GEOPHYSICAL TECHNOLOGIES TO IMAGE OLD MINE WORKS

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Abstract

ZapataEngineering, Blackhawk Division performed geophysical void detection demonstrations for the US Department of Labor Mine Safety and Health Administration (MSHA). The objective was to advance current state-of-practices of geophysical technologies for detecting underground mine voids. This paper describes the results of the geophysical demonstrations conducted at a known abandoned underground coal mine in eastern Illinois (Hanna, et al, 2006).

The presence of old mine works above, adjacent, or below an active mine presents major health and safety hazards to miners who have inadvertently cut into locations with such features. In addition, the presence of abandoned mines beneath roadways has a great impact on the performance of the transportation infrastructure in terms of cost and public safety. Both are of major concern to the state Departments of Transportation (DOT's). Roads constructed over abandoned mines are subject to potential differential settlement, subsidence, sinkholes, and/or catastrophic collapse. Thus, there is a need to utilize geophysical imaging technologies to map and locate old mine works.

Several surface and borehole geophysical imaging methods and mapping techniques were employed at the investigation site to delineate the location and extent of old works. These included: 1) surface high-resolution seismic (HRS) using compressional P-wave (HRPW) and shear S-wave (HRSW) reflection methods collected with three-dimensional (3-D) techniques; 2) cross-hole seismic tomography (XHT); 3) guided waves; 4) reverse vertical seismic profiling (RVSP); and 5) borehole sonar mapping. In addition, several exploration borings were drilled to confirm the presence of the imaged mine voids.

Based on the results and analyses obtained from the geophysical and void drilling confirmation investigations, ranking factors were developed to evaluate the performance of the geophysical technologies deployed at the test site. The evaluation has shown the effectiveness of the RVSP as the most viable method to accurately detect the old mine works. The RVSP method can be complemented by the use of borehole mapping tools such as sonar (for water-filled voids), laser or borehole camera (for air-filled voids) to determine the vertical and lateral extent of the voids. This paper presents the significant results obtained from this investigation.

The information obtained from the RVSP and sonar mapping can then be used by: a) the mine operator to perform exploratory drilling while approaching detected old mine works to avoid cutting into the voids, thus eliminating unexpected hazardous conditions; and b) state DOT's engineers involved in geotechnical site investigations, road rehabilitation and construction, and risk assessment of the potential of roadway collapse and remediation efforts.

Site Description

The known abandoned mine test site was located adjacent to an active room-and-pillar coal mine in the east-central subdivision of the Illinois coalfield, near Georgetown, Illinois. The primary geologic feature of interest within the active underground mine is the Herrin #6 coal seam. This seam is one of the most important strata of coal located near the top of the Pennsylvanian-Period Carbondale Formation and averaged 1.8 m (6 ft) thick at a depth of approximately 71.6 m (235 ft). The abandoned mine operated from 1917 to 1947 and used room-and-pillar methods to mine the Herrin #6 coal seam. Based on the available historical mine maps, the mine layout consisted of four-entry mains oriented north-south which branched into two-entry submains oriented east-west and production rooms. The entries are 3.1 m (10 ft) wide separated by pillars that are 6.1 m (20 ft) wide and 12.2 to 18.3 m (40-60 ft) long.

The test site was located on private agriculture property. The property consisted of an open field partially cultivated and intersected by a tree line, wire fence, power lines, and a dirt access road. Figure 1 is representative of site conditions showing the plowed portion of the test area during data collection.

Geophysical Methods

The selected geophysical methods were employed at the same survey site to provide: 1) a more comprehensive data interpretation; 2) the basis for the performance evaluation; and 3) to determine the advantages and limitations of these technologies to accurately detect mine voids in a cost-effective manner.

Figure 1: HRS source and receiver locations.

The HRS survey grid, whose size is 45.7 by 320.4 m (150 x 1,050 ft), was strategically positioned so that the grid would overlay both the mined and un-mined coal areas. This layout allowed the survey to cross diagonally over two portions of the old mine entry system; i.e., the four-entry mains in the north-south direction and the two-entry submains in the east-west direction. Figure 2 shows the location of the HRPW and HRSW 3-D reflection survey grid. The data were acquired using a vibratory seismic source (one vibrator during P-wave data acquisition and two synchronized vibrators during S-wave data acquisition), a 144-channel seismograph, and high frequency geophones (see Figures 3 and 4).

The XHT survey design was based on the HRS reflection anomalies and the location of the historical mine map. A total of six boreholes were positioned outside of the mains and submains areas to avoid drilling into the mine voids. The boreholes were drilled to a depth of 91.4 m (300 ft). The distance between the boreholes ranged from 30.5 to 68.6 m (100-225 ft) apart. For this survey, downhole and surface seismic sensors (receivers) were used. The downhole receivers consisted of a 12-channel hydrophone string with 0.31 m (1 foot) hydrophone spacing. The surface receivers consisted of single Mark Product 40 Hz geophones spaced at 3.5 m (10 ft) intervals in a line between the boreholes. The seismic downhole source used for this survey was a Bolt DHS 5500 air-gun with a 41 cubic centimeter (2.5 cubic inch) air chamber. In conjunction with the XHT survey, the data obtained were also used as part of the seismic guided waves and the RVSP surveys. The guided waves method is only capable of determining whether a discontinuity exists in the coal seam between boreholes and has the lowest resolution of all the methods tested.

RVSP is a special type of seismic reflection survey that deploys a source in a borehole in conjunction with surface geophone arrays, which are used to record the reflected seismic signals, as discussed above. The data used for the RVSP processing were obtained from a subset of the data collected from the XHT survey. The survey geometry was not optimal for the RVSP acquisition; however, these data were of sufficient quality to provide better images of the old mine works. The seismic downhole source was activated 10 times per shotpoint at nominal 0.61 m (2 ft) shotpoint intervals. Three 2-D RVSP data sets were collected in this manner.

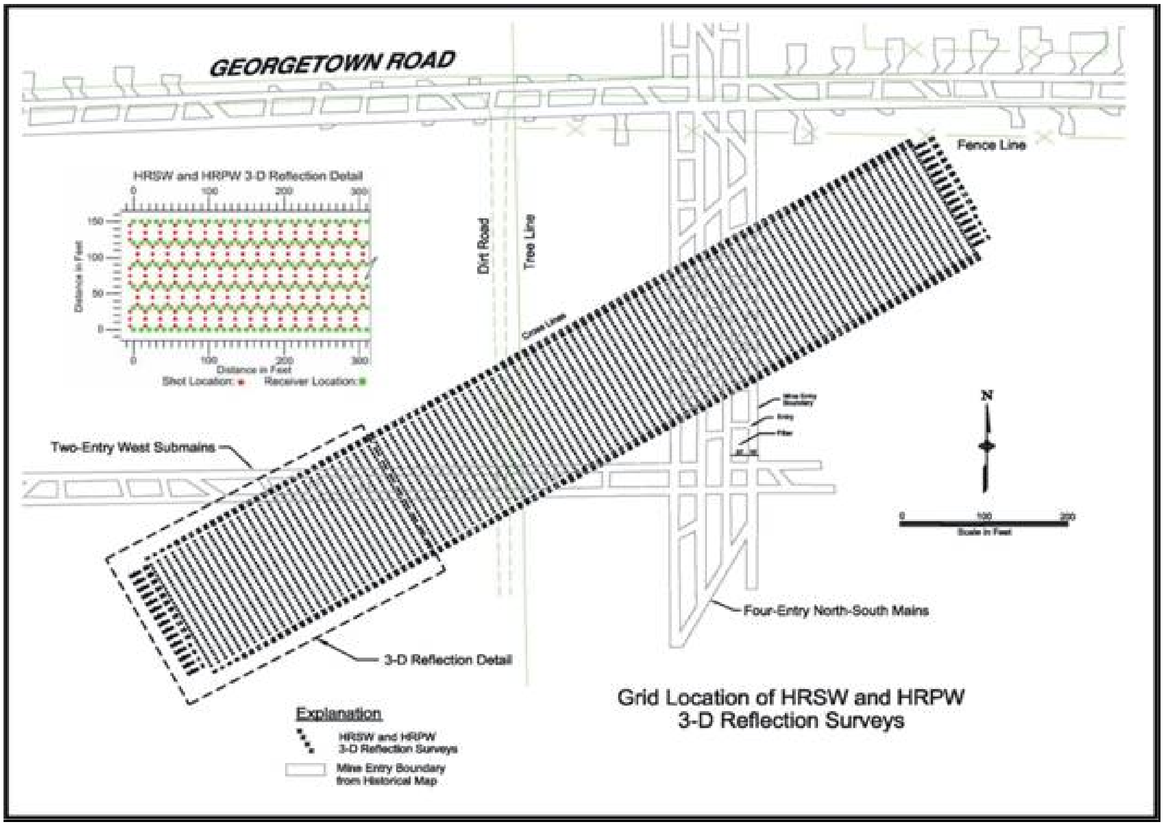


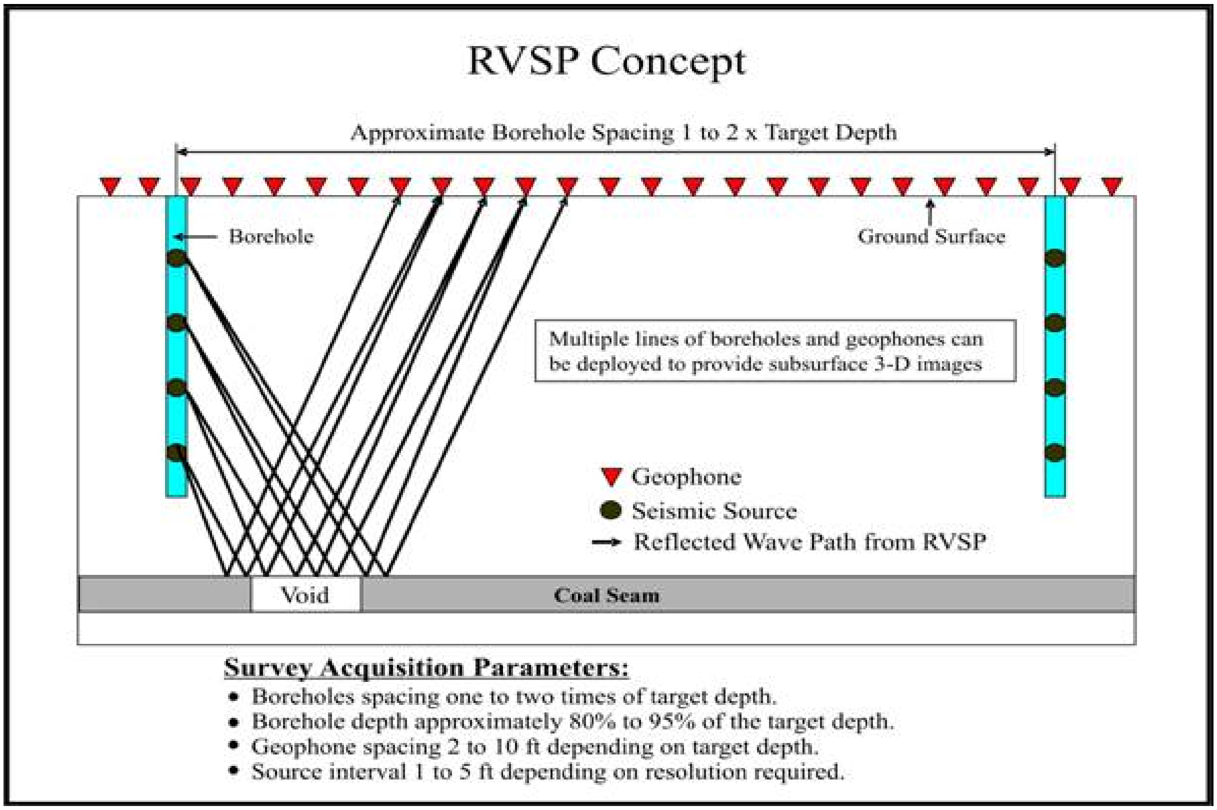
Figure 2: Grid locations of HRSW and HRPW 3-D reflection survey.

Figure 3: HRS acquisition using dual MicroVib source

Figure 4: HRS recording system

The design and acquisition geometry for the RVSP (i.e., number of surface geophones and offset, depth of borehole, and source interval) will depend on the amount of information available on the old mine works including void/pillar geometries, target depth, geology, and resolution required. An optimal layout for an RVSP survey along a 2-D line is shown on Figure 5. The boreholes should be spaced at a distance approximately equal to twice the depth of the target and drilled to a depth above the target horizon. For shallow targets, up to about 61 m (200 ft), the required depth of the source borehole may vary from 1.5 m to 6.1 m (5-20 ft) above the target horizon. For deeper targets, up to 304.8 m (1,000 ft), the borehole depth may vary from 15.2 m to 61 m (50-200 ft) above the target horizon depending on the target size being investigated. When multiple coal seams are present, the borehole should be drilled to a depth below the coal seam immediately above the target horizon. Similarly, the geophone spacing may vary from 0.61 to 3.5 m (2-10 ft) for shallow and deep targets, respectively. The surface geophones could then be laid out in a line extending between the boreholes and the source deployed in each of the boreholes. This will allow continuous coverage over the entire length of the line between the boreholes. Additional boreholes could be located along a line, depending on the distance that is required for an investigation.

This method can be extended to a 3-D survey around the borehole, although this would require some increase in cost for additional equipment, field effort, and processing time. Therefore, 3-D surveys should only be performed when very little information is available on the location and orientation of the old mine workings.



Survey Acquisition Parameters:

- Boreholes spacing one to two times of target depth.
- Borehole depth approximately 80% to 95% of the target depth.
- Geophone spacing 2 to 10 ft depending on target depth.
- Source interval 1 to 5 ft depending on resolution required.

Figure 5: Anomalous coal response from P-wave analysis

Discussion of Results

The following summarizes the significant results obtained from the HRS (HRPW and HRSW), XHT, guided waves, RVSP, and sonar mapping surveys.

HRPW and HRSW 3-D

The high-resolution primary wave method obtained clear reflection from the Herrin #6 coal seam, and showed consistent data quality throughout the survey. As shown on Figure 6, the north-south mains are well defined while the submains are somewhat less defined. Amplitude variations are clustered around the old mine works, in addition to extending out beyond the area of the historical mine works. These high amplitude anomalies may correspond to old mine works not shown on the historical mine map, thinning of coal seam, presence of rolls, and/or variations in the vertical and horizontal stresses. The high amplitude anomaly north of the submains was further investigated during void drilling confirmation. Boring in this area had confirmed a five ft thick solid coal seam, which might be indicative of the presence of rolls in the coal seam roof.

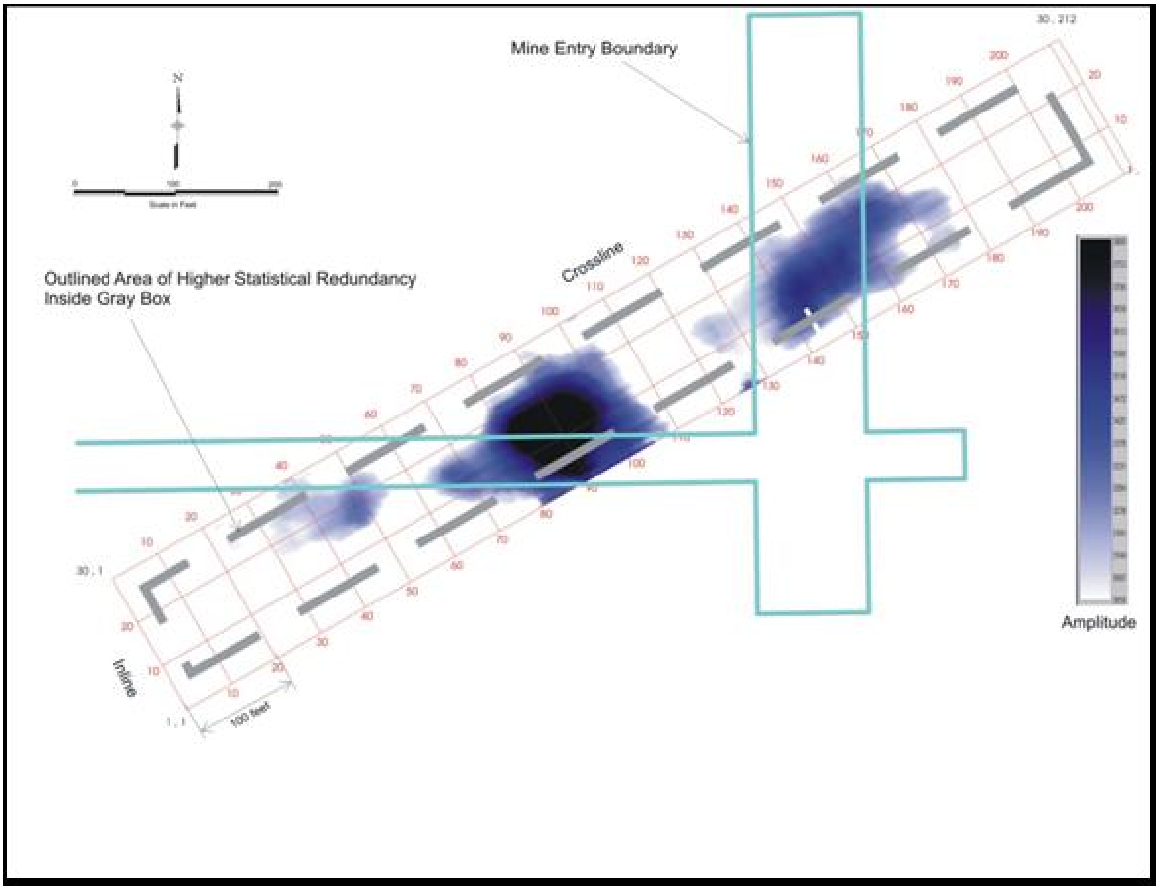


Figure 6: Anomalous coal response from P-wave analysis

The S-wave method obtained some reflection data from the upper Danville #7 coal horizon which is approximately 27.4 m (90 ft) above Herrin #6, but little information was obtained from the Herrin #6 coal seam itself. This is due to the high reflection coefficient of the upper coal seam that limited the transmission of the S-wave seismic energy below it. Acquisition of shear wave data was also hindered by the soft soils in the near surface and partially plowed fields in this area. Although two vibrators were deployed to increase the source energy output, the seismic energy was still insufficient to adequately compensate for the signal loss.

The P-wave, and to a lesser degree the S-wave data, did identify the general area of the old mine works, but neither of the methods identified the location of the individual rooms (voids) and/or pillars. The amplitude response seen in the P-wave and S-wave data is the result of the combined effect of the rooms and pillars.

The cost of conducting and processing the P-wave and S-wave 3-D surveys for this demonstration program was relatively high. Therefore, the P-wave method may be feasible to use in situations where the target is shallower and near-surface conditions provide better transmission of the seismic energy. Because the compressional-wave velocities of coal and water are very similar (1,585 m/sec vs 1,494 m/sec (5,200ft/sec vs 4,900 ft/sec)), improved results may also be obtained if the voids are air-filled. The S-wave survey was originally selected because of the high impedance contrast between coal and both air-filled voids and water-filled voids. S-waves have an advantage over P-waves for void detection because S-waves do not propagate through water or air, such that the void contents should not affect the ability of S-waves to detect a void. The S-wave method potentially could be used in areas where the uppermost coal seam is the target, where no overlying coal seam would prevent the transmission of the S-wave energy.

XHT

Figure 7 shows a 2-D representative tomographic inversion plot for the panel between the NS #6 and the NS #5 boreholes. The lower portion of the figure also shows the layout of the six boreholes used in this survey. The “hotter” colors (red and yellow) show higher velocity regions and the “cooler” colors (blue and green) show regions of low velocity. Coal seams and voids should be indicated by the lower velocity colors because of their relatively low velocity compared to the surrounding strata. The results obtained from this survey show that the tomographic method was unable to image Herrin #6 coal seam and the associated old mine works within the subsurface. This is likely due to:

- Larger than optimal spacing between the boreholes due to site access restrictions;
- High velocity layers above and below the Herrin #6 coal seam that were faster routes of travel than through the coal seam, and therefore masked the low velocity coal seam and related mine workings; and
- Potentially poor velocity contrast between the coal and the water-filled void (P-wave velocities of 1,585 and 4,900 m/sec (5,200 and 4,900 ft/sec, respectively)).

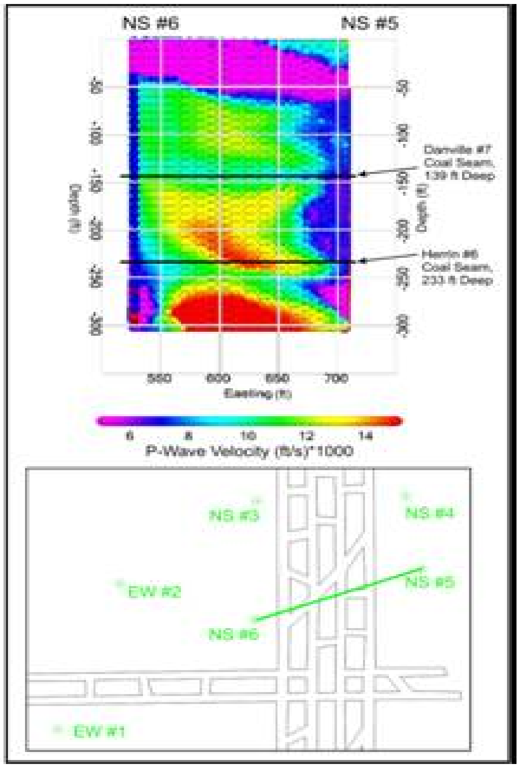


Figure 7: Velocity tomgram for panel between boreholes NS #5 and NS #6

Guided Waves

The results obtained from the guided waves method were inconclusive at differentiating mined and un-mined coal seams due to the presence of the tube waves in both cases. Tube waves are a primary indicator of the presence of guided waves. It is possible that the guided waves were propagating through or around the water-filled voids in the coal seam. The guide waves records for zones with and without old mine works appeared similar at the site. This method may not be reliable for locating flooded mine voids.

RVSP

The RVSP data were processed using a processing flow that included a proprietary imaging transform developed by Sterling Seismic Services. An example of one of the processed RVSP profiles is shown on Figure 8, for the section between boreholes NS #6 and NS #4. The solid line in the index map (Figure 8) represents the area with data coverage. The plot is displayed in color showing the interpreted top of the Herrin #6 along with instantaneous amplitude of the seismic data. The high amplitudes occur primarily near the Herrin #6 coal seam reflector. Peaks in the instantaneous amplitude at the Herrin #6 reflector are observed to correlate with the location of the voids which were determined from a registered historical mine map. It should be noted that the RVSP profile on the figure extends from the source borehole (NS #6) to the end of the data, as shown on the map inset.

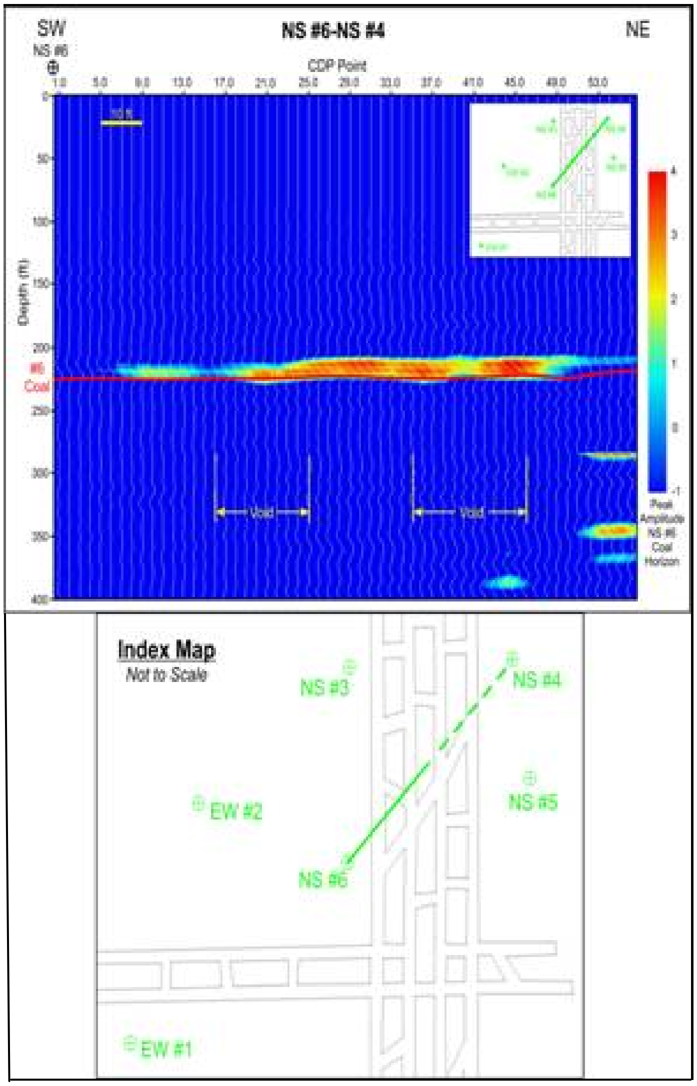


Figure 8: Instantaneous amplitude from RVSP profile across the mains

In order to visualize the amplitude variation's relationship to the possible mined void locations, the amplitude at the peak of the coal horizon was extracted from each RVSP section. Figure 9 shows the extracted amplitude along the top of the Herrin #6 coal seam at each common depth point (CDP) displayed as color coded dots and overlain on the referenced historical mine map. The color of each point correlates to the relative amplitude along the line, with the "warmer" colors showing high amplitudes and the "cooler" colors showing the lower amplitudes. It is clear that peaks in the amplitude of the reflector correspond to the location of voids due to mining activities.

Figure 10 shows the extracted amplitudes from Figure 8 displayed in a graph format. On this amplitude graph the locations along the profile where the main entries (obtained from the historical mine map) intersect the profile are shown. The solid line in the index map (Figure 10) represents the area with data coverage. The maxima in the amplitudes along the profile all correspond to the presence of voids.

Furthermore, the RVSP amplitudes also show the presence of a pillar corner that approaches the profile location on the historical map. The impact of the pillar corner on the amplitude may be due to errors in the geo-referencing of the historical map. These were observed in the borehole sonar mapping and a more significant portion of the pillar may actually intersect the profile.

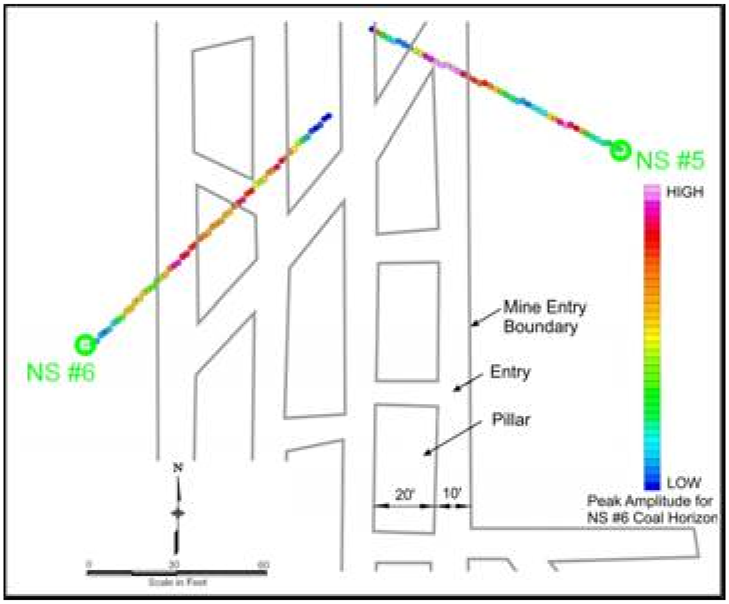


Figure 9: Extracted instantaneous amplitude from Herrin #6 coal horizon overlain on historical mine map

Borehole Sonar Mapping

Borehole sonar was used in four confirmation boreholes that intersected voids resulting from old mine workings. The unit used in this survey was a Wet Ferret developed by Carnegie-Mellon University (Figure 11). This unit can be deployed in 101.6-mm (4-in) diameter boreholes. The Wet Ferret consists of a profiling sonar unit, color underwater camera, backlit magnetic compass, support frame, and tether.

The Wet Ferret uses the profiling sonar unit to take measurements up to 300 ft in 360-degree horizontal planes referred to as scans. Scans are referenced using the depth from the ground surface, borehole surface coordinates, and the camera view of the magnetic compass. By taking multiple scans at different elevations, a 360-degree 3-D model of the void can be produced. For this survey, scans were obtained at one ft depth intervals from the top of the void to the point where the instrument encountered obstacles. The scanned void can be geo-referenced and correlated with the magnetic compass and underwater camera integrated into the device. A sample record is shown in Figure 12. The colored dots on the screen represent the strength of the sonar return from a solid surface (walls of coal mine). The unit is clearly able to distinguish the walls of the mine void. The inset image, where the scan was taken at the top of the mine void, shows the presence of a timber roof brace used in the support of the mine roof.

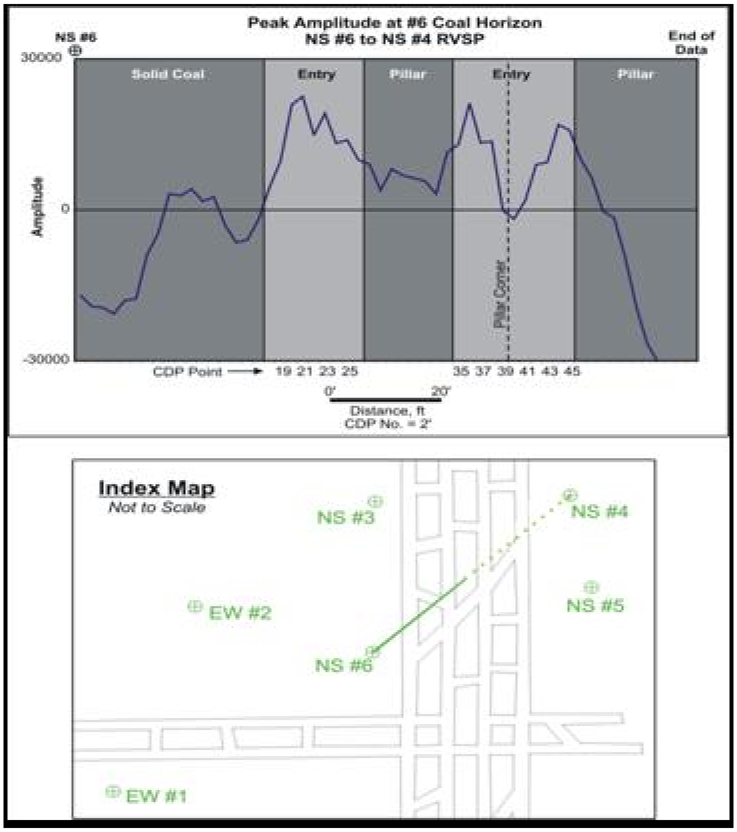
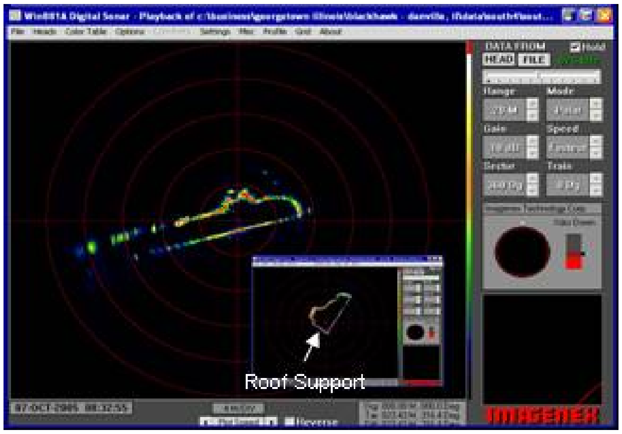


Figure 10: RVSP peak amplitude at the Herrin #6 coal horzon from NS #6 to NS #4Extracted instantaneous amplitude from Herrin #6 coal horizon overlain on



The final combined result of the four borehole sonar scans is shown on Figure 13. Each color of the dots represents the interpreted location of the void boundaries from a single borehole sonar survey. The combined result was obtained by positioning the location of the borehole where it intersects the top of the void using borehole deviation data, preliminarily aligning the results using the magnetic compass, then iteratively aligning the results from different boreholes so that the lines of signal returns from the walls of the mine voids align.

The plot clearly shows the north-south oriented mains as well as the diagonal cross-cuts and east-west oriented crossover cut. Based on the results from the borehole sonar, the historical mine map which had been scanned and then positioned using known features was shifted from the actual coordinates by approximately 3.1 m (10 ft) to the north and 0.91 m (3 ft) to the west.

Performance Evaluation

Based on the results and analyses obtained from the investigations, seven ranking factors were developed to evaluate the performance of the geophysical technologies deployed at the test site. Each geophysical method was ranked from excellent to poor based on how well it met each criterion. The cost of each method was ranked from very high to low. These ranking factors are summarized in Table 1. The evaluation has shown the effectiveness of the RVSP as the most viable method to image the boundary of the old mine workings as well as the individual entries and pillars with high accuracy. The positional error of the RVSP interpretations was approximately 0.91 to 1.5 m (3-5 ft). This is notably precise considering the depth of the target horizon was 71.6 m (235 ft) and that the field geometry was not optimal for RVSP processing. Once the voids were located, a borehole sonar tool was deployed. This allowed mapping of the boundary of water-filled voids to a distance of approximately 30.5 m (100 ft) away from the borehole and provided invaluable information that confirmed the historical mine maps as well as allowing the map to be correlated to actual ground location with accuracy of approximately 0.31 m (1 ft). These two methods provided complementary information that was cost-effective and accurately delineated the vertical and lateral extent of the mine voids.

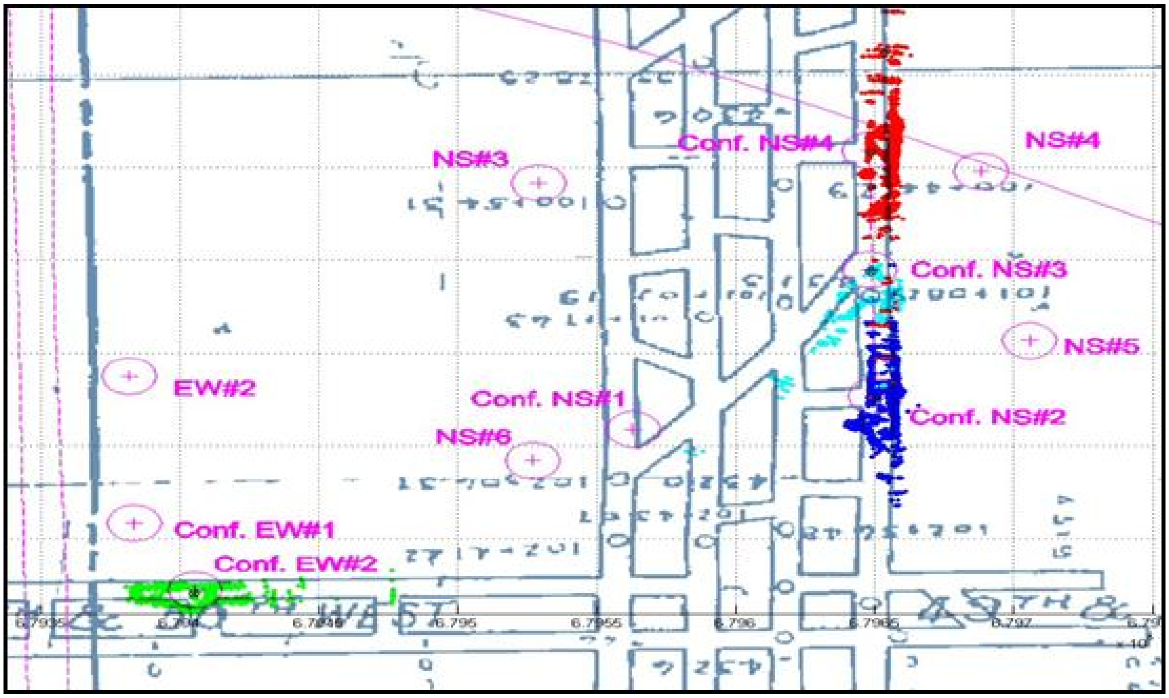


Figure 13: Combined results of four boreholes sonar surveys overlain on historical mine map.

Table1: Performance evaluation of geophysical methods

Method **Criterion**	**HRPW**	**HRSW**	**XHT**	**Guided Wave**	**RVSP**	**Sonar Mapping***
Ability to Locate Voids	Fair	Fair	Poor	Poor	Good	n/a
Resolution	Poor	Poor	Poor	Poor	Very Good	Excellent
Depth of Investigation	Good	Poor	Good	Good	Good	Very Good
Anticipated Repeatability	Good	Fair	Good	Fair	Good	Very Good
Robustness Under Various Geologic/Surface Conditions	Fair	Poor	Fair	Fair	Good	Very Good
Cost	High	Very High	Medium	Low	Medium	Medium
Void Content	Poor	Good	Poor	Poor	Good	Good
** Sonar mapping can only be used in a borehole that has intersected a mine void.*						

Conclusions

Several geophysical techniques were employed at the abandoned mine site to evaluate their effectiveness in detecting mine voids.

The P-wave, and to a lesser degree the S-wave data, did identify the general area of the old mine works, but neither of the methods identified the location of the individual rooms (voids) and/or pillars. The amplitude response seen in the P-wave and S-wave data is the result of the combined effect of the rooms and pillars.

The XHT tomograms showed similar velocity distributions across areas containing old mine works and solid coal (nonmined areas) within the Herrin #6 coal seam. This method was unable to image the target coal seam horizon and the associated old mine works. This is likely due to high-velocity layers above and below the coal seam and potentially poor velocity contrast between the coal and the water-filled void.

The guided waves method is only capable of determining whether a discontinuity exists in the coal seam between two boreholes. The results were inconclusive at differentiating mined and un-mined coal seam. This may be due to the presence of water within the voids that transmitted the guided waves through or around the coal seam. This method may not be reliable for locating flooded mine voids.

The RVSP method was more effective than the surface P-wave and S-wave reflection surveys at imaging the location of the old mine works and individual voids at this site. It appeared to provide sufficient accuracy in locating the mine void to allow the placement of four confirmation boreholes that reliably intersected the voids. The sonar mapping complemented the confirmation drilling by mapping the void geometry and the extent of the mine entries. This method offers accuracy and reliability unobtainable from any other remote method in almost all geologic conditions and at depth up to 244 m (800 ft) below ground surface. Sonar mapping can only work in water-filled voids; however, alternative instrumentation can work in air-filled voids using a laser or borehole camera tools.

In summary, the RVSP method was demonstrated to be practical and accurate for detecting mine voids at this site. The RVSP method can be complemented by the use of borehole mapping tools, such as sonar, laser, or borehole camera, to very accurately determine the vertical and lateral extents of the mine voids.

Recent successful applications of the RVSP technology for geotechnical mine subsidence investigations in various topographic, geologic, and cultural settings proved to be effective in providing subsurface information with greater detail and accuracy with or without historical abandoned mine information.

Acknowledgment

The authors would like to express their appreciation to MSHA, for their undivided attention in guiding and directing this project, and providing valuable technical assistance during the field demonstrations. The idea of using a subset of the cross-hole tomography data as an RVSP data set was originally suggested by Dr. Brian Fuller of Sterling Seismic Services. He also processed the RVSP data and was critical to the success of this project. Workhorse Technologies provided expert personnel and equipment to conduct the borehole sonar survey.

References

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