Electrical Imaging of Deep Clay-Mine Voids

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Abstract

In the late 1890s through the 1920s, deep mining of a local clay bed beneath 35 to 50 feet of Pennsylvanian-aged rock resulted in mine voids in the St. Marys, Pennsylvania area. Recently, long subsidence troughs have been noted locally in this area. The history of the deep mining has been all but lost to the local residents; however, recent mine maps show that deep mining has occurred near these residents.

Shallow-focused continuous vertical electric sounding profiles imaged subsurface haulways and rooms. Inverted measured apparent resistivity values indicate areas of subsurface voids presumable saturated. The deep mine map prepared in the 1920s shows an excellent correlation between the electrical imaging prediction of voids and the mapped voids.

Introduction

Electrical imaging can be an effective method for locating subsurface voids, specifically those from mine voids (Hutchinson and Barta, 2004; Orr, et al., 2002). A small subdivision within St. Marys, Pennsylvania was proposed for development south of an area where trough-like subsidence was noted. The developers were uncomfortable with the potential for post-development subsidence and opted for an electrical imaging survey to determine if mine voids existed beneath the proposed development (Figure 1). Due to the age of the clay mine, the shallow overburden above the mine, fluctuating groundwater conditions, and recent land development in the area, conditions are ideal for subsidence. The subsurface movement can cause extensive property damage and poses as a threat to the public health and safety.

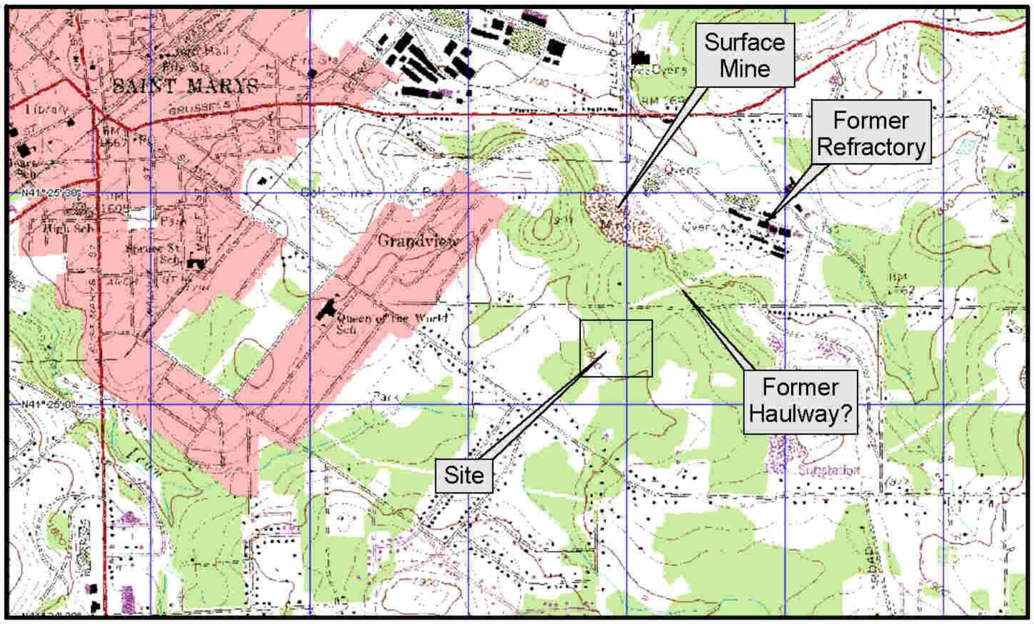

Figure 1.: Location of site, St. Marys, Pa, (St. Marys 7.5" USGS Topographic Map, 1" = 2,000').

Geology

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 Wisconsinan(?)-aged till described as brown silt and sand with lesser proportions of clay that ranged in thickness from 3 feet to 15 feet.

Bedrock is part of the lower section of the undifferentiated Pennsylvanian-aged Pottsville Group. 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 (Figure 2).

The Brookville Coal consists of approximately 18 inches of a low grade bituminous coal and a 2- to 3-foot thick plastic underclay. 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.

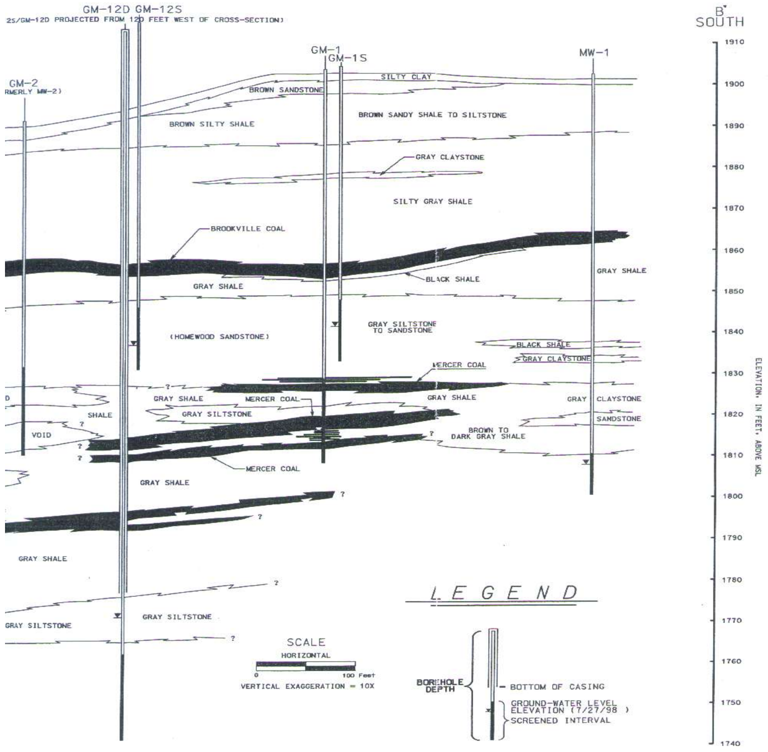

Figure 2.: Generalized north-south cross section showing the coal seams and underclays in the St. Marys, PA area (scale as shown; from HydroSystems Management, Inc., 1998)

Electrical Imaging

Theory

Electrical resistance is based upon Ohm's Law:

$$R = \frac{V}{I} \tag{1}$$

Where, resistance, **R**, is equal to the difference between the current flow, **I**, and voltage differential, **V**. However, resistivity depends upon the bulk property and geometry of the material. Consequently, resistivity is measured in Ohm-meters.

Currents are carried through earth materials by motion of the ions in connate water. Ions in connate 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:

1. Fractional volume of the rock occupied by water;
2. Salinity content of the water;
3. Permeability of the pore spaces; and,
4. Temperature.

Materials that lack pore space (i.e., limestone, igneous rocks) or lack water in the pore space will show high resistivity (Mooney, 1958). Most earthen materials, 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. Many electrode placements have been proposed (for examples, see Reynolds, 1998); however, the Schlumberger configuration has proven to be an effective configuration for imaging voids in bedrock settings. The following Schlumberger configuration was used in the collection of data:

$$R_i = \frac{\pi a^2}{b}\left[1 - \frac{b^2}{4a^2}\right]R;\ a \geq 5b \tag{2}$$

Where, R_i, resistivity, is related to the number of poles, n, the separation of the current source b, and pole spacing, **a**, is from Ohm's Law.

Maximum imaging depth (i.e., resolution) is based upon electrode spacing for this survey and was derived from:

$$D = \frac{BA}{2} + \frac{AM}{2} \tag{3}$$

Where, the depth, **D**, is a function of the pole spacing for the electrodes, **A**, **B**, and **M**. The pole spacing for the collection of data in the range of interest for the site is 3 meters.

Methodology

The resistivity survey was performed using the ARES multi-electrode cable system (GF Instruments, s.r.o., Brno, Czechoslovakia). The survey was conducted using stainless-steel electrodes and stainless-steel relay box-bearing cables. Three Schlumberger array resistivity survey lines were collected normal to the orientation of the presumed haulways and total approximately 1,700 linear feet resistivity data collection.

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 (deGroot-Hedlin and Constable, 1990; Loke and Barker, 1996). The smoothness-constrained least-squares method is based upon the following equation:

$$J^{T} g = \left(J^{T} J + \mu F \right) d \qquad (\mathbf{4})$$

Where, **F** is a function of the horizontal and vertical flatness filter, **J** is the matrix of partial derivatives, **μ** is the damping factor, **d** is the model perturbation vector and **g** is the discrepancy vector. The EarthImager program divides the subsurface 2D space into a number of rectangular blocks. Resistivities of each block are then calculated to produce an apparent resistivity pseudosection. The pseudosection is compared to the actual measurements for consistency. A measure of the difference is given by the root-mean-squared error.

Analysis

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 3).

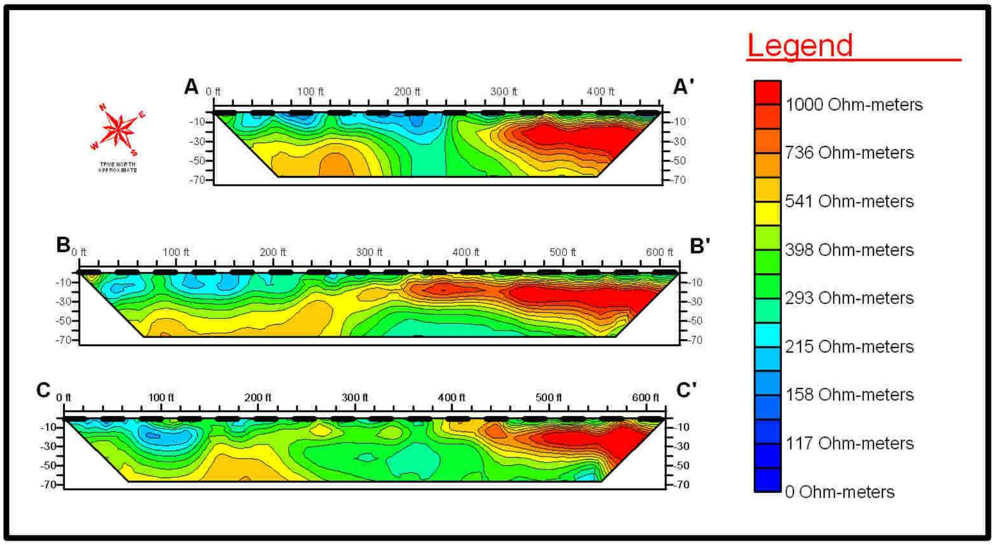

Figure 3.: Inverted apparent resistivity values indicative of mine voids (scale as noted, no vertical exaggeration).

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 with a hand-drawn 80 year-old document. The profiles show an excellent agreement with the mine as mapped (Figure 4).

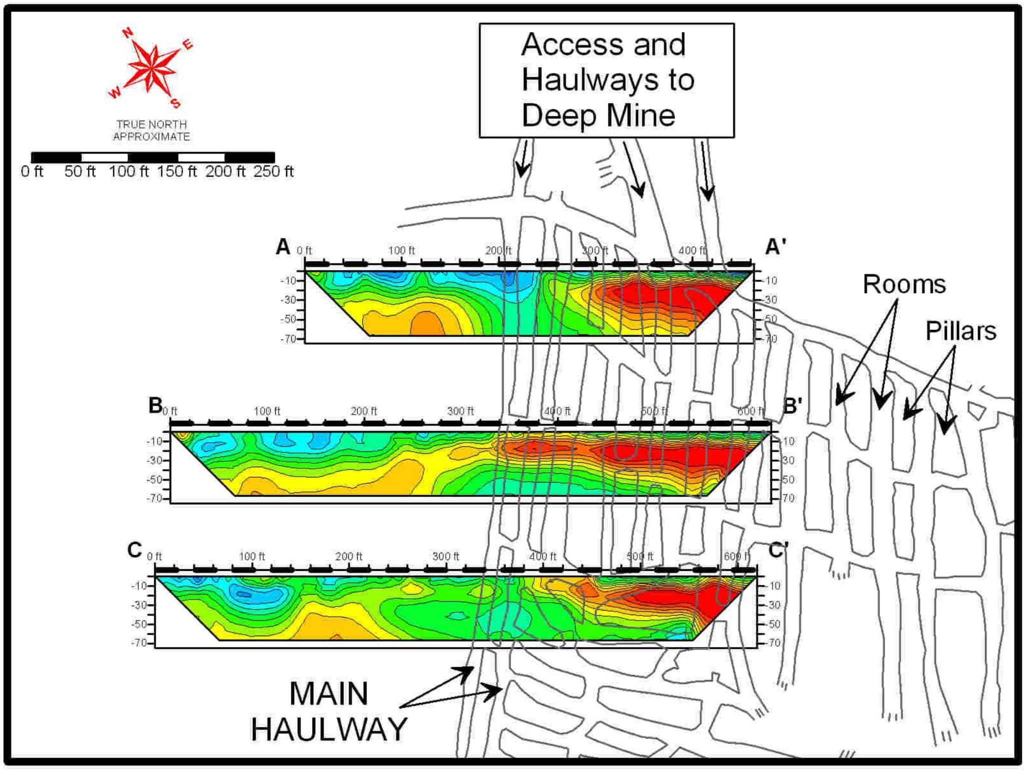

Figure 4.: Hand-drawn mine map showing examples of rooms and pillars superimposed upon the exact locations of the EI profiles (scale as noted).

Profile A-A' 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.

Profile B-B' 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' indicates that the mine is developed to the northwest (i.e., northwest of the main haulway). 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 also 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 mine voids are present at this depth. The lower apparent resistivity measurements above the mine voids are attributed to subsidence and increased permeability (thus better conductivity) in the roof materials. Surface expression of subsidence was not apparent in the field.

Conclusions

Electrical imaging of the shallow subsurface can help determine the location of potential hazards associated with the occurrence of deep-mine voids. Three continuous vertical electrical sounding profiles that traversed over 1,700 feet in St. Marys, PA indicate that mine voids are present. The superposition of the mine map and the electrical imaging profiles show that the profiles are an excellent predictor of the presence of deep mine voids.

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