem with barrier integrity towards the southern end of this PRB. This suggests that the problem is associated with bypass flow of contaminant around the southern edge of this barrier. We anticipate improvements in electrical imaging of PRBs by application of 3D data acquisition and inversion algorithms.

Acknowledgements

This work was supported by US Department of Energy under contract DE-AC04-01-AL66850. UMKC undergraduate student Richard Rudd assisted with field data acquisition.

References

1. Bing, Z. and S.A. Greenhalgh (2000), "Configurations for cross-hole resistivity tomography", *Geophysical Prospecting*, 48, 887-912.
2. Binley, A., Ramirez, A. and W. Daily, "Regularised image reconstruction of noisy electrical resistance tomography data", in: *Process Tomography - 1995, Proceedings of the 4th Workshop of the European Concerted Action on Process Tomography*, Beck, M.S., Hoyle, B.S., Morris, M.A., Waterfall, R.C. and Williams, R.A., ed., Bergen, 6-8 April 1995. 401-410.
3. Dahlin, T. and M.H. Loke, (1998) "Resolution of 2D Wenner resistivity imaging as assessed by numerical modelling", *Journal of Applied Geophysics*, 38, 237-249.

4. Dahlin, T. and Z. Bing, Z. (2001), “A numerical comparison of 2D resistivity imaging with eight electrode arrays”, *Proceedings of the Seventh Meeting of Environmental & Engineering Geophysics, EEGS-European Section*, September 2nd-6th, Birmingham, UK.
5. Daily, W. and A. Ramirez, (1995), “Electrical resistance tomography during in-situ trichloroethylene remediation at the Savannah River site”, *Journal of Applied Geophysics*, 33, 239-249.
6. Daily, W. and A. Ramirez (2000), “Electrical imaging of engineered hydraulic barriers”, *Geophysics*, 65, 83-94.
7. Daily, W., Ramirez, A., Newmark, R. and V. George (2000), “Imaging UXO using electrical impedance tomography”, *Journal of Environmental and Engineering Geophysics*, 5, 11-24.
8. Gavaskar, A.R., Gupta, N., Sass, B.M., Janosy, R.J. and D. O’Sullivan, (1998), “Permeable reactive barriers for groundwater remediation”, Batelle Press, Columbus, OH, 176pp.
9. LaBrecque, D.J., Miletto, M., Daily, W., Ramirez, A. and E. Owen, (1996), “The effects of noise on Occam’s inversion of resistivity tomography data”, *Geophysics*, 61, 538-548.
10. Ramirez, A., Daily, W., Binley, A., LaBrecque, D. and D. Roelant, (1996), “Detection of leaks in undeground storage tanks using electrical resistance methods”, *Journal of Environmental and Engineering Geophysics*, 1, 189-203.