



Case Studies of Mine Voids Using Continuous Vertical Electrical Sounding Methods

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Abstract

Deep-mine voids are an insidious hazard and early identification is imperative to minimizing subsidence to roads, bridges, buildings and other infrastructures. Continuous vertical electrical sounding (CVES) can be a rapid and effective tool for the detection of deep-mine voids; however, there are inherent issues with CVES including cultural noise, surface mining, and anomalous lithology. CVES imaging of a recently exposed limestone cave in State College, Pennsylvania documents the usefulness of CVES for the detection of subsurface anomalies.

Deep-mining for clay in St. Marys, Pennsylvania, an unusual and unexpected deep-mined rock type, proved to be a potentially hazardous threat to a proposed subdivision. The 7-meter thick sandstone overlying a 140-year old mine void in the Akron, Ohio area is slowly collapsing and subsidence may adversely impact roads and residences. CVES profiles indicated that subsidence may affect only 25 residences and that only 6 residences were exposed to immediate subsidence. A field in western Pennsylvania was cleared for the installation of a manufacturing facility; however, CVES showed that the building footprint overlapped a highwall and deep-mined workings. Borings showed that the highwall and deep-mine workings were present and the building was redesigned to accommodate the potential hazards from subsidence.

Introduction

Developing deep-mined properties has proven to be a considerable challenge to the engineer. The use of geophysical methods to image deep-mined properties has provided the design engineer options for development of otherwise untenable deep-mined properties. Continuous vertical electrical sounding (CVES) is arguably the most effective and least expensive geophysical method for imaging mine voids within 30 meters (100 feet) of the surface, which is considered the effective depth of potential surficial damage related to subsidence. The effective depth of potential significant surficial damage from deep-mine subsidence is regarded as 10 times the size of the height of the void (Piggot and Eynon, 1978).

This paper explores the capabilities of CVES to image subsurface voids associated with deep-mining. Three case studies are provided, including a clay deep mine, a deep-mined residential subdivision, and a surface and deep-mined property. An example of a profile across an exposed outcrop provides documentation of the effectiveness the CVES for imaging the subsurface.

Materials and methods

Electrical resistance is based upon Ohm's Law:

$$R = \frac{V}{I}$$

Where, resistance, **R**, is equal to the ratio of voltage, **V**, and to current flow, **I**. Resistivity depends upon the bulk property and geometry of the material, and is measured in Ohm-meters.

Currents are carried through earth materials by the motion of the ions in groundwater. Ions

in groundwater water come from the dissociation of salts and provide for the flow of electric current. Further, resistivity decreases in water-bearing rocks and earth materials with increasing; fractional volume of the rock occupied by water, salinity content of the water, permeability of the pore spaces, temperature (Mooney, 1980). Materials that lack pore space (i.e., limestone, igneous rocks) or lack water in the pore space will show high resistivity. Most earthen materials bearing some saturation, however, show medium to low resistivity.

In homogeneous ground, the apparent resistivity is the true ground resistivity; however, in heterogeneous ground, the apparent resistivity represents a weighted average of all formations through which the current passes. There are three main types of electrode configurations; Wenner, Schlumberger, and dipole-dipole. Each method exploits a different electrode array to image shallow or deep using their unique geometry. Additionally, the maximum depth of penetration is based, in part, upon electrode spacing, such that the greater the electrode spacing the deeper the survey depth of penetration.

Equipment

The resistivity surveys were performed using the ARES multi-electrode cable system (GF Instruments, s.r.o., Brno, Czechoslovakia). The ARES unit uses brass-steel alloy electrodes and stainless-steel cylinder-bearing cables. The CVES survey consisted of a 3-meter electrode spacing and line locations and elevations were ascertained with a differentially-corrected global positioning system (Trimble TSC-1).

Processing

A forward modeling subroutine was used to calculate the apparent resistivity values using the EarthImager program (AGI, 2003). This program is based upon the smoothness-constrained least-squares method (Loke and Barker, 1996). The smoothness-constrained least-squares method is based upon the following equation:

Where, \mathbf{F} is a function of the horizontal and vertical flatness filter, \mathbf{J} is the matrix of partial derivatives, μ is the damping factor, \mathbf{d} is the model perturbation vector and \mathbf{g} is the discrepancy vector.

The EarthImager program amortizes the bulk data into a series of horizontal and vertical rectangular blocks, with each box containing a number of records. Resistivities of each block are then calculated to produce an apparent resistivity pseudosection. The pseudosection is compared to the actual measurements for consistency (i.e., if the processed pseudosection varies significantly from the measured then the forward model is assumed to be inaccurate, and the model is rejected). A measure of the difference is given by the root-mean-squared error. Topographic corrections were applied to the profiles.

Case Studies

Three case studies are reviewed herein; however, a visual example is provided to show how CVES images the subsurface. The visual example was collected above a recent roadcut and shows the effectiveness of CVES to image the subsurface.

Visual example

The Cambrian-aged Warrior Formation is a karst-forming limestone deposit that crops out locally in central Pennsylvania (Figure 1). The Warrior Formation is a 400-foot thick, dark, argillaceous, fine-grained limestone that is characterized by containing oolites, stromatolites, and other fossils (Kauffman, 1999). Thin beds of dark, finely crystalline, silty dolomite are intercalated with the more massive limestone. This formation appears to have been deposited as a cyclic unit.

The Warrior is exposed at various locations in central Pennsylvania and is exposed in a recent road cut west of State College, Pennsylvania (Figure 1). The Warrior in this area occurs as the core of a local anticline and bedding has a strike of N65°W and dip of 40°SW (Hunter, 1977; Berg and Dodge, 1981). Topographic depressions indicative of karst terrain are evident in the area. A clay residuum of up to 3 meters overlies the Warrior throughout this area.

The construction of a highway ramp exposed the formation and a fracture-derived void. Close inspection of the partially clay-filled fracture void shows that the void opens up into the outcrop. The top of the outcrop was stripped of 2.1 meters of soil cover on the south side and the north side was left intact (Figure 2).

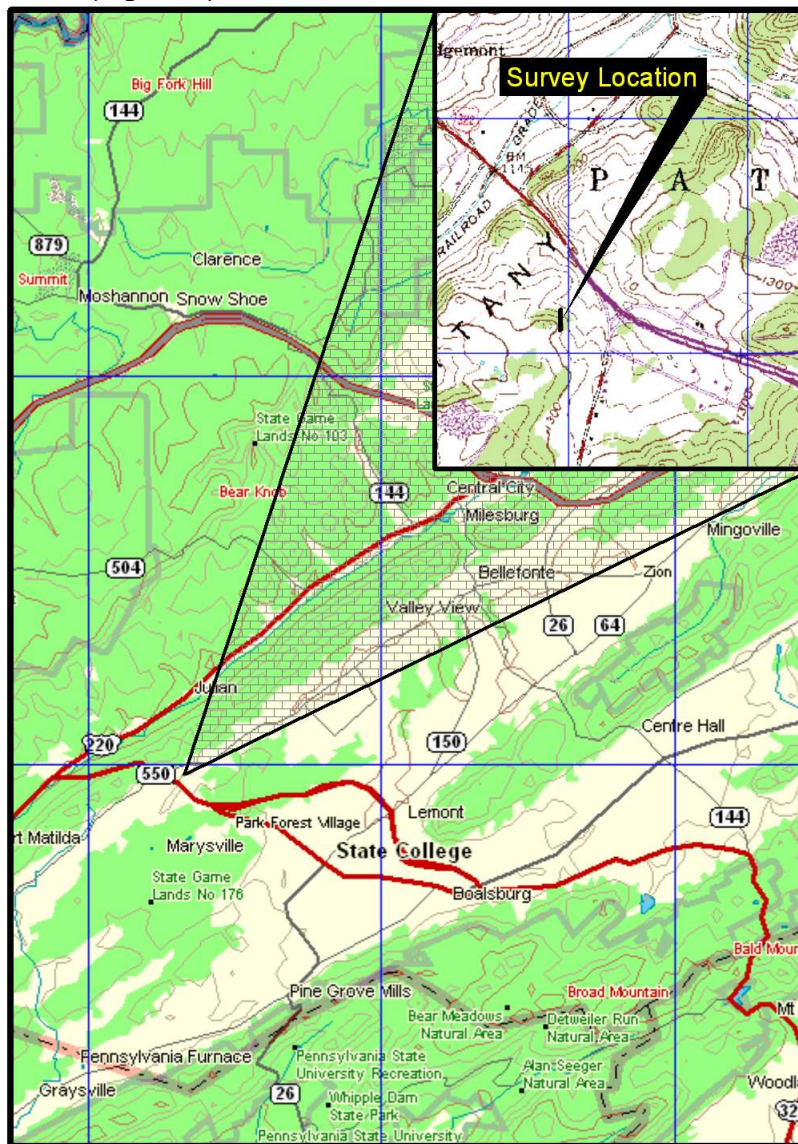


Figure 1. Location map of the recently exposed outcrop in central Pennsylvania, USA (scale 1" = 10 miles; inset scale 1" = 2,000', north to top of page).

The advantage of a computer-driven CVES system is that a large volume of data can be collected with a minimum of fieldwork (Reynolds, 1997). These profiles were collected approximately 15 meters back from the high wall for safety reasons; consequently, there may be rock variations within the outcrop that cannot be predicted from an examination of the exposed outcrop.

Massive limestone with a measured apparent resistivity of greater than 300 Ohm-meters is ubiquitous throughout the outcrop (Figure 3). The southern base of the outcrop has much lower apparent resistivities, suggesting that there is a void or at the least fractured and/or weathered bedrock within the outcrop. The northern half of the profile area had in-situ residuum at the surface; whereas in the southern half of the survey, the residuum had been stripped off during highway construction.

The profile imaged the centrally-located fracture-void, which has a 32° dip to the north. Further, the profile imaged bedding to a limited degree. The profile also predicts that another fracture may exist in the subsurface to the north of the one exposed at the outcrop. The weathered/fractured zone to the south is also well displayed on the dipole-dipole profile.

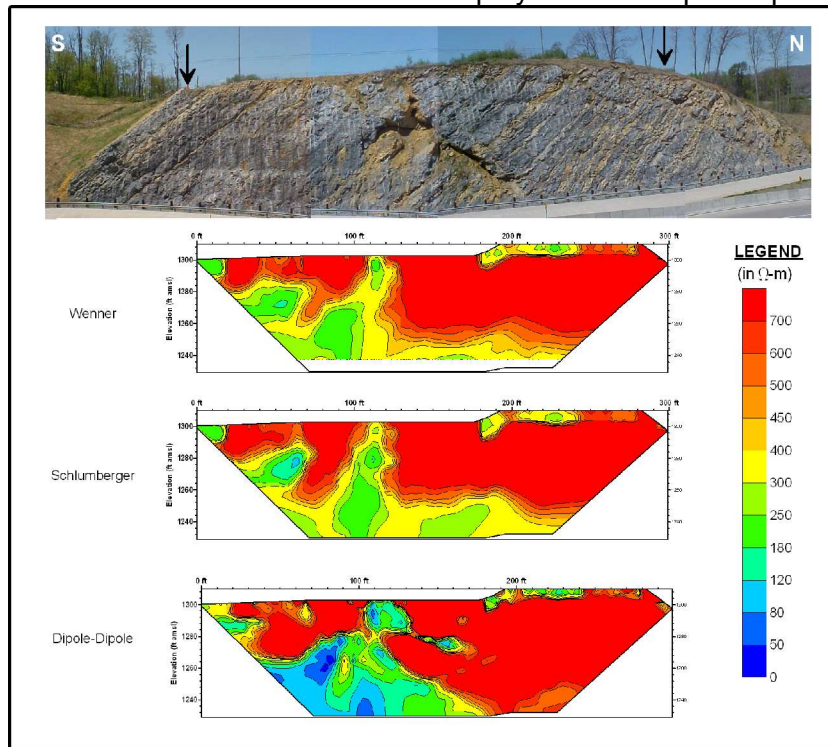


Figure 2. Selected CVES-array images of the recently exposed outcrop in State College, Pennsylvania.

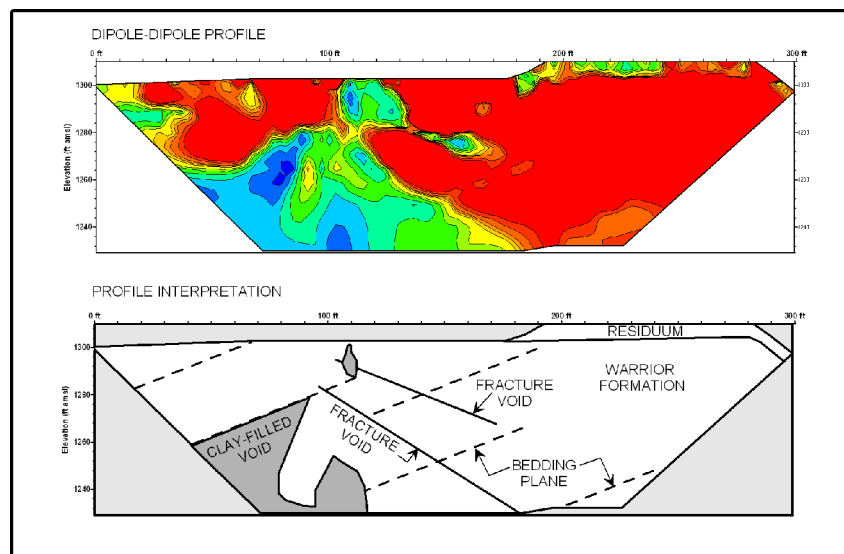


Figure 3. Interpretation of the dipole-dipole CVES profile.

Case study 1

The first case study compares the CVES profile with known mine maps and is based upon work provided in Hutchinson (2005) (Figure 4). The site is located in Elk County, which is within the glaciated portion of the Appalachian Plateau region of Pennsylvania (Heath, 1988). The soil in the study area consists of a thin veneer of Wisconsin(?) -aged till described as brown silt and sand with lesser proportions of clay that ranged in thickness from 3 feet to 15 feet.

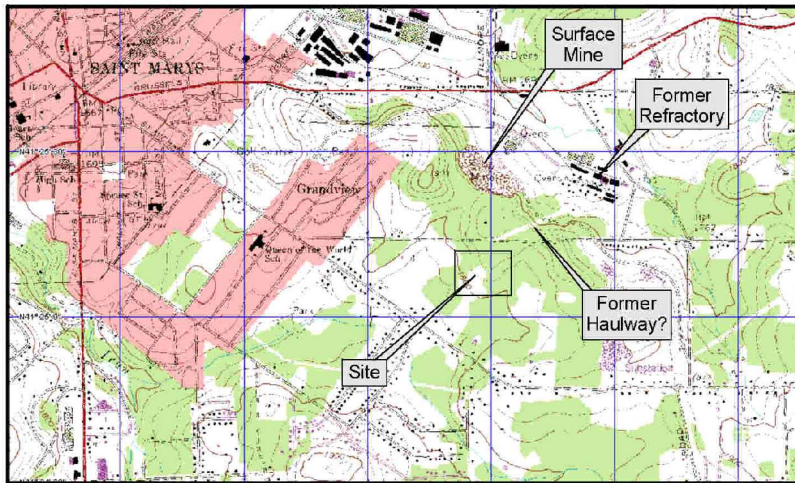


Figure 4. Portion of the St Marys, Pennsylvania 7.5 minute USGS topographic map showing the Case Study 1 area (scale 1" = 2,000').

Bedrock is part of the lower section of the undifferentiated Pennsylvanian-aged Pottsville Group (Figure 5). The Pottsville Group is relatively flat-lying and described as a weathered, brown claystone to siltstone with local thin coal seams. The Brookville Coal is exposed at the surface in the area and is underlain by the upper Mercer coal complex. The Upper Mercer Coal Complex occurs approximately 35 feet below the Brookville.

The Brookville Coal consists of approximately 18 inches of a low grade bituminous coal and a 2- to 3-foot thick plastic underclay (Figure 5). The underclay was exploited by surface mining methods at the turn of the last century for reportedly making sewer pipes. The Brookville Coal, a by-product of the clay mining operation, was used for firing the ovens. The underclay to the Brookville Coal is a plastic clay, reportedly rich in kaolinite.

The Upper Mercer Coal complex occurs at approximately 35 feet below the Brookville Coal and consists of an upper 12- to 18-inch thick coal and a lower 12- to 18-inch coal. Reportedly, these coal seams consist of a low quality bituminous coal, separated by 4 feet to 6 feet of plastic kaolinite-rich underclay. The deep mine for the Upper Mercer Coal complex included a drift from the Brookville Coal and underclay surface mine to the Upper Mercer Coal complex. Reportedly, the underclay to the upper coal and the lower coal were mined, with the lower coal used as an energy source for the operation of the ovens.

Inversions of measured apparent resistivity values with depth are interpreted to be subsurface anomalies (i.e., voids). In a relatively flat-lying homogeneous clastic stratigraphic setting, the resistivity profiles should show horizontal bedding; however, non-horizontal phenomena are interpreted to be subsurface voids. Deep apparent resistivities of less than 90 Ohm-meters (i.e., below the higher resistivities) were considered to be anomalous (Figure 6).

The area to the north of the investigation showed obvious signs of subsidence. The resistivity profiles show that several voids exist in the shallow subsurface at the site. A mine map

was procured from the Pennsylvania Department of Natural Resources and overlain on the profiles in as accurate a position, as is possible using the hand-drawn 80 year-old document. The profiles show an excellent agreement with the mine as mapped (Figure 6).

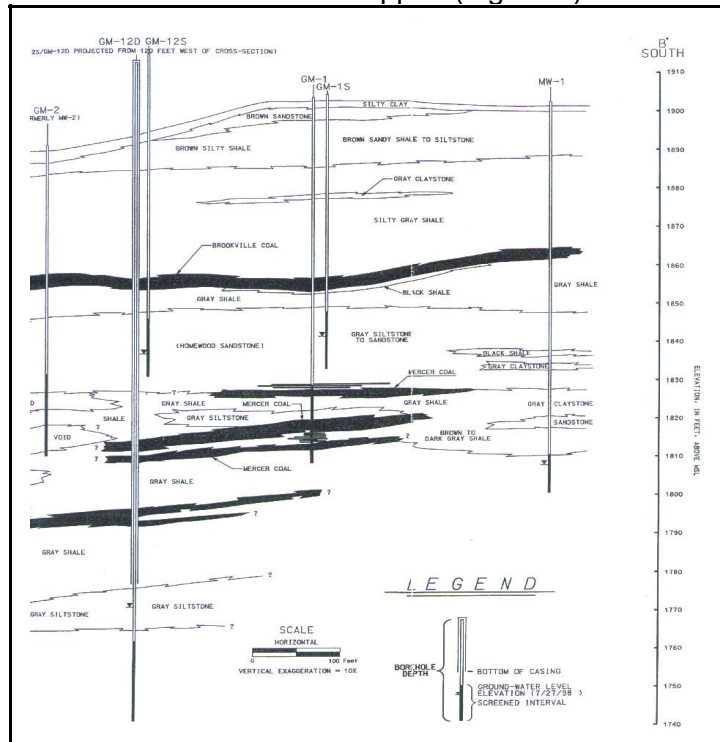


Figure 5. Generalized north-south cross section showing the coal seams and underclays in the St. Marys, PA area (scale as shown; from HydroSystems Management, Inc., 1998)

Profile A-A' (Figure 6) shows that there is no development of the mine to the northwest, which is consistent with the mine map. The southeastern portion of the profile indicates the presence of an inversion that extends 100 feet to the southeast. The map shows the presence of the main haulway and adjacent room located in this area. At approximately 350 feet along the profile, a minor inversion is noted and coincides with a room.

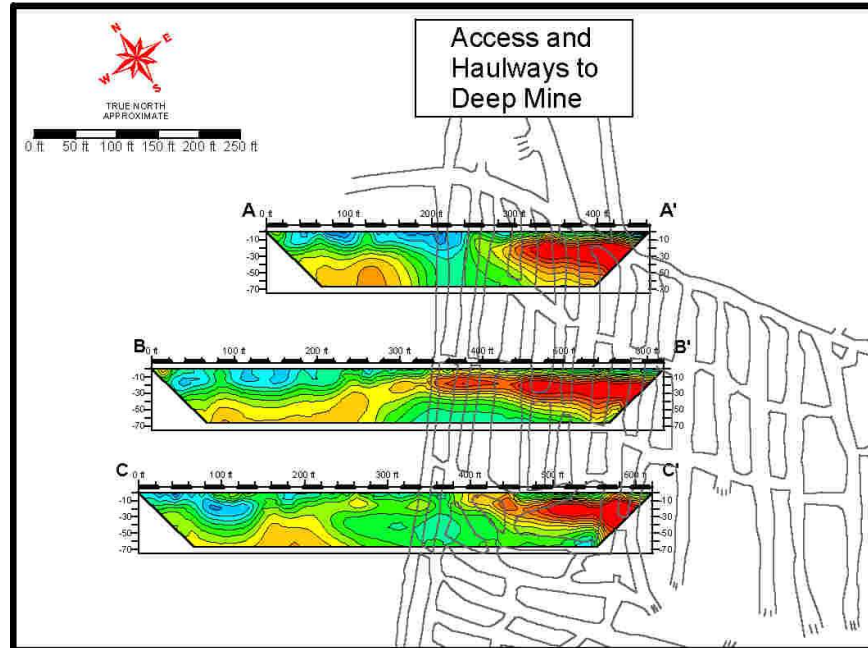


Figure 6. Hand-drawn mine map superimposed upon the exact locations of the EI profiles (scale as noted).

Profile B-B' (Figure 6) also shows no development of the mine to the northwest, consistent with the mine map. An inversion is present from 350 feet to 525 feet along the profile. The mine map shows that this inversion is the main haulway and a series of rooms that extend to the end of the profile. Note the room shown at the end of the profile coincides with a room.

Profile C-C' (Figure 6) indicates that the mine is developed to the northwest. The mine map also depicts a room extending to the northwest at this location. To the southeast, the profile shows a series of rooms that are evident on the mine map. One pillar is only vaguely shown on the profile. Collapse of the pillar may have interfered with the imaging of this feature.

The depth of the mine is reported to be 35 feet to 50 feet below grade. The profiles show that the mine voids are present at this depth. The lower apparent resistivity measurements above the mine voids are attributed to subsidence and increase permeability (thus better conductivity) in the roof materials. Surface expression of subsidence was not apparent in the field.

Case study 2

The second case study examines the impact of a 140-year-old deep mine beneath a residential subdivision. The work is based upon the work of Hutchinson and Barta (2003).

A subdivision within the City of Barberton was developed on a shallow, unmapped abandoned underground coal mine that dates to the 1870s (Figure 7). The mine exists beneath a 25-foot thick sandstone that is now, after 140 years, undergoing subsidence. Recently, localized subsidence in the subdivision overlying the deep-mine has prompted officials to determine if the homes are at risk. Shallow-focused electrical imaging profiles were collected near approximately 70 homes. Elevated measured apparent resistivity values indicate areas of subsurface voids or zones of fracturing related to adjacent voids.

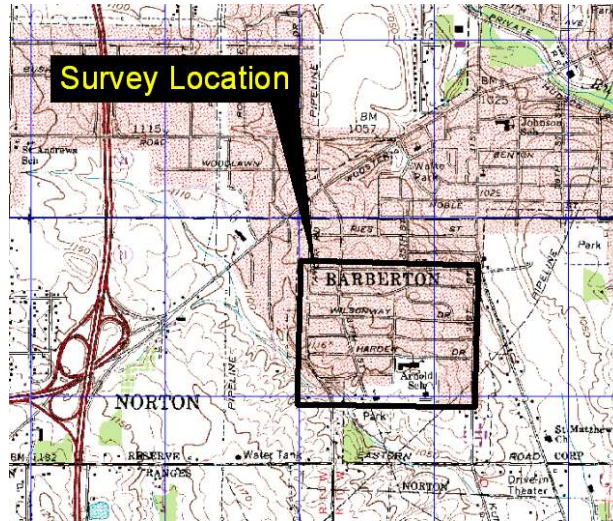


Figure 7. Portion of the Doyleston, Ohio 7.5 minute USGS topographic Quadrangle, showing Case Study 2 area (Barberton) (scale 1" = 2,000').

Due to the age of the coal mine, the shallow overburden above the mine, fluctuating groundwater conditions, and recent land development in the area, conditions were ideal for subsidence. The subsurface movement can cause extensive property damage and poses as a threat to the public health and safety.

The initial drilling program indicated that the occurrence of coal was local and not easily determined; consequently, voids would be difficult to locate and remediate (Figure 8). Twenty-five borings of 47 advanced, encountered mined-out areas (void, collapsed void, fractured overburden); 12 borings recovered coal, and 10 encountered non-coal deposits (Collins, 2001). An earlier investigation concluded that 1 church, 1 school, and potentially 56 homes lie above the mined out area.

The site is located in Summit County, which is within the glaciated portion of the Appalachian Plateau region of Ohio (Heath, 1988). The soil in the study area consists of Wisconsin(?) -aged till described as brown silt and sand with lesser proportions of clay that ranged in thickness from 3.0 feet to 15.0 feet, however, most soil extended somewhere in the range of 10.0 to 12.0 feet in depth (Collins, 2001).

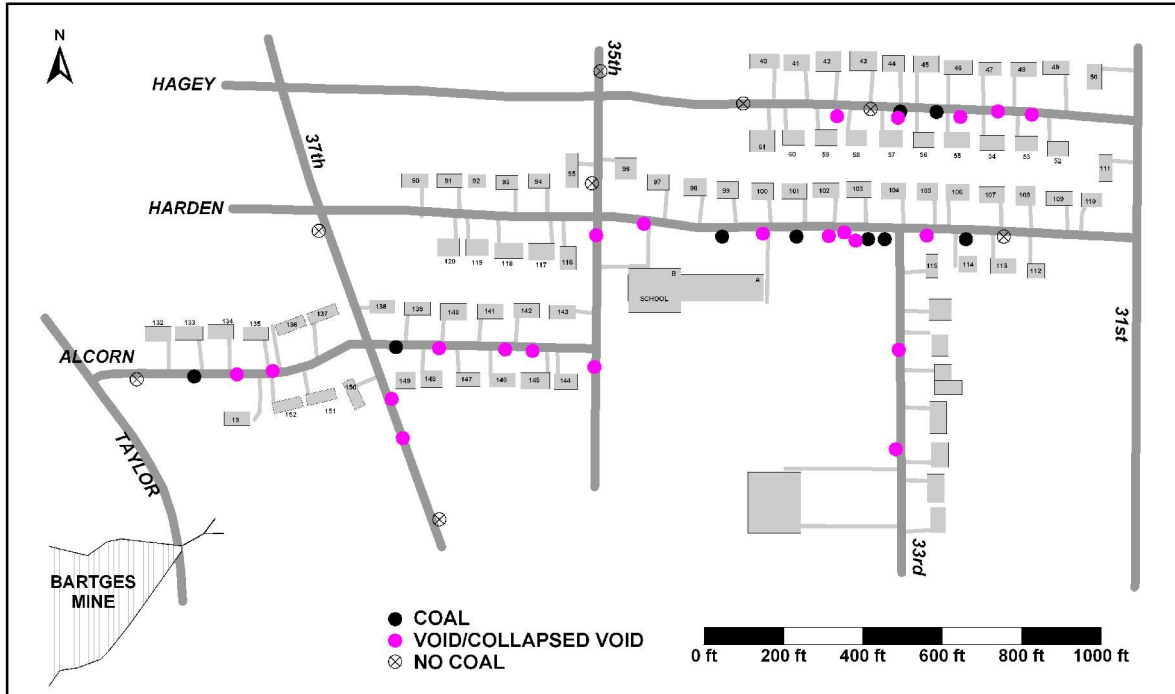


Figure 8. Location of borings in the Barbarton subdivision showing the occurrence of voids, coal, and non-coal deposits (scale as noted).

Bedrock is relatively flat-lying and described as a weathered, brown sandstone unit, with visible red (rust) staining. The sandstone unit, the Massillon Sandstone, contains an intercalated dark gray shale and is the roof material for the coal mine. Below the coal lies an approximately 2-foot thick under clay. The sandstone and coal are part of the Mississippian-aged Pottsville Formation. The deep-mined coal is designated as the Sharon (#1) coal.

The area of distribution of the Sharon (#1) coal seam in Summit County is localized due to deposition on uneven terrain and local erosion and deposition. The 10- to 25-foot thick Massillon Sandstone overlies the Sharon coal and locally replaces the coal entirely; resulting in a feature referred to as a “horseback.”

Recorded coal-mining activity occurred across the valley (i.e., west of the study area) at the Bartges mine (Map St-14; DeLong, 1981). The A.F. Bartges Company operated the mine in the late 1870’s and abandoned operations in 1876. The Sharon (#1) coal was removed using the drift entry method of coal extraction. The mine map shows that the face cleat is oriented N28oE. No deep-mine maps exist for the study area and the coal was removed either commercially or privately from this study area.

In a relatively flatlying homogeneous clastic stratigraphic setting, the resistivity profiles should show horizontal bedding; however, non-horizontal phenomena are interpreted to be subsurface voids. Resistivities of less than 90 Ohm-meters were considered background and resistivities between 90 Ohm-meters and 200 Ohm-meters were considered to be anomalous (Figure 9).

The area investigated shows obvious signs of subsidence and many residents complained of the appearance of holes in their yards. The resistivity profiles show that several voids exist in the shallow subsurface at the site (Figure 9).

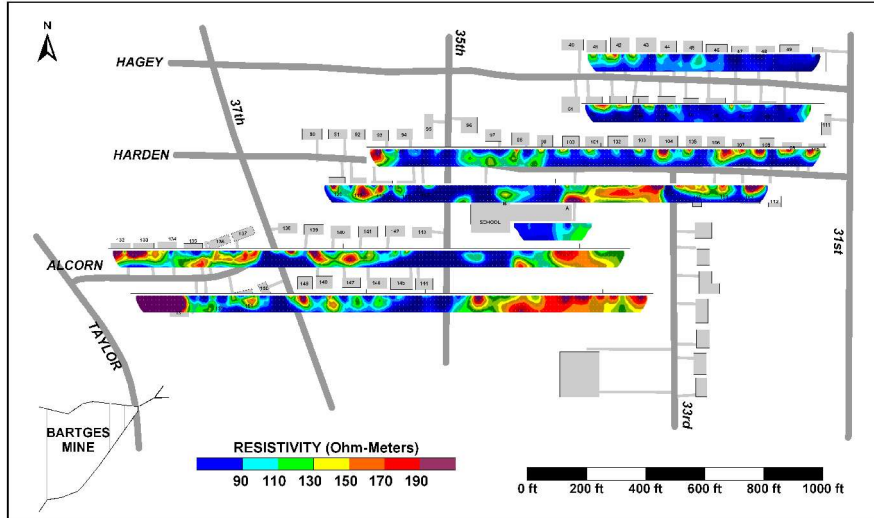


Figure 9. Seven electrical imaging lines located along the profile spatial position; showing undisturbed rock in dark blue and voids in red (no vertical exaggeration).

Electrical profiles imaged the subsurface in the front of 69 homes; of which 25 homes were considered to have a subsurface anomaly that may warrant further investigation (Hutchinson and Barta, 2004). Forty-four homes were not interpreted to have a subsurface anomaly that warrants further investigation. Of the 25 homes considered at risk, 9 are considered low risk (matrix value of between 16 and 18) than and 6 are considered high risk. Subsequent drilling of 10 wells, 9 targeting CVES-identified voids and 1 targeting solid coal, encountered 9 voids and 1 coal stump, as predicted through CVES methods.

Additional analysis of the study area mine can be derived from a review of the 1876 Bartges Mine map, which delineated a mining pattern to the development of the Bartges Mine (DeLong, 1981). Presumably mining in the study area occurred in a pattern similar to that of the Bartges Mine. This assumption is not too difficult to accept since miners often exploit coal preferential to butt and face cleat orientations, which would be structurally similar for both mine areas (Figure 10). Further, the presence of coal or voids in borings and the location of geophysically-imaged voids show a good agreement with the predicted mine pattern (Figure 10).

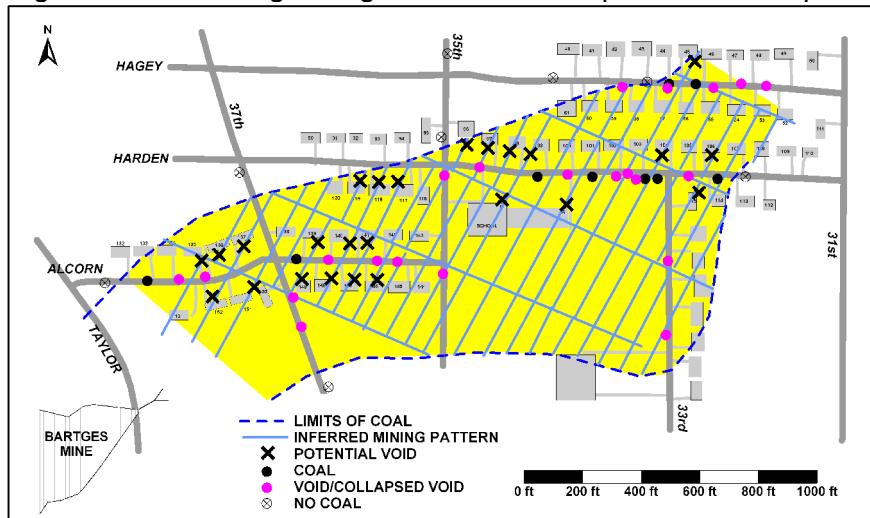


Figure 10. Projection of the Bartges Mine development orientation onto the study area, showing the boring and imaging analysis (scale as noted).

Case study 3

In the mid 1900s surface mining of the Pennsylvanian-aged Pittsburgh Coal, an 8-foot thick bituminous coal, exposed a highwall in the study area south of Florence, Pennsylvania (Figure 11). Reportedly, deep-mining also occurred behind the highwall. Subsequently, the former highwall was buried by removing the top of the adjacent deep-mined hill and placing it into the former surface mine, with plans to develop the site as light industrial properties. The location of the buried highwall was necessary prior to designing any building foundations.

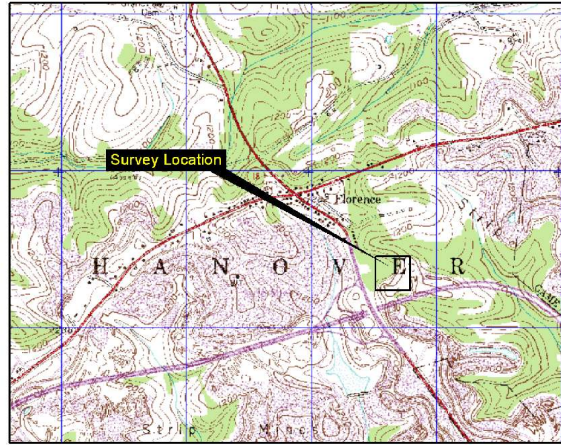


Figure 11. Portion of the Burgettstown, Pennsylvania 7.5 minute USGS topographic Quadrangle, showing the Case Study 3 area (scale 1" = 2,000').

Three CVES profiles were collected to determine the position of the highwall and to determine if the property behind the highwall was deep-mined (Figure 12). Line 1 (Figure 13)

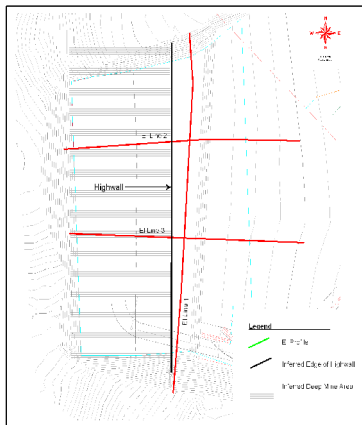


Figure 12. Location map of CVES profiles and highwall location interpretation (contour interval 2 feet; scale 1" = 100').

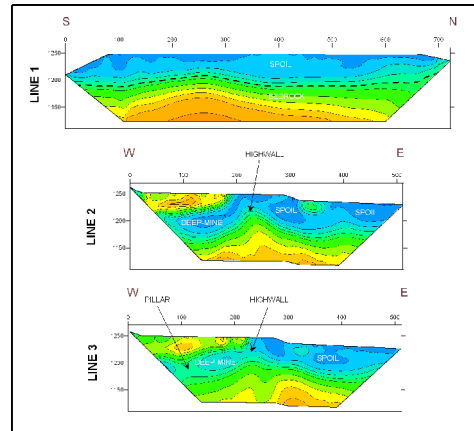


Figure 13. CVES profiles from the Case Study 3 area (no vertical exaggeration, scale as shown in feet).

imaged the base of the spoil (dashed line), which is approximately 50 feet below grade. The base of the relatively flat-lying 8-foot thick Pittsburgh coal has been mapped at an elevation of approximately 1,180 feet above mean sea level, which is consistent with the results of the CVES survey (Skema, 1987). Lines 2 and 3 (Figure 13) were collected normal to the buried highwall and show the edge of the highwall in profile. Further, the inversion in apparent resistivities west of the inferred location of the highwall is interpreted to be a deep-mine void. (Figure 13).

Elevated resistivities within the inferred deep-mined portion of Line 3 are interpreted to be in-situ coal pillars (Figure 13). If this is the case, then CVES can be used, in the shallow subsurface, for potentially mapping coal mine pillars, thus providing better control for the use of the property.

Conclusion

Electrical imaging of the shallow subsurface can help determine the location of potential hazards associated with the occurrence of dissolution or deep-mine voids. Mine maps of a clay mine substantiate the CVES profile interpretation of the presence of mine voids. These images helped the contractor plan the subdivision to avoid subsidence issues. Electrical imaging profiles that traversed over 69 homes in a subdivision of Barberton, Ohio indicate that mine voids may exist beneath 25 homes. Rehabilitation of these homes through grout injection is expensive and these CVES profiles show which homes are in potential need of subsurface grouting. CVES profiles documented the former highwall and deep-mine activities in a proposed light-industrial subdivision. The occurrence of the highwall was necessary for the placement of the factory; however, the presence of voids from the deep-mine required the use of a more expansive footing. While geophysics cannot replace intrusive confirmation of subsurface voids, CVES can aid in directing future investigations. Further, CVES is another tool the engineer can exploit to design a safer facility.

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