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# Using Helicopter Electromagnetic Surveys to Identify Potential Hazards at Coal Waste Impoundments

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**ABSTRACT:** In July 2003, helicopter electromagnetic surveys were conducted at 14 coal waste impoundments in southern West Virginia. The purpose of the surveys was to detect conditions that could lead to impoundment failure either by structural failure of the embankment or by the flooding of adjacent or underlying mine works. Specifically, the surveys attempted to: 1) identify saturated zones within the mine waste, 2) delineate filtrate flow paths through the embankment or into adjacent strata and receiving streams, and 3) identify flooded mine workings underlying or adjacent to the waste impoundment. Data from the helicopter surveys were processed to generate conductivity/depth images. Conductivity/depth images were then spatially linked to georeferenced air photos or topographic maps for interpretation. Conductivity/depth images were found to provide a snapshot of the hydrologic conditions that exist within the impoundment. This information can be used to predict potential areas of failure within the embankment because of its ability to image the phreatic zone. Also, the electromagnetic survey can identify areas of unconsolidated slurry in the decant basin and beneath the embankment. Although shallow, flooded mineworks beneath the impoundment were identified by this survey, it cannot be assumed that electromagnetic surveys can detect all underlying mines. A preliminary evaluation of the data implies that helicopter electromagnetic surveys can provide a better understanding of the phreatic zone than the piezometer arrays that are typically used.

## INTRODUCTION

On February 26, 1972, a coal waste impounding structure on Buffalo Creek in West Virginia collapsed, releasing approximately 132 million gallons of water (Davies and others, 1972). The resulting flood killed 125 people, injured 1,100, and left more than 4,000 homeless. Factors contributing to the impoundment failure included heavy rainfall and deficiencies in the foundation of the dam that led to slumping and sliding of the waterlogged refuse bank. This disaster resulted in regulations that govern the design of embankment structures for new impoundments (National Research Council, 2002). Since the implementation of regulations, no new embankments have failed. However, other types of impoundment failure have released water and coal slurry into streams. Some of these involved the breakthrough of water and coal slurry from impoundments into underground mines. The most notable incident occurred on October 11, 2000 near Inez, Kentucky where 250 million gallons of water and 31 million gallons of coal slurry from an impoundment broke into an underground mine and flowed via mine workings into local streams (National Research Council, 2002). Aquatic life was destroyed along miles of stream and temporary shut downs were imposed on a large electric generating plant and numerous municipal water supplies. This incident caused Congress to request the National Research Council to examine ways to reduce the potential for similar accidents in the future. The findings and recommendations of the National Research Council were published in a book titled

"Coal Waste Impoundments, Risks, Responses, and Alternatives" (National Research Council, 2002).

In response to the recommendations of the National Research Council, the Robert C. Byrd National Technology Transfer Center (NTTC) at Wheeling Jesuit University in Wheeling, West Virginia contracted Fugro Airborne Surveys to conduct helicopter electromagnetic (HEM) surveys of 14 coal waste impoundments in southern West Virginia. The Department of Energy, National Energy Technology Laboratory (NETL) was asked to process, interpret, and validate survey data. The surveys were part of a federally funded pilot project to help reduce the dangers of coal slurry impoundments by: 1) identifying saturated zones within the coal waste, 2) delineating the paths of filtrate flow beneath the impoundment, through the embankment, and into adjacent strata or receiving streams, and 3) identifying flooded mine workings underlying or adjacent to the waste impoundment. It was anticipated that HEM surveys could show the flow path of filtrate through the embankment or into adjacent strata. This information may be useful for predicting impoundment failures or detecting possible impoundment-related contamination of local streams and aquifers.

## Survey Description

### *Site Selection*

NTTC selected 14 impoundments for airborne FDEM surveys from a list of impoundments in southern West Virginia that were given a moderate or high hazard potential rating based on the height of the embankment, the volume of material impounded, and the downstream effects of an impoundment failure (MSHA, 1974, 1983). Impoundments with moderate hazard potential are in predominately rural areas where failure may damage isolated homes or minor railroads, disrupting services or important facilities. Impoundments with a high hazard potential are those where failure could reasonably be expected to cause loss of human life, serious damage to houses, industrial and commercial buildings, important utilities, highways, and railroads.
The list of selected impoundments was transferred to the National Energy Technology Laboratory where flight areas were determined by constructing a bounding rectangle that enclosed the impoundments and ancillary structures, and included approximately a 1-km wide buffer around the impoundments. An effort was made to include known underground mines in the surveyed areas. The corner coordinates for flight area boundaries were transferred to Fugro Airborne Surveys for final flight planning.

### *Data Acquisition*

In July 2003, Fugro Airborne Surveys performed frequency domain electromagnetic (FDEM) surveys of the selected coal refuse impoundments using the RESOLVE electromagnetic data acquisition system. This system consists of five coplanar transmitter/receiver coil pairs operating at frequencies of 385 Hz, 1.70 kHz, 6.20 kHz, 28.1 kHz, and 116 kHz and one coaxial transmitter/receiver coil pair that operated at a frequency of 1.41 kHz. Separation for the five coplanar coil pairs was 7.9 m; separation for the coaxial coils was 9 m. A complete description of the RESOLVE data acquisition system is available at http://www.fugroairborne.com/service/resolve.php. An optically pumped cesium vapor magnetometer mounted within the RESOLVE sensor was used to acquire total field magnetic data concurrent with the collection of electromagnetic data.

The surveys were flown using an Ecureuil AS350-B2 helicopter with the RESOLVE sensor suspended about 30 m beneath the helicopter as a sling load. Survey information was acquired by flying parallel lines approximately 50 m apart while attempting to maintain the sensor at an altitude of 35 m. However, the average sensor height during these surveys was 45 m because the rugged terrain, trees, and numerous power lines necessitated flying higher in certain areas for safety. At an average flight speed of 90 km/hr, the 10 Hz data acquisition rate resulted in one reading every 2.5 m along the flight line.

### *Data Processing*

Preliminary data processing, including leveling and digital filtering, was performed by Fugro Airborne Surveys. Electronic data were then transmitted to NETL for additional processing, analysis, and interpretation. These data included conductivity maps for six frequencies, a total magnetic field (TMF) map, and a comma separated value (CSV) file containing leveled in-phase and quadrature data, and navigational data.

At NETL, conductivity and TMF maps were incorporated into GIS projects constructed for each site. Within the GIS environment, the locations of conductivity anomalies were spatially related to specific attributes of each coal refuse impoundment and the locations of known underground mine workings. In-phase and quadrature data were used to construct conductivity/depth images (CDI) using EM1DFM software. CDI sections were related to features on maps and air photos using custom viewing software developed at NETL (Veloski and Lynn, 2005).

## RESULTS AND DISCUSSION

Coal waste impoundments are predominantly constructed of both coarse and fine coal waste, which can contain varying amounts of water. Coarse coal waste is used to construct the embankment of the impoundment because it is relatively homogeneous in particle size and strength characteristics, and is therefore a predictable construction material (National Research Council, 2002). Slurry containing fine coal waste is hydraulically discharged into the decant pond behind the embankment where solids settle, the coarsest material closest to the discharge point. In the more distal parts of the settling basin, water is decanted and recycled to the processing plant. Water also filters through the coarse coal refuse in the embankment or infiltrates into adjacent or subjacent strata. In typical impoundment construction, lifts of coarse coal refuse may be juxtaposed or superposed with fine coal refuse depending on the type of embankment raising employed.

### Magnetic Response of Coal Waste

Coal waste commonly contains fugitive magnetite from the coal cleaning process and, therefore, exhibits a magnetic response that contrasts sharply with that of surrounding strata. A map of the total magnetic intensity (Fig. 1) can be used to delimit the areal extent of coal waste.

Furthermore, during the construction of a coal refuse impoundment, coarse and fine coal refuse are handled separately and differently, and this may result in different magnetic signatures. Fine coal waste is deposited from a slurry, which allows magnetite dipoles to orient with the earth's magnetic field (detrital remanent magnetism) prior to deposition. In contrast, the orientation of magnetite dipoles in coarse coal refuse is random because the material is mechanically emplaced using trucks or conveyers followed by grading and compaction. Magnetic signatures from both coarse and fine coal waste are expressed downstream from the crest of the embankment where coarse coal waste overlies fine coal waste. Fine coal waste predominates in the decant basin of the impoundment; the magnetic signature for slurry deposited coal waste is expressed in this area.

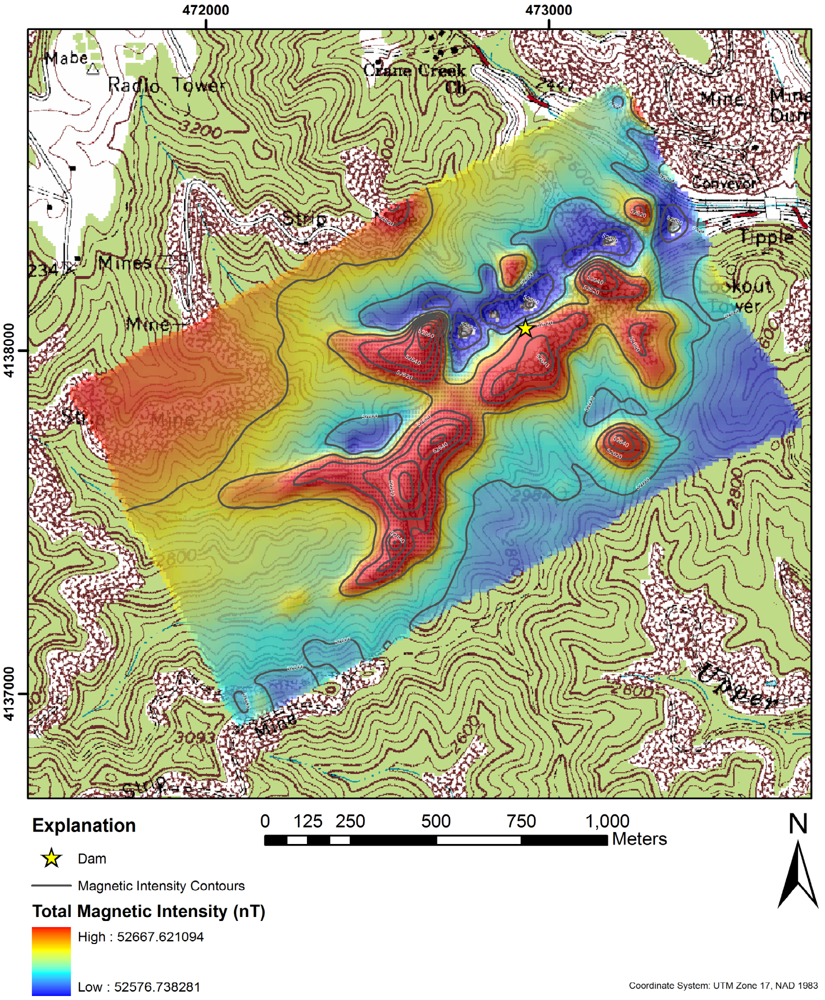


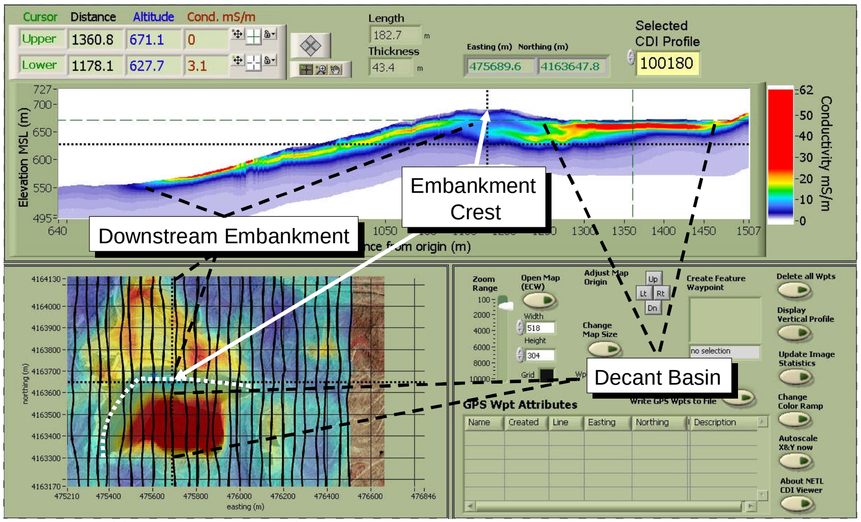
**FIG. 1.** Total magnetic field map of a coal waste impoundment in southern West Virginia.

## Electromagnetic Mapping of Coal Waste Impoundments

The HEM response to different materials within the coal waste impoundment depends largely on the porosity of the material and the degree of water saturation, given that the electrical conductivity of impoundment water is much greater than the bulk conductivity of dry coal refuse. Saturated material with high porosity will be the most conductive. Saturated, well compacted material (lower porosity) will be somewhat less conductive. The least conductive material will be poorly compacted, coarse coal waste that is placed above the water table. Because of significant conductivity differences between saturated and unsaturated material, HEM can provide a clear demarcation between the vadose and phreatic zones within the embankment. When material is obviously below the water table, HEM provides an indication of porosity; more porous material will be more conductive. However, HEM does not provide an indication of permeability.

Figure 2 is a screen capture from custom NETL software that relates positions on a conductivity/depth image (CDI) to locations on a topographic map or georeferenced air photo. The CDI shows the EM1DFM model section for a flight line that crosses a coal waste impoundment. In the bottom left of the figure is an air photo of an impoundment with a colored, near-surface conductivity map and flight line map superimposed. Small, black-dotted crosshairs show coincident locations on the CDI and the air photo. Annotations point out major features of the coal waste impoundment including the decant basin and the crest and downstream parts of the embankment. The decant basin is the most conductive part of a coal waste impoundment because it often contains conductive, standing water several meters deep. In this case, the surface is less conductive than deeper areas of the decant basin, which may indicate that the conductive surface water has infiltrated or that lifts of coarse coal waste have been placed on the surface of the basin. The embankment crest is usually the least conductive area because it is composed of coarse coal waste placed high above the water table. The downstream embankment commonly contains conductive layers that represent the paths taken by water filtering through the embankment. Seeps are located where conductive layers are at or near the ground surface.

Figure 3 is a CDI and associated near-surface conductivity map that shows two conductive layers beneath parts of the decant basin and within the downstream embankment. Part of the decant basin’s surface is conductive, which may indicate the location of standing water. The embankment crest is also conductive, probably from efflorescence, a deposit of soluble minerals brought to the surface by capillary action and evaporation. The downstream embankment contains two conductors, a near-surface conductor and a deeper conductor that is about 30 m below the surface. The presence of two strong conductors in the downstream embankment is unique to this impoundment. Other impoundments contain only one or sometimes no strong conductors in the downstream embankment. This impoundment has a downstream raised embankment, which afforded the operator the opportunity to incorporate blanket drains during embankment construction. The deep conductor beneath the downstream slope of the embankment probably depicts the location of a blanket drain. Conductive areas on or near the surface of the downstream embankment are seeps where filtrate water surfaces or concentrations of soluble minerals were deposited by evaporation.



| Cursor | Distance | Altitude | Cond. mS/m |
|---|---|---|---|
| Upper | 1360.8 | 671.1 | 0 |
| Lower | 1178.1 | 627.7 | 3.1 |

Length 182.7 m

Thickness 43.4 m

Easting (m) 475689.6

Northing (m) 4163647.8

Selected CDI Profile 100180

Width 518

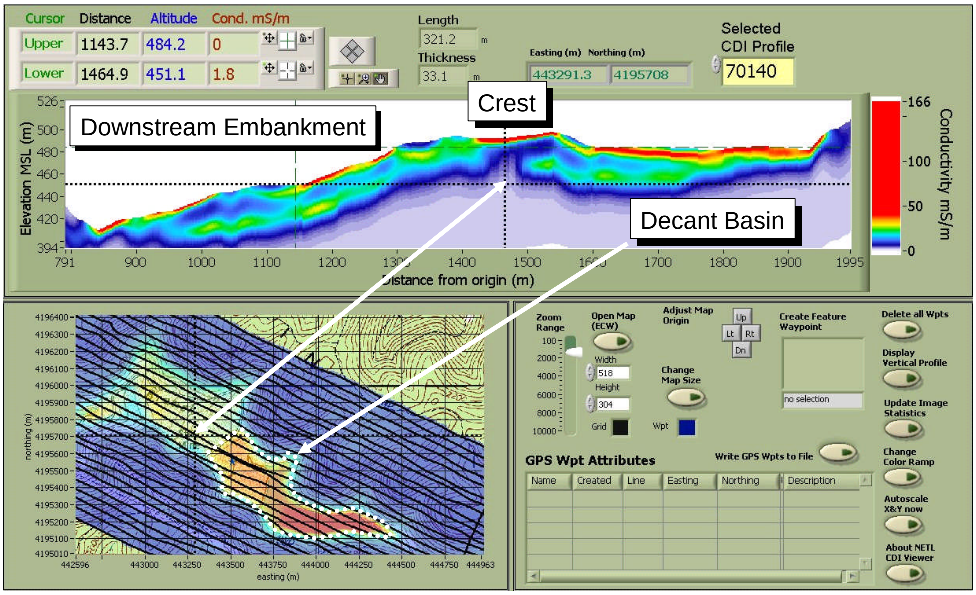
Height 304

GPS Wpt Attributes

| Name | Created | Line | Easting | Northing | Description |
|---|---|---|---|---|---|

no selection

**FIG. 2.** CDI showing different areas of a coal waste impoundment and typical electromagnetic response.



| Cursor | Distance | Altitude | Cond. mS/m |
|---|---|---|---|
| Upper | 1143.7 | 484.2 | 0 |
| Lower | 1464.9 | 451.1 | 1.8 |

Length 321.2 m

Thickness 33.1 m

Easting (m) 443291.3

Northing (m) 4195708

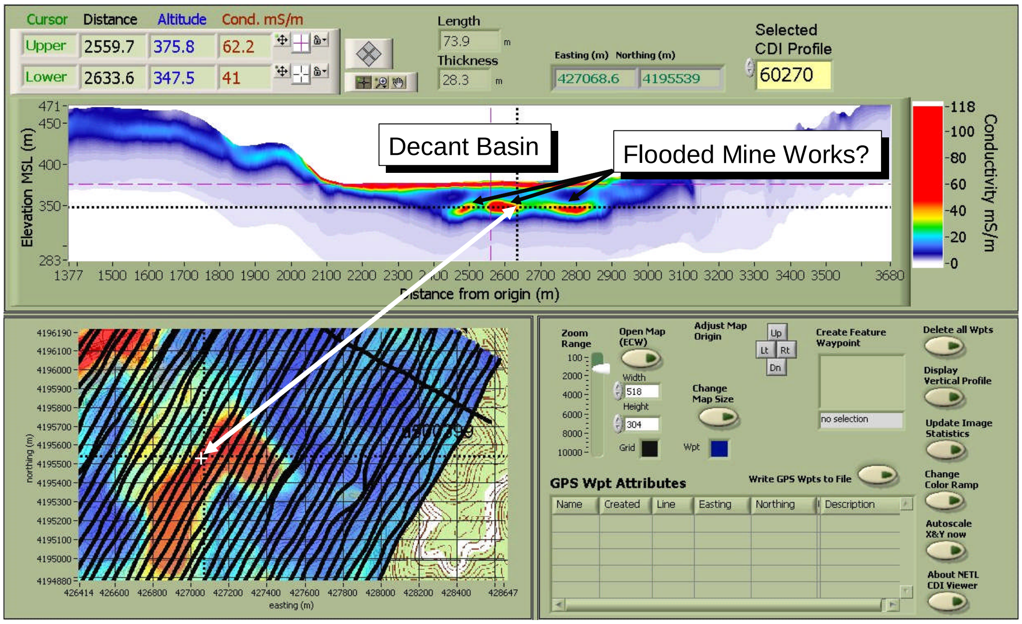
Selected CDI Profile 70140

Width 518

Height 304

no selection

**FIG. 3.** CDI from a flight line that crosses an impoundment with a downstream raised embankment.



| Cursor | Distance | Altitude | Cond. mS/m |
|---|---|---|---|
| Upper | 2559.7 | 375.8 | 62.2 |
| Lower | 2633.6 | 347.5 | 41 |

Length 73.9 m

Thickness 28.3 m

Easting (m) 427068.6

Northing (m) 4195539

Selected CDI Profile 60270

Width 518

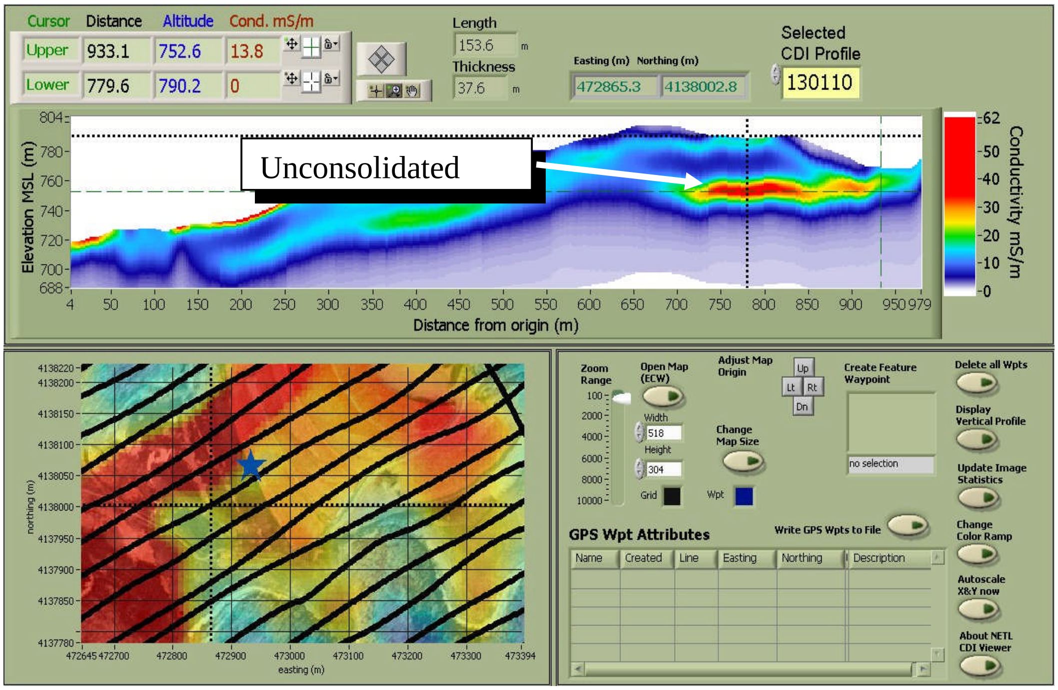
Height 304

no selection

**FIG. 4.** CDI showing flooded mine workings beneath decant basin.

Figure 4 is a CDI from a flight line that crosses the decant basin of an impoundment thought to be leaking into underground mine workings. This figure depicts a discontinuous conductor about 30 m below the surface of the decant basin that may represent flooded underground mine workings. Resistivity surveys conducted as part of the ground verification activities confirmed the existence of this conductor (data not shown). Although there are no records of an underground mine at this location and elevation, there are permits on record to auger mine the Winnifrede Coal at this location. The Winnifrede Coal occurs at the same elevation as the conductive anomalies. We suspect that the Winnifrede Coal was auger mined from a strip bench now buried beneath the decant pond, and that the flooded auger bores are the source of the conductive anomalies. Although, HEM surveys of the 14 impoundments identified numerous flooded mine workings that are above drainage, this is the only CDI that may show flooded, underground mine workings beneath the impoundment.

The flowable nature of unconsolidated slurry is a potential cause of impoundment failure, especially when deeply buried within the embankment. Unfortunately, locating pockets of unconsolidated slurry is a hit-or-miss adventure when drilling is used for detection. HEM can quickly locate pockets of unconsolidated slurry so that drilling and monitoring activities can be concentrated on smaller areas. Figure 5 is a CDI that shows a pocket of unconsolidated slurry 38 m below the top of the embankment. The coordinates for this conductive anomaly can be imported into a GPS-equipped PDA with a moving map, which would allow the impoundment operator to walk to a location on the embankment that is directly over the anomaly. Drilling efficiency is increased when directed by HEM results because all holes would be on target.



| Cursor | Distance | Altitude | Cond. mS/m |
|---|---|---|---|
| Upper | 933.1 | 752.6 | 13.8 |
| Lower | 779.6 | 790.2 | 0 |

Length 153.6 m

Thickness 37.6 m

Easting (m) 472865.3

Northing (m) 4138002.8

Selected CDI Profile 130110

Width 518

Height 304

no selection

GPS Wpt Attributes

| Name | Created | Line | Easting | Northing | Description |
|---|---|---|---|---|---|

**Figure 5.** CDI showing a pocket of unconsolidated slurry buried 38 m deep in the embankment.

## CONCLUSIONS

Helicopter electromagnetic surveys provide a 3-dimensional picture of the conductivity distribution within coal waste impoundments. NETL personnel have used ground resistivity surveys to confirm the accuracy of HEM results (ie. to corroborate the location, depth, thickness, and conductivity of conductors). For the purposes of this study, water is assumed to be the most conductive component of coal waste impoundments, and conductive areas are assumed to be areas of greater water content. Hydrologic interpretations that have been made using HEM data from 14 coal refuse impoundments appear to justify this assumption. However, if hydrologic interpretations based on HEM data are to be used for making regulatory decisions, the interpretations must be substantiated with results from accepted sources of hydrologic data.

Currently, we suggest only that HEM results be used to target investigations that use conventional methods to directly measure physical or hydrological properties.

Results of this study suggest that conductivity/depth images generated from HEM data can be used to identify many hydrologic features of coal waste impoundments. For example, the pathways taken by filtrate through the embankment can be discerned easily by following conductors from the decant pond through the embankment until they emerge on the downstream face. One can predict areas prone to seepage by noting where conductors are at or near the surface. Also, HEM should be able to detect flooded mine workings that are adjacent to coal waste impoundments. Detection of flooded mine workings beneath the impoundment is less certain, however, because the exploration depth of HEM is limited by the conductive materials that comprise the impoundment. HEM appears to be able to identify pockets of unconsolidated slurry in the decant pond or beneath the embankment.

Hydrologic features detectable by HEM have been linked to past impoundment failures. For example, HEM should be able to depict the location of the phreatic surface between the decant basin and its emergence on the downstream slope of the embankment. This knowledge will help identify sites of internal erosion (piping) or surface erosion. HEM also can locate large areas of unconsolidated slurry beneath the embankment that may be subject to fluid-like flow under certain conditions. Finally, any flow of water or slurry from the decant basin into flooded mine workings or aquifers will be detected by HEM if within the exploration depth of HEM.

The 14 impoundments were chosen for HEM surveys because they were assigned a medium to high hazard potential indicating the amount of damage possible should they fail. Because HEM can identify some subsurface conditions that are linked to impoundment failure, the higher density of coverage provided by HEM surveys (versus conventional monitoring) gives added assurance that potential problems at these impoundments will be identified and corrected.

## REFERENCES CITED

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