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Technical Article

Resistivity Level Runs to Detect Water-filled Mine Voids between Drill Holes

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Abstract. Resistivity level runs are collected by lowering a current source down one well and measuring the resulting voltage at the same depth in another well. Mine voids between the wells that contain acid water appear as conductive anomalies on the resulting apparent resistivity profiles. Resistivity level runs can be collected rapidly and without lowering expensive equipment down holes of unknown stability. The data can be interpreted on-site, and are relatively insensitive to positioning errors. The method is well suited to sites where several drill holes have failed to intersect a known mine void. We demonstrated the feasibility of resistivity level run profiling at an abandoned mine complex in central Pennsylvania, where resistivity level runs were successfully used to locate haulage ways containing mine water.

Key Words: Acid mine drainage; abandoned mine lands; geophysics; resistivity; Pennsylvania; Fireclay

Introduction

The characterization and remediation of acid mine drainage (AMD) sometimes involves drilling into underground mines. In many cases, the locations of these mines are not known exactly, due either to inaccuracies in mine maps or difficulty in aligning mine maps with the existing surface. Also, at depths of even tens of meters, small deviations in drillhole inclination may cause holes to miss their targets. As a result, it is possible to drill a number of holes in a small area over a suspected mine without drilling into it.

Many geophysical methods have been used to detect mine voids. For near-surface mine voids, either surface geophysics (e.g. Anderson et al. 1998; Culshaw et al. 2004; Sheets 2002) or airborne surveys (Ackman 2003; Love et al. 2005) can be used. However, these methods may not have sufficient resolution to detect deeper targets (e.g. Hammack et al. 2004). When a pair of wells are present, crosswell tomographic surveys can be used to detect voids; published examples have used seismic (Rechtien et al. 1995), radar (Becht et al. 2004), and electrical methods (Maillol et al. 1999). Data sets for crosswell tomography consist of hundreds to thousands of data points. Processing and inverting these data can be a slow process, and the resulting tomograms are sensitive to 3-D effects (Wilkinson et al. 2006). In addition, these methods require equipment costing thousands of dollars to be lowered down boreholes.

One simple and cost-effective method for mapping mine voids at depth is the mise-à-la-masse approach, where a current electrode is placed in a borehole intersecting a conductive, AMD-filled mine void and voltages are measured at the surface (e.g. Rodriguez and Rodriguez 2000). However, in the coal basins of central Pennsylvania, it is common for several different seams to have been mined. The mise-à-la-masse method cannot be used if the mine of interest is overlain by a shallower mine.

Level run profiling (also known as zero-offset profiling) is commonly used in crosswell radar surveys (e.g. Rucker and Ferré 2005). In a level run, data are collected with the radar transmitter and radar receiver at the same depth in adjacent boreholes. Radar level runs can be collected rapidly, and the data is easy to interpret, but they require specialized borehole radar antennas.

In this study, we assessed the use of resistivity level runs to characterize the subsurface between five well pairs in the Brubaker Run watershed in central Pennsylvania. This approach uses a standard resistivity control unit, and borehole electrodes, which can be metal weights attached to wires, thus minimizing the financial risks associated with borehole collapse. Moreover, data can be collected rapidly and interpreted in minutes.

Resistivity Level Runs

The geometry of a resistivity level run is illustrated in Figure 1. Current is injected between an electrode at the surface and an electrode in a well. The resulting voltage is measured between a different electrode at the surface and an electrode in a nearby well. The

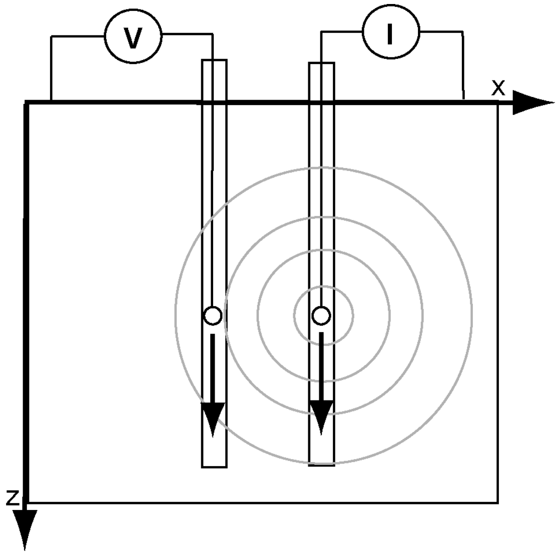

Figure 1. Schematic illustration of a resistivity level run: current is injected into an electrode in a borehole and the voltage is measured at an electrode at the same depth in an adjacent borehole. A 1-D apparent resistivity profile is obtained by taking measurements with the two electrodes at a series of depths. The current source (I) and voltmeter (V) are part of a standard resistivity control unit.

downhole electrodes are kept at the same depth in different wells. By making measurements at a series of depths, a profile of the electrical properties of the subsurface with depth is collected.

If the boreholes are water-filled at the depths of interest, then the downhole electrodes can be as simple as a weighted wire exposed at the end. The measurements can be made using a conventional resistivity control unit.

The apparent resistivity (ρ_{app}) of a level run measurement is given by

$$\rho_{app} = 4\pi L \frac{V}{I} \quad (1)$$

where I is the injected current and V is the voltage measured a distance L away from the current electrode. While non-linear effects in a heterogeneous earth make this equation an approximation, the use of ρ_{app} corrects for well separation, allowing values measured in different well pairs to be compared.

AMD-filled voids are more conductive than the surrounding material, so they should appear as minima on the apparent resistivity profile. In theory, air-filled mine voids could appear as maxima, but they have a smaller effect on resistivity measurements (Maillol et al. 1999) since electrical current will preferentially flow around them.

One shortcoming of the technique is that the measurements are sensitive to mine voids in the vicinity of the boreholes as well as between them. Wilkinson et al. (2006) found that three-dimensional tomographic inversion is required to correctly place resistivity anomalies due to mine voids. Resistivity level runs are merely able to detect the presence of an anomaly.

Cross-well resistivity measurements cannot be made through metal or PVC casing. While uncased holes are preferable, it is possible to make measurements through slotted PVC well screen.

Another possible limitation of resistivity level run profiling is the effect of conductive borehole fluid on measurements. Osiensky et al. (2004) showed that electrical current can be channelled through borehole fluid to low resistivity pathways. This is of particular concern at AMD-impacted sites, as water in the borehole may be particularly conductive. However, for resistivity level runs, the lowest apparent resistivities should still be measured at the level of the conductive mine voids.

Brubaker Run Site

The Brubaker Run watershed is located about 5 miles south of Ashville and 2 miles north of Altoona near the Allegheny front in central Pennsylvania (Figure 2A). The Mercer, Brookville, Lower Kittanning (B), Upper Kittanning (C’), Freeport (D), and Upper Freeport (E) coals have been mined in the area, with both surface and underground mines (Figure 3). A fireclay below the Mercer coal was also mined extensively. About 1.1 m^3/min (300 gpm) of pH 3 water discharges into Brubaker Run from the portal of one of the clay mines discharges, impairing a 19 km (12 mile) section of Clearfield Creek.

As part of a remediation program, the Clearfield Creek Watershed Association attempted to drill into the clay mine at a point where the flow from the eastern portion of the clay mine is channelled through twin haulage ways at a depth of about 95 m. These haulage ways were roughly 3 m wide and 2 m high (Figure 2B). At the chosen drill site, they were approximately 95 m below the surface. The likely location of the haulage ways was determined using mine maps, and eight wells were drilled in an area roughly 20 m by 20 m (Figure 4A). The wells went through a deep mine on the C’ seam at 30 m: those that encountered a mine void at that depth were cased to 35 m. Most of the wells were water-filled below 45 m. At the time of the geophysical

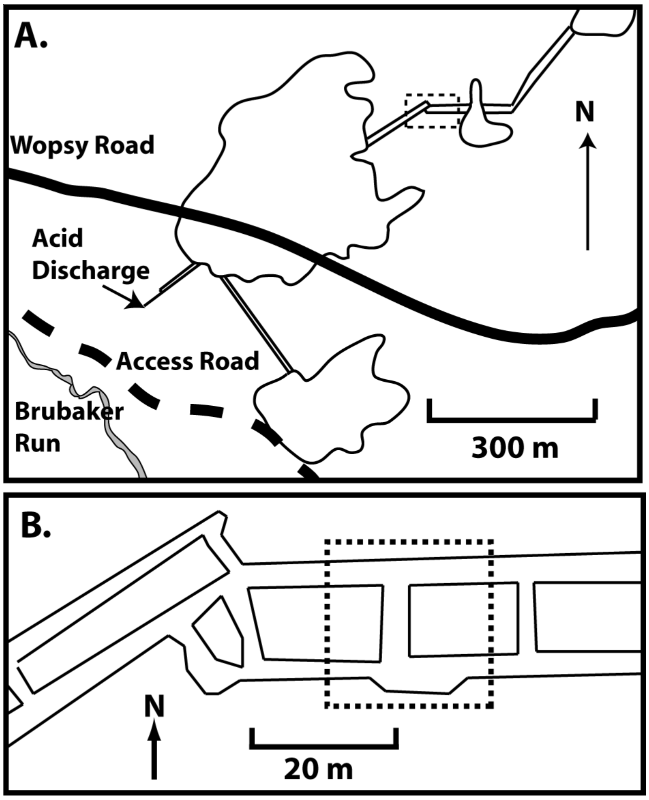

Figure 2. A. Map of the stoped areas and haulage ways of the clay mine beneath the Mercer coal seam; the location of figure 2B is shown as a dashed box. The inset shows the location of the site within Pennsylvania. B. The haulage ways linking the easternmost portion of the mine to the discharge point. This location was chosen for drilling because the wide portion of the southern haulageway presented a large target. The dashed box is the area shown in Figure 4.

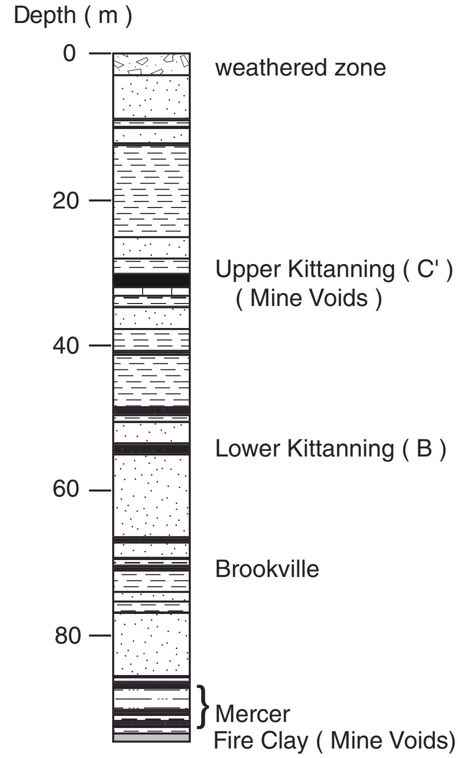

Figure 3. Approximate stratigraphic column for the Brubaker Run Site. The Freeport (D) and Upper Freeport (E) coals have been removed by surface mining.

survey, the drilling results were unpromising. Of the eight wells, only B7 encountered a small void (roughly 30 cm in length) at the depth of interest.

The depth and size of the target precluded the use of surface or airborne geophysics to locate the haulage way, and the presence of the C' seam mine ruled out mise-à-la-masse surveys. As the stability of the holes was uncertain, we were reluctant to use expensive downhole geophysical equipment. We also needed to determine whether the target was present quickly so that drilling could continue. These factors made resistivity level run profiling the best method for the problem.

We constructed downhole electrodes by attaching steel electrodes to wire, ensuring that the exposed ends of the wire were in electrical contact with the steel. We then attached these wires to the voltage and current terminals of a standard resistivity unit, with the other terminals grounded to electrodes approximately 100 m from the wells. The survey consisted of lowering the electrodes to pre-determined depths (marked on the wires) and recording the injected current and the measured voltage at each depth. We focused data collection at the suspected haulage way depth (90-98 m). We were able to collect profiles between five well pairs in roughly half a day.

Subsequent to the surveys discussed here, borehole camera surveys, borehole deviation surveys, and additional drilling were carried out at the site. Figure 4B shows the position of the haulage ways as determined using these data.

Interpretation

Profile Patterns

The results of the surveys are shown in Figure 5. The profiles can be broken into two distinct groups. The profiles collected between well pairs B1-B2, B9-B11, and B9-B12 are relatively constant between 90 and 93 m, and decrease smoothly below that. In contrast, the profiles collected between well pairs B1-B11 and B10-B11 increase sharply between 94 and 95 m and decrease between 95 and 96 m. We would expect an

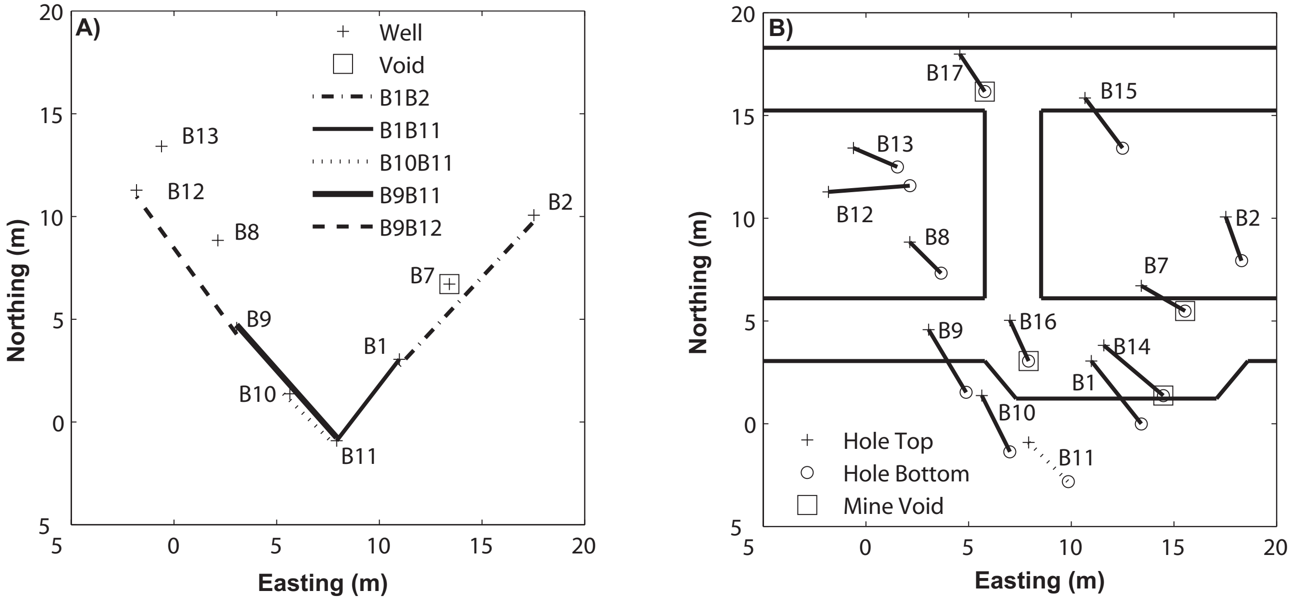

Figure 4. A. Positions of the well pairs used for resistivity level runs collected at the Brubaker Run Site. Only the wells that had been drilled at the time of the surveys are shown. Hole B7 intersected a 30 cm void. B. Revised mine map based on additional drilling, borehole deviation logging, and borehole camera investigation. No deviation log was collected for B11: the average deviation of the 12 logged wells was used to plot an approximate bottom position.

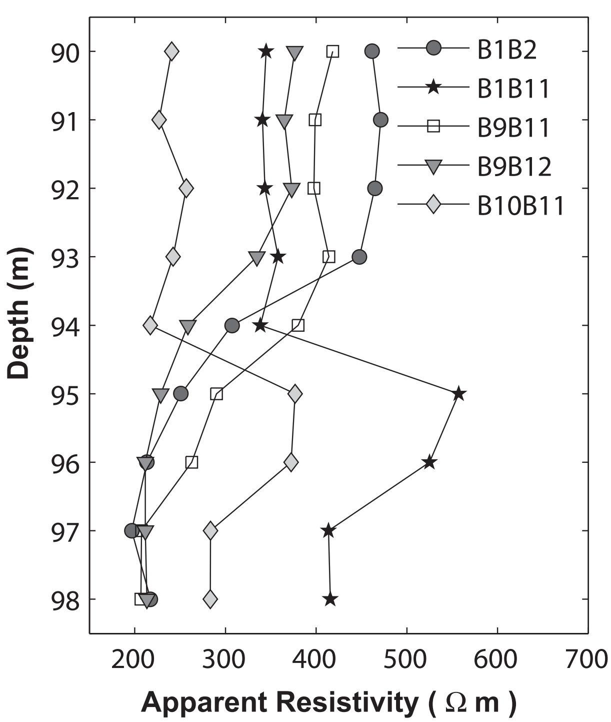

Figure 5. Resistivity level runs collected at the Brubaker Run Site. The circles correspond to well pair B1-B2, the stars to B1-B11, the squares to B9-B11, the triangles to B9-B12, and the diamonds to B10-B11.

AMD-filled haulage way to be a conductive anomaly, so we infer that the haulage ways are detected between well pairs B1-B2, B9-B11, and B9-B12. The high apparent resistivities measured between well pairs B1-B11 and B10-B11 at depths of 95 and 96 m may either be due to the Mercer coal or the kaolinite-rich fireclay.

The mine map based on additional wells, wellbore deviation logs, and borehole camera work (Figure 3B) shows that the southern haulage way runs between well pairs B1-B2 and B9-B12, as predicted by the resistivity level runs. While the haulage ways do not intersect B9-B11, it appears that the southern haulage way is within 1 - 2 m of the line between the two wells (there is no deviation log for B11, so the distance is approximate). This offset appears to be small enough that the haulage way can act as a preferential path for the flow of current between the wells, reducing the apparent resistivity.

Apparent Resistivity Values

The apparent resistivity values in the profiles are less informative than their patterns. We would expect the level runs to have similar apparent resistivities at depths between 90 and 93 m in the undisturbed rock above the haulage ways. The spread in these data could be caused by the use of incorrect well separations in Equation 1. We have used well separations based on the surface locations of the wells, but wellbore deviation changes the separations at 90 m depth. We

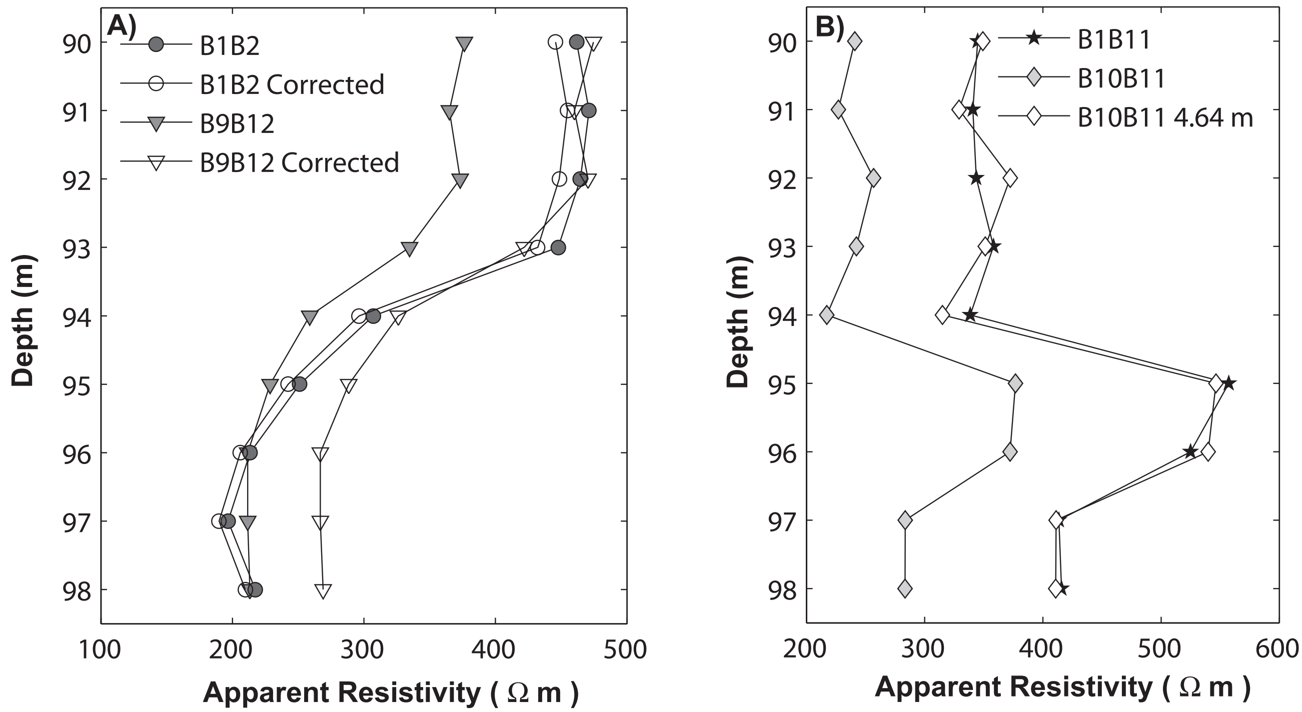

Figure 6. A. The effect of wellbore deviation on profiles B1-B2 and B9-B12. B. The effect of a different well spacing (4.64 m rather than 3.2 m) on profile B10-B11. The 4.64 m separation was chosen to minimize the difference between the B10-B11 profile and the B1-B11 profile.

can use wellbore deviation surveys to correct the profiles of two level runs (Figure 6A): B1-B2, where a 0.34 m change in well separation decreases the apparent resistivities by 3.5%, and B9-B12, where a 2.37 m change in well separation increases the apparent resistivities by 26%. These changes show that the close agreement between the profiles for B1-B2, B9-B11, and B9-B12 at the depth of the haulage ways in Figure 5 is a coincidence (it cannot be a systematic error in the data, as the voltage-to-current ratio for each data point has been multiplied by a different well pair separation). The electrical current must pass through a different amount of unmined rock for each well pair, so we should not expect the apparent resistivities to be identical.

At 95 m depth, the profiles for B1-B11 and B10-B11 have values of 557 m and 376 m, respectively. As this well pair has the lowest interwell spacing (3.2 m), we would expect the effect of deviation to be greatest. The profile between well pair B10-B11 agrees well with the profile between well pair B1-B11 if it is multiplied by a factor of 1.45 (Figure 6B). This factor translates to a well pair separation of 4.64 m, a difference of 1.24 m. Unfortunately, we do not have a wellbore deviation log for B11, but figure 6B shows that the apparent resistivity difference between profiles B10-B11 and B1-B11 could be due solely to wellbore deviation.

Conclusions

We have shown that resistivity level runs can be used to detect AMD-filled voids between drill holes. We collected five level runs in half a day using a standard resistivity control unit, and interpreted the data on-site. The equipment lowered down the holes is inexpensive, meaning that data can be collected in holes of unknown stability. Our surveys confirmed the presence of mine voids at the site, justifying further drilling.

The values of apparent resistivity measured by resistivity level runs are sensitive to wellbore deviation, borehole fluid conductivity, and the exact position of the mine void relative to the wells. In the study presented here, the pattern of the resistivity profiles was more useful than the actual apparent resistivity values in determining which profiles were influenced by the haulage ways.

In conclusion, we note that resistivity level runs do not provide the same level of detail as would larger data sets analyzed using tomographic inversion. Given the low cost of the equipment and the rapidity of their collection and interpretation, however, we believe that they may be the best option in some situations.

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