Shallow EM investigations of AMD at an abandoned coal mine in northern West Virginia

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The production of acid mine drainage (AMD) from surface and underground coal mines in northern West Virginia is a major environmental problem and continues to receive much attention in affected communities. Remedial procedures are often established in response to the need to be in compliance with Surface Mining Control and Reclamation Act water quality standards. Lack of site-specific subsurface information often limits the effectiveness of remediation efforts and increases its cost. Current reclamation efforts are generally based on limited subsurface information and often do not include geophysical assessment studies. The potential use of terrain conductivity to characterize these sites, monitor remedial efforts, and provide additional subsurface information is often overlooked. Traditional methods of site characterization and evaluation include water quantitative and qualitative testing. Additional understanding of the subsurface conditions at a site can be obtained through terrain conductivity measurements.

Terrain conductivity, also known as electromagnetic (EM) induction, has been used successfully in the last 15 years to delineate zones of AMD and detect pillar locations of shallow coal mines. High conductivity associated with AMD and its sources (primarily pyrite) is a good target for electromagnetic detection. Because terrain conductivity data can be collected rapidly and interpreted easily, it is found to be the most effective geophysical technique for characterizing surface mine sites before implementation of remediation programs. A similar study using shallow EM to characterize a manufacturing site with disposal pits was successfully completed by Nobes and McCahon (1999).

Data were collected over a mine spoil area in northern West Virginia and used in conjunction with hydrologic, geochemical, and borehole data previously collected to develop a better understanding of subsurface conditions at the site. The 80-acre mine site investigated (Figure 1) has produced some of the worst AMD problems in West Virginia surface mines due to low pH, high acidity, high metal concentration, and high sulfate content. Terrain conductivity surveys revealed possible locations of post-treatment sludge and lime slurry plumes at 4.5-25.5 m depth. The metal-rich sludge and alkaline slurry appears as an anomalously high conductivity region. High conductivity zones extending downgradient from sludge-filled and slurry-filled pits at the surface suggest the terrain conductivity method can be used to identify preferred flow paths in a mine-spoil area as well. Other anomalies observed in the spoil may help define AMD source and collection areas and help assist in the design of remedial efforts.

Site background. The Pittsburgh and Sewickley coal seams were mined using surface mining techniques between 1981 and 1987 and the site was later backfilled and recontoured to the original topography. Efforts to characterize the mine-spoil aquifer have included the installation of 38 wells. Five of these wells are 4-inch injection wells for alkaline fluids. Efforts to treat the AMD in situ have taken place in recent years and have included injection of sodium hydroxide (NaOH) into the spoil as well as surface applications of posttreatment alkaline sludge and lime slurry into ditches. It was found that the injected sodium hydroxide had little if any impact on the pH of springs that discharge from the aquifer.

Injection of NaOH solutions have likely produced sludge of reaction products on the pitfloor surrounding the injection wells. Concentrated sodium hydroxide and metal-rich sludge have higher conductivity than native groundwater; therefore, remaining plumes and/or sludge bodies are likely to be detected as regions of anomalously high conductivity.

On the surface, three trenches were dug to dispose of treated sludge and AMD. These trenches are located near a groundwater divide and trend northwest-southeast in the western portion of the site (Figure 1). The sludge is a slurry of alkaline metal-rich hydroxide solids formed by lime treatment of AMD seeping from the spoil. Application of activated lime and ammonia to AMD at the site results in an increased pH, and the associated geochemical reactions cause the metals in solution to precipitate in ponds downstream of the treatment area. Because the sludge is moderately alkaline and because its disposal is expensive, it is transported to the top of the mine spoil by vacuum truck as needed and emptied into the southern surface trench. The alkalinity left in the sludge is believed to help neutralize AMD in the spoil, increasing its pH. The metal-rich sludge appears more conductive than the surrounding spoil and creates an anomalously high conductivity at the surface.

Terrain conductivity. Data collected at the site included three terrain conductivity profiles and a 2D grid of EM profiles over the two older trenches. A 20-ft station grid was used for the EM31 (3.7 meter vertical dipole) surveys, and
A 40-ft spacing was used for the 10- and 20-m horizontal and vertical (EM 34-3) surveys. These data are presented as lines 1 through 3 in profile form (Figures 2a-4a) and as cross-sectional plots of conductivity (Figures 2b-4b). The cross-sectional plots were generated by using the exploration depth of each reading as the Y-axis and plotting the actual measurement in the Z-axis. In this section, numerous interpretations are made.

**Line 1.** Several anomalous features appear in the profiles. Line 1 runs north-northwest to the southeast on the east side of the trenches in the center of the spoil, as shown in Figure 1. Changes in apparent conductivity along the line indicate a change in subsurface conditions from the central and northern end of the line to the southern end. The high conductivity region between wells GR-17 and GR-14 may be the result of sludge plumes migrating downward and outward from the sludge trenches to the west of the line.

**Line 2** runs perpendicular to line 1 and intersects it at GR-17 (Figure 1). This line passes between the surface trenches. Along this line, two distinct conductivity highs appear on either side of the trenches, each with a different character. The locations of these peaks adjacent to the trench suggest they are the result of sludge plumes migrating down into the spoil from the surface trench. However, this interpretation is complicated by the fact that a buried sludge-filled trench is present west of the existing trench and would be expected to create a conductivity high. Although the western peak may be a static high related to a buried trench, the eastern peak may represent a currently active sludge migration pathway. The region west of well GR-17 remains highly conductive, with the highest readings coming from the deepest sounding (20 m vertical). This suggests that the conductivity high is from a deeper source on the pitfloor or in the bedrock and may be associated with ponding of AMD or sludge on the pitfloor.

**Line 3** runs east-west along the break in slope in the northern section of the spoil. The western third of the line
shows relatively low conductivity at the surface with moderate conductivity readings at depth. A spike in conductivity at ~280 ft along the line may be associated with residual high conductivity material related to injections of sodium hydroxide (NaOH) in fall 1996. The western two-thirds of line 3 reveals the presence of increased shallow and deep conductivities. This implies that the subsurface in this region contains either greater quantities of conductive fluids.

**EM31 grid.** The EM31 instrument (3.7-m coil spacing) was used to collect regularly spaced data in the area around the sludge-filled trenches present at the site. The EM31 was operated in the vertical dipole orientation which provides an optimal exploration depth of approximately 4.7 m (15.2 ft). A 20-ft grid spacing was used to collect the data and a fairly complete grid was collected in six field days. The red area labeled Grid 1 in the Greer Site Map (Figure 1) represents the location of this grid. The EM31 response over the grid along with individual station locations is shown in Figure 5. The plot shows distinct conductivity highs around the trenches extending outward, anomalies B and C from the northern trench and anomalies D and E from the southern trench. The location of anomaly C also correlates to a buried trench. An additional conductivity high is seen in the northeastern quadrant of the plot (anomaly A). This feature is relatively linear and is believed to be a coal-refuse disposal pile. This pile is believed to be near the surface rather than on the pitfloor and is believed to contain significant quantities of pyrite-rich, AMD-producing refuse. Mine employees note that a refuse pile was placed in the area of anomaly A.

In March 1999 the EM31 grid was resurveyed to provide a time-lapse image of the shallow subsurface in this area. Comparison of the two surveys reveals relatively minor differences in the location and orientation of the anomalies. Some change was observed in anomaly B, which is less extensive and less intense in the latter survey. This is interpreted to be associated with migration of sludge into the spoil from the south trench. The change in extent and intensity of the high is interpreted to arise from the migration of sludge into the spoil.

**Terrain conductivity modeling.** Model studies of the data collected over the mine spoil are illustrated in the model derived along line 1 which crosses the northern trench in Grid 1 (Figures 1 and 5). This line was modeled to evaluate the possibility that plumes of sludge migrate down and out from the surface trenches. In this model the conductivity of the spoil was set at 6 mmho/m (the approximate lowest reading of the EM 34 over the site, representative of dry spoil) with a fixed depth of 20 m (6 ft) over the line (approximate depth to the pitfloor). An infinitely thick 10 mmho/m layer lies below the spoil. Within the spoil, a high conductivity (100 mmho/m) variable thickness plume of sludge was assumed to be present. This conductivity value comes from water conductivity of the sludge solution in well GR 17. The trench that this line transects was no longer being filled with sludge. The resulting three-layer model, where the thickness and depth of the sludge were varied, was derived through inversion to best fit the data (Figure 6a).

Comparison of observed and calculated values is shown in Figure 6b. The resulting model (Figure 6a) suggests that the higher conductivity zones near the trench are related to sludge applications at the surface. It also sug-
gests that high conductivity sludge plumes are still present in the subsurface near the northern trench and that they extend to the pit floor. The model-derived plumes come to within 2 m of the surface beneath the trench. The slightly irregular geometry of the plumes suggests that preferred flow paths may be present in the spoil.

**Conclusions.** Conductivity highs surrounding surface trenches filled with posttreatment sludge suggest that sludge plumes can be detected using measurements of terrain conductivity. Model studies suggest that applications of lime slurry into surface trenches affect the terrain conductivity along the flow path of the slurry and that these flow paths can be detected using terrain conductivity measurements.

This study suggests that terrain conductivity data will help assess how well in-situ remedial techniques such as sodium hydroxide injection and sludge additions are working. This study also provides evidence that geophysical techniques can be used during remedial efforts to target problem areas, site injection and monitoring wells, and better remedy the problems at a given site. By monitoring the changes in terrain conductivity during and after applications of sludge and slurry, it appears possible to map the flow paths of this injected material.

Future efforts at similar sites should include the use of geophysics in the planning and the initial stages of remedial efforts. Geophysical data collected in the early stages of a remedial effort provide baseline information on subsurface conditions at a site, help identify AMD source areas and, overall, provide background information to be used to better plan future activities and target areas of interest or concern. Additionally, geophysical efforts should include a time-lapse set of measurements to help discriminate changes associated with remedial efforts from those associated with topographic effects, differences in depth to target, variations in near-surface geology, the influence of preexisting fracture zones, etc., that produce conductivity variations across an area.


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