Using helicopter electromagnetic surveys to identify potential hazards at coal waste impoundments

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ABSTRACT
In July 2003, 14 coal waste impoundments in southern West Virginia, USA, were electromagnetically surveyed to detect conditions that could lead to impoundment failure, either by structural failure of the embankment or leakage through adjacent or underlying mine works. Specifically, the surveys attempted to: 1) identify saturated zones within the coal waste, 2) delineate the paths of filtrate flow through the embankment and into adjacent strata or receiving streams, and 3) identify flooded mine workings underlying or adjacent to the waste impoundment. In-phase and quadrature data from the helicopter surveys were inverted using EM1DFM software to generate conductivity/depth images. Conductivity/depth images were then spatially linked to georeferenced air photos or topographic maps for interpretation. The data indicates that helicopter electromagnetic surveys can provide a picture of the hydrologic conditions that exist within the impoundment. A similar approach can likely be used to detect potential problems at tailings dams.

INTRODUCTION
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 behind the embankment where solids settle, the coarsest material closest to the discharge point. In the more distal parts of the settling basin, some water is decanted and recycled to the processing plant. Other water 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. In general, the procedures employed are similar to those used in the construction of tailings dams.

On February 26, 1972, a coal waste impounding structure on Buffalo Creek in West Virginia collapsed, releasing approximately 132 million gallons of water (Davies *et al.*, 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 still govern the design of embankment structures for new impoundments in the U.S. (National Research Council, 2002). Since the implementation of these 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 945 million L of water and 117 million L of coal slurry from an impoundment broke into an underground mine and flowed via mine workings into local streams (National Research Council, 2002) (Figure 1). 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 the U.S. 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 the survey data.

Figure 1. River and bank material blackened with coal waste material due to impoundment failure near Inez, Kentucky

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 and that this information could 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 believed to have a moderate or high hazard potential 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 were in predominately rural areas where failure could damage isolated homes or minor railroads, disrupting services or important facilities. Impoundments with a high hazard potential were 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 using a bounding rectangle that enclosed the impoundment and ancillary structures and included approximately a 1-km wide buffer around the impoundment. An effort was made to include known underground mines in the surveyed area. Information pertaining to each impoundment is provided in Table 1. 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

Table 1. Coal waste impoundments surveyed using HEM

Name	Fugro ID	County	Company	MSHA Hazard Rank
Tioga	A	Nicholas	Gauley-Eagle Holdings	High
Cannelton	B	Kanawha	Cannelton Industries	High
Uneeda	C	Boone	Omar Mining Co.	High
Sylvester	D	Boone	Elk Run Coal Co.	High
Bob White	E	Boone	Jupiter Coal Co.	High
Sharples	F	Logan	Hobet Mining	High
Wharton	G	Boone	Eastern Associated Coal Co.	Moderate
Packville	H	Raleigh	Marfork Coal Co.	Moderate
Wharncliffe	I	Mingo	Mingo-Logan Coal Co.	High
East Gulf	J	Raleigh	Left Fork Coal Processing	High
Itman	K	Wyoming	Consolidation Coal Co.	High
Dott	L	Mercer	Consolidation Coal Co.	High
McComas	M	Mercer	Consolidation Coal Co.	High
Gary	N	McDowell	Antaeus Gary Project	Moderate

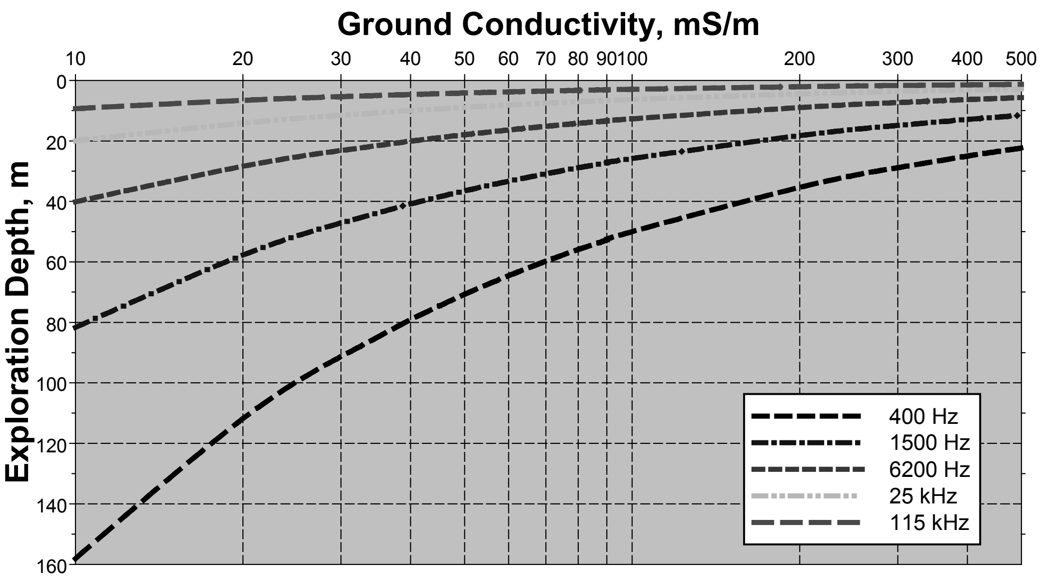

Figure 3. The lower the frequency, the greater average depth of the response

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. 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. A complete description of the RESOLVE data acquisition system is at: http://www.fugroairborne.com/Services/airborne/EM/resolve/index.shtml, but the key information is that lower frequencies penetrate deeper and thereby provide a signal that is averaged over a greater depth (Figure 3).

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 higher flight 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:

1. conductivity maps for six frequencies,
2. total magnetic field intensity map, and
3. leveled in-phase, quadrature, and navigational data.

At NETL, conductivity and total magnetic field intensity maps were incorporated into GIS projects constructed for each site. Within the GIS environment, the locations of conductivity anomalies can be spatially related to specific attributes of the coal refuse impoundment as well as 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 & Lynn, 2005).

Ground validation of airborne data
Ground verification generally confirmed the airborne results. DC resistivity profiles were acquired across recent pushouts (where coarse coal waste is mechanically placed on top of fine coal waste) at 2 impoundments to calibrate inversion results and verify CDI sections. The DC resistivity profiles were obtained using an AGI Supersting R8/IP resistivity meter with a Swift automatic 56-electrode system. IAlso, data from pre-existing piezometers were consulted, where available.

RESULTS AND DISCUSSION

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 (Figure 4) 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. The magnetic signature for slurry-deposited coal waste is expressed in the decant basin of the impoundment where fine coal waste predominates.

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 either the fine coal refuse or the coarse 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.

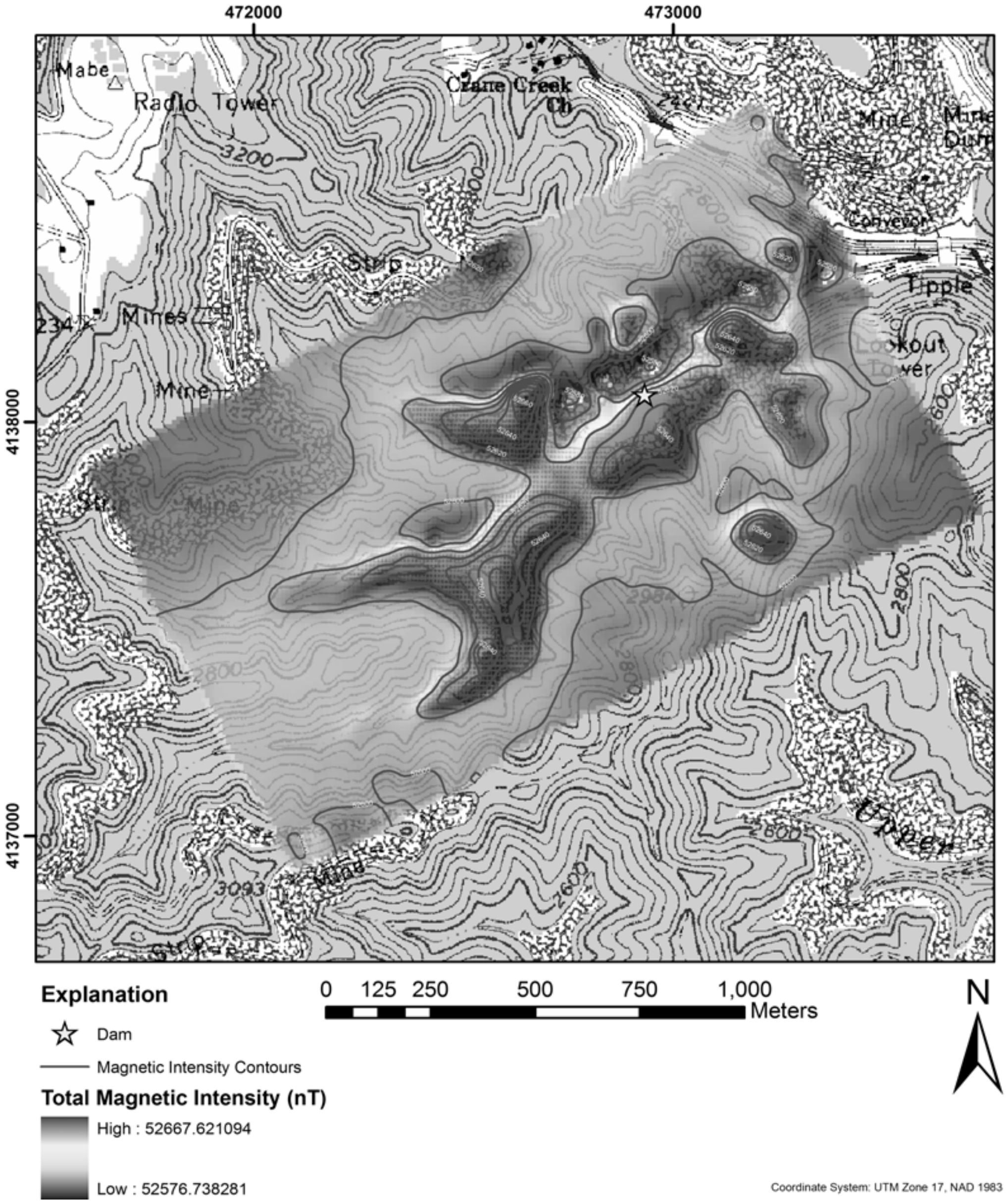

Figure 4. Magnetic intensity image of a coal slurry impoundment

Unfortunately, the conductivity/depth images lose much of their vitality when reduced to greyscale, so only a few of the many images will be reproduced here, and their potential value will be much clearer when viewed in color during the presentation. Figure 5 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 and springs are located where conductive layers are at or near the ground surface.

Figure 6 is a CDI and associated near-surface conductivity map that shows two distinct conductivity layers beneath the decant basin and within the downstream embankment. Unlike Figure 5, most of the surface of this decant basin is conductive, which may indicate the presence of standing water. The crest of the embankment is also conductive, which is unusual and may indicate operating procedures unique to this site. 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 also is unique to this impoundment. Other impoundments contain only one or sometimes no strong conductors in the downstream embankment.

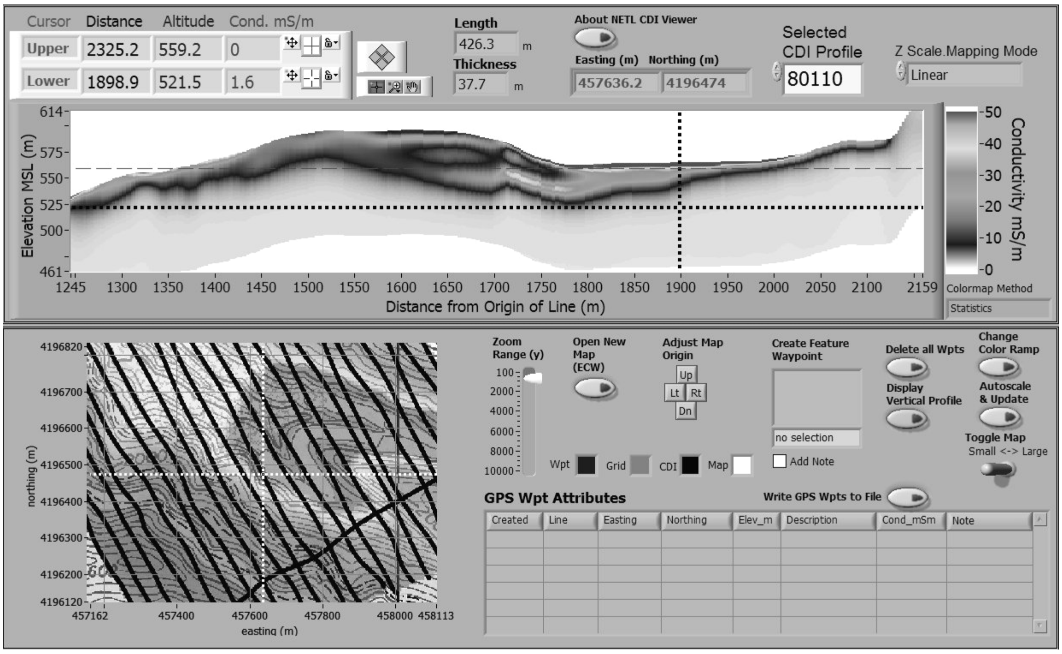

Figure 5. CDI of a coal waste impoundment showing filtrate flow path through the embankment

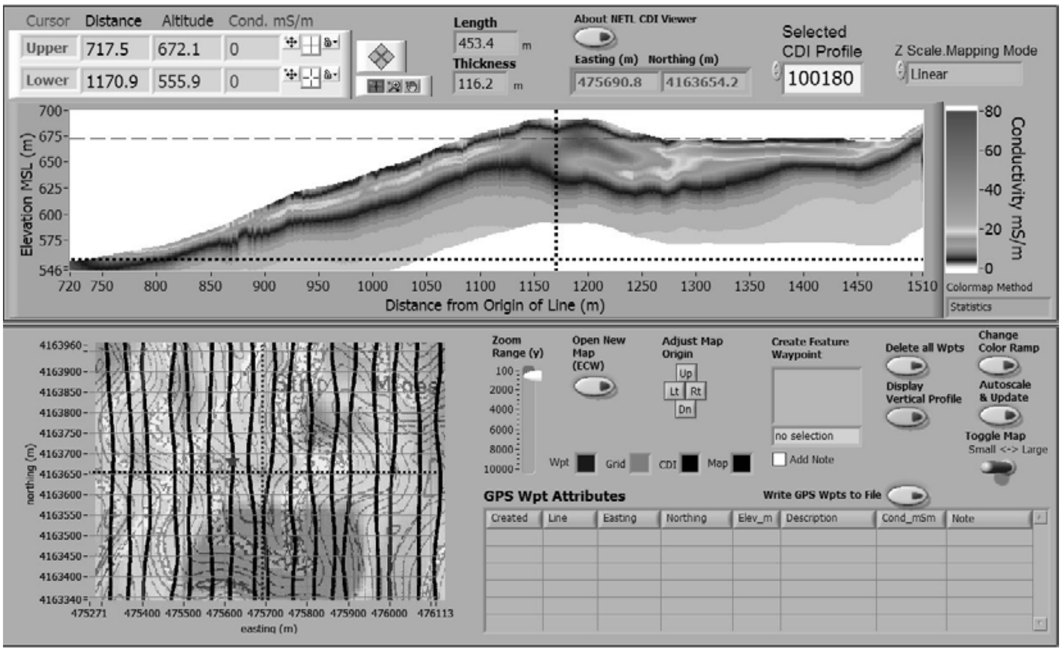

Figure 6. CDI of a coal waste impoundment with a shallow and a deep conductive layer downstream of the impoundment

Figure 7 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. The HEM surveys of the 14 impoundments identified numerous flooded mine workings that are above drainage. However, this is the only CDI that may show a below-drainage, underground mine.

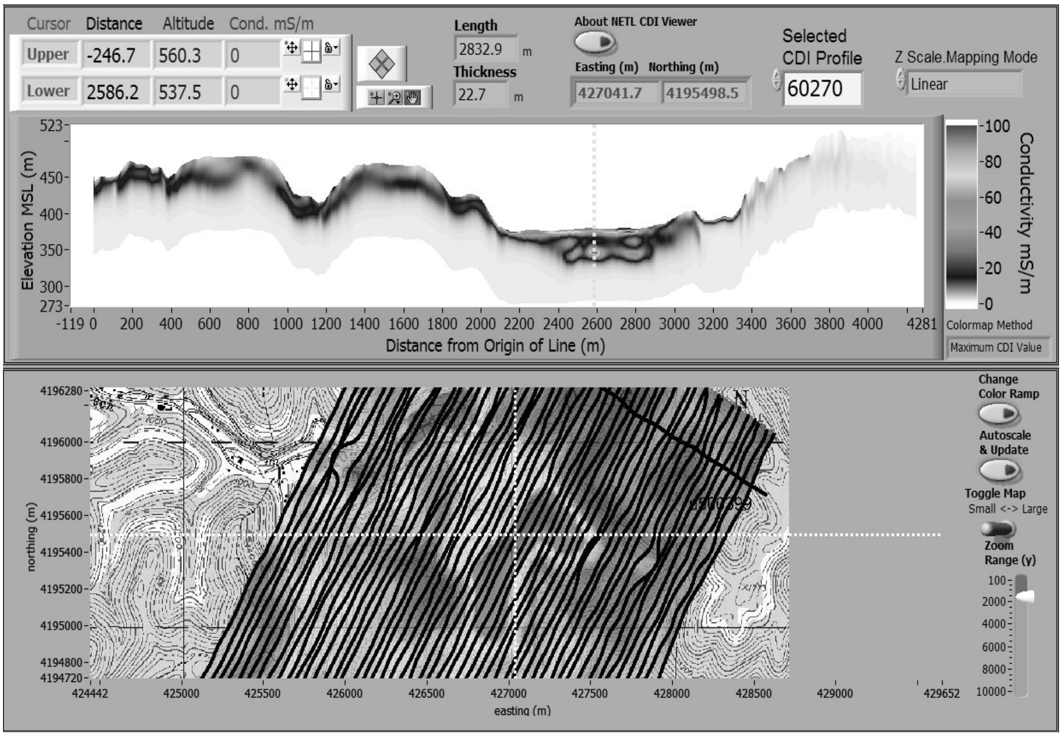

Figure 7. CDI of coal waste impoundment showing a discontinuous deep conductor that may represent flooded mine works

CONCLUSIONS

HEM surveys appear to provide a picture of hydrologic conditions within and to some extent beneath coal waste impoundments. Certainly, the paths taken by conductive filtrate through the embankment can be discerned easily. Moreover, porous, water-saturated zones within the decant basin are immediately recognizable. Results of these surveys suggest that HEM can detect flooded mine workings 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.

At this time, it would be premature to assume that a specific hydrologic feature identified by HEM surveys is an indicator of potential impoundment failure. Any such conclusion would require on-site confirmation of HEM results as well as an evaluation of details pertaining to the construction of each impoundment. However, the potential utility of obtaining useful and timely information about the subsurface without the necessity of expensive drilling, which is how subsurface information is currently obtained, is obvious. However, airborne EM and ground resistivity methods must be “calibrated” using conventional methods Ground investigations will be initiated soon to obtain down-hole induction logs and geophysical soundings, which will be used to calibrate or validate the EM1DFM model sections. Also, engineering drawings will be obtained for each impoundment so that hydrologic features identified by HEM can be related to specific design features such as the location of drains or the placement of specific types of coal waste. Saturated zones within the embankment that cannot be explained by impoundment design will then be evaluated as possible indicators of potential embankment failure.

The potential value of this technology to tailings impoundments should be obvious, and indeed, we have learned of at least one instance (unpublished) where an airborne electromagnetic survey was successfully used to assess leaks in a tailings dam. The survey also showed that a lake downstream was being affected by these leaks, based on increased conductivity.

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