Borehole Tomography and Surface 3D Radar for Coal Mine Subsidence Detection

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ABSTRACT

Experimental cross-hole and surface-penetrating radar surveys were conducted along a section of highway that had collapsed into underground coal mine workings. The cross-hole radar method provided information about bedrock and overburden conditions at depths not attainable using surface radar, while the surface radar enabled a detailed analysis of the roadway conditions. Through coincident analyses of borehole tomograms and surface three-dimensional plots, additional locations along the highway where mine-related disruption has occurred, and where a relatively high potential for future collapse exists, were detected. The results of this study demonstrate the applicability of radar methods to mine-related subsidence problems, and show that a more complete characterization can be achieved by employing both borehole and surface radar methods.

KEYWORDS: GPR, radar, 3D, borehole, tomography, coal, subsidence, mining, geophysics
INTRODUCTION

We conducted borehole and surface-penetrating radar surveys along Interstate 70 (I-70) in Guernsey County, Ohio, where the roadway had previously collapsed into underground coal mine workings (Figure 1). Our principal research objectives were to test the ability of each of the techniques for providing useful information for mine-related subsidence studies, and to use the results from both of the methods to help locate additional regions along the roadway in the study area with high potential for future subsidence-associated failure.

Cross-hole constant offset profile (COP) and multiple offset gather (MOG) data (Guy and Radzevicius, 2001), and three-dimensional (3D) surface radar data (Conroy and Radzevicius, 2003; Daniels et al. 2003) were acquired along a 671 m long undermined section of I-70. COPs were acquired by raising the transmitter (Tx) and receiver (Rx) antennas, located in separate boreholes at the same rate, while MOG data were acquired by fixing the Tx at a position in one hole and lowering the Rx in another hole (Figure 2). MOG data were acquired with the Tx located at different depths, so that velocity tomograms (physical property models) for the media plane between the boreholes could be constructed. Parallel two-dimensional (2D) surface radar profiles were acquired along the roadway, so that 3D block images could be constructed (Figure 3).

Mining engineering applications of cross-hole COP and 2D radar methods, including fracture detection (Sato and Miwa, 2000), cavity, tunnel, and void detection (Adams et al., 1996; Haeni et al., 2002), and lithologic, structural and soil water content determination (Guy et al., 2001; Gilson et al., 1996), have been demonstrated. While it is known in theory that radar measurements can be potentially used to detect the subsurface physical property changes associated with subsidence activity, there have been no publications to date that demonstrate the successful application of both borehole tomography and surface 3D radar techniques towards mine-related subsidence problems. The results from this paper demonstrate that by applying both borehole tomography and 3D surface radar, a more complete characterization of the mine-related subsidence problems at a site may be achieved than with either method applied independently.

STUDY AREA: GEOLOGY AND SUBSIDENCE HISTORY

The study area subsurface generally consists of Paleozoic sedimentary rocks with unconsolidated overburden materials containing the water table. The upper 1.5 to 4.6 m beneath I-70 consists of silt and clay fill materials, with silts, clays, and interbedded sand lenses down to bedrock. The total unconsolidated materials thickness above bedrock ranges from 9.1 to 15.2 m. Bedrock is predominantly arenaceous shale, which ranges in thickness from 3.0 to 7.6 m and lies above a bituminous coal seam. The coal seam is 1.5 to 2.1 m thick, is underlain by claystone, and was mined at an average of 1.8 m in thickness using the room-and-pillar mining method.

The Murray Hill mine complex that underlies the I-70 study area was operated from 1912-1935. During 1994 an abandoned underground coal mine, down dip and south of the Murray Hill mine was intercepted by a surface mining operation. As a result, extensive dewatering occurred in the Murray Hill mine because the complexes are connected by entries. Subsequent to this dewatering, localized roof failure between coal pillars and soil piping above the mine workings occurred in the I-70 study area (Hoffman et al., 1995). Surface mining and dewatering stopped and water levels...
Figure 1. Map view of the I-70 eastbound lanes (road stations 469+00 to 485+00) showing the locations of boreholes used to acquire cross-hole radar data, the sections of roadway where surface radar data presented in this paper were acquired, locations of underground coal mine workings, previous collapse zone, observed collapse pits and pavement depressions.
Figure 2. Schematic showing typical COP cross-hole radar data acquisition configuration and possible ray-paths. During MOG data acquisition, the transmitter (Tx) and receiver (Rx) antennas are positioned at multiple depths.
Figure 3. Generic surface penetrating radar data examples showing energy scattered from a copper pipe buried in dry sand: (a) a single trace, (b) a two dimensional profile, and (c) a 3D block with translucence applied for optimal target isolation (Conroy and Radzevicius, 2003).
returned to pre-dewatering levels. Nonetheless, subsidence of the weak overburden continued and resulted in catastrophic failure of the I-70 eastbound lanes in March 1995 (Figure 4a). The collapse was sudden and caused an accident involving four vehicles.

Following roadway collapse a mine remediation project was initiated (Figure 4b). This work consisted of drilling and grouting to secure voids and fill rock fractures. Following remediation the roadway reopened, but additional surface depressions developed along I-70 during 1996 in the location of previously drilled boreholes. Exploratory drilling revealed unconsolidated soils and voids in several previously grouted locations and a second phase of grouting was completed during 1997. While there have been no more roadway collapses following remediation, concern continues regarding roadway stability. Consequently, our research focused on testing and developing methods to determine whether subsurface subsidence processes had continued in the study area, and to identify other areas of active subsidence or soil piping into subsurface collapse features.

RADAR-BASED SUBSIDENCE DETECTION: BACKGROUND AND BASIS

Radar application to subsidence problems involves detecting subsidence-induced changes in media dielectric permittivity ($\varepsilon$) and electrical conductivity using electromagnetic (EM) waves. An increase in dielectric permittivity causes a decrease in radar velocity, while an increase in electrical conductivity causes an increase in signal attenuation. Although magnetic permeability can be a factor, its influence is not typically significant in practice. Electrical property changes are measured and detected as scattering (reflection/refraction) from boundaries, or as changes in the velocity and/or attenuation of the radar signal. For geologic media, relative permittivity ($\varepsilon_r$) values typically range from 3 to 25, depending upon mineralogy and water content. Water has an $\varepsilon_r$ value of 81 while concrete can have $\varepsilon_r$ values of 6-30 depending on type, curing time and water content. Electrical conductivity also varies depending on lithology and water content; e.g., 0.01 mS/m (milli-Siemens/m) for dry sand, 0.5 mS/m for fresh water, 1-100 mS/m for shales and siltstones, and 2-2000 mS/m for clays (Annan, 1997).

Borehole radar involves using a borehole to bring antennas close to areas in the subsurface not practically investigated using surface radar due to inadequate depth of penetration through overburden with high electrical conductivity. Borehole radar surveys are usually conducted in the 10 MHz to 200 MHz frequency range and are most often employed using a cross-hole configuration to investigate the media electrical properties between the boreholes by measuring changes in EM-wave propagation velocity and material attenuation. Since water content is related to porosity in fully saturated media, any changes in primary or secondary porosity of fully saturated media will result in EM velocity and amplitude attenuation changes. An increase in secondary porosity due to fracturing and void formation should occur in subsurface media where subsurface subsidence processes have been active. Therefore, by determining EM velocity and attenuation changes in the media between two boreholes, the potential for using cross-hole radar to locate areas of active mine-related subsidence within the subsurface exists.

An example of using the change in the characteristics of a propagated radar signal as a function of depth to detect fractured rock and water-filled void features between two boreholes is presented in
Figure 4. Photographs of a coal mine-related roadway collapse, 3.1 m in diameter that formed in the I-70 eastbound lane (a) (Figure 1) and subsequent remediation efforts (b). Photographs were taken by Gannet Fleming Corddry & Carpenter (a), and the Federal Highway Administration (b).
Figure 5. These plots consist of EM-wave velocity and amplitude data, COP data, geologic information, and an EM velocity tomogram constructed from MOG data acquired between borings GC212 and GC213 separated by 3.12 m (Figure 1). There is a good correlation between COP data-derived average EM-wave amplitude and velocity variations versus depth, velocity distribution in the tomogram, and mineral content and porosity differences of media mapped during drilling. From 12.5 to 17.5 m depth, shale with no heavy fracturing detected during drilling is seen to correlate with relatively high values of average amplitude (~2000 to 2500 micro-V) and velocity (~0.078 to 0.085 m/ns or bulk $\varepsilon_r$ of ~15 to 12). There is a large decrease in both average amplitude (< 800 micro-V) and velocity (< 0.06 m/ns corresponding to bulk $\varepsilon_r > 25$) within the depth range of 17.5 to 19.0 m, which correlates with heavily fractured shale and water-filled void features encountered during drilling. In this case, it is apparent that EM velocity has decreased and radar signal attenuation has increased due to the fracturing, as $\varepsilon_r$ and conductivity have increased due to water content increase. Radar scattering losses from electrical property discontinuities have also likely increased.

Surface-based radar is commonly employed in the 10 MHz to 3 GHz frequency range. Its typical basis for use is EM-wave scattering from features in the subsurface that possess adequate geometry and electrical property contrast with the host media. Similar to borehole data, surface radar data are acquired in single trace measurements (Figure 3a). Traces are collected using Tx and Rx antennas (often dipole) set at a fixed distance that are typically oriented parallel (co-dipole) with one another and perpendicular to the line of survey. By collecting measurements at multiple stations along a survey line, a 2D cross-section can be created by placing traces next to one another (Figure 3b). Additionally, a 3D block image of the subsurface can be constructed if multiple parallel survey lines are collected (Figure 3c). The depth of a scattering object can be calculated using time information and measured medium velocities. Due to the high sensitivity of the surface penetrating radar method any changes in structure of a roadway, including velocity changes of the concrete or small disruption of the rebar structure, can often be detected. As decreased subsurface support will ultimately lead to roadway failure, it is reasonable to expect that continued subsidence-related activity beneath a roadway will have an effect on its physical properties which may be detected using surface radar.

DATA ACQUISITION, PROCESSING AND IMAGING

Borehole Radar Data

Cross-hole radar data were acquired using a Sensors and Software, Inc. system, with 100 MHz omni-directional dipole antennas located in PVC-cased wells. The radar system relied on 30.0 m long, ~10 mm in diameter, dielectrically coated conductive cables for signal transmission between surface-located electronics and the antennas. COP and MOG configurations were determined based on study objectives, radar system and antenna characteristics, and the signal-attenuating characteristics of the study area media. COP data were acquired by raising transmitter and receiver antennas located in separate boreholes at the same rate while collecting data every 0.125 m. MOG data were acquired by keeping the transmitter antenna at a fixed position in the eastern-most hole while lowering the receiver antenna at constant rate in the other hole, collecting data every 0.25 m. The maximum vertical offset between transmitter and receiver antennas used in MOG surveying was 4.0 m.
Figure 5. Average EM-wave velocity and amplitude plots, borehole radar COP data, geologic information obtained from drill logs, and EM velocity tomogram for borings in the study area separated by 3.12 m, located in the I-70 eastbound travel lane (Figure 1). Note: the term void in the figure indicates fractured rock and water-filled void features.
COP data processing involved calculating the average absolute amplitude of each trace within a specific time window. This allowed relative media attenuation characteristics related to conductivity and scattering loss for a given set of measurements to be made. Additionally, it provided a means for comparing amplitudes of traces acquired in similar media but at different borehole separations. Average radar propagation velocities for media between boreholes were calculated based on COP trace direct arrivals. The velocities determined were based on assumptions that the boreholes did not deviate from vertical with depth, and that velocity was laterally constant throughout the media between the boreholes. Direct arrival times were interpolated across depths where high attenuation of radar signal or surface-refraction interference (Guy et al., 2001) prevented accurate direct arrival picks from being made.

MOG data processing was similar to COP data processing, with inversion conducted using direct arrival travel time picks for tomographic imaging purposes. The basic idea behind velocity inversion/tomography is that when multiple travel time measurements along different ray paths (i.e., at different viewing angles) through a media plane of interest are obtained, the velocity distribution within the media plane can then be inferred from these measurements if the spatial relationships of the sources and receivers are known. MOG travel time inversion was conducted using the MIGRATOM (Jackson and Tweeton, 1993) ray tracing computer code. Calculated velocity distributions were plotted, and a pixel interpolation function was applied to gently smooth images. MOG data were acquired from 1.0 m depth to the maximum possible depth for all boreholes (limited by borehole depths and separation, and cable lengths). However, signal attenuation (a function of the distance between boreholes and near-surface clay-containing materials) and refraction interference (caused by the velocity discontinuity at the ground and air interface, and unable to be suppressed without degrading signal) often prevented accurate tomography for the top several subsurface meters. Due to these factors, surface radar was an excellent compliment at the site for investigating near-surface conditions. The surface radar EM-wave two-way distances, to and from near-surface features of interest, were shorter than the one-way EM-wave travel distances between boreholes, and refraction interference was not an issue with surface radar.

Surface Radar Data

Surface radar data were acquired using a 450 MHz Geophysical Survey Systems, Inc. shielded antenna. A 50 MHz test line was acquired on the roadway during initial method evaluation, but it did not penetrate the rebar mesh as the 450 MHz did; lower frequency essentially coupled to the shallow rebar due to relatively long wavelength. A co-dipole orientation with the center of the antennas kept at a fixed offset of 23 cm was employed, and data were acquired along multiple parallel survey lines located along each road lane and median shoulders. The spacing between survey lines was 0.3 m, and lines extended 6.1 m on either side of the dividing line between driving lanes. Trace spacing, which was governed by a survey wheel that triggered transmitter antenna pulse firing, was 0.055 m per line. Each trace consisted of 512 samples collected for 100 ns. Variant field frequency filters and gains were applied, based on daily field conditions, in order to facilitate real-time data visualization and quality control.

Subsequent to data collection in the field, the processing sequence applied to surface radar data was accomplished in two steps: signal-to-noise ratio improvement, and the application of utilities and the selection of translucence settings for 3D display (Conroy, 2002). Signal processing conducted in MATLAB consisted of the removal of field gain settings, the application of a band-pass frequency filter (15 to 600 MHz) and the re-application of a linear gain to improve the
contrast of target-scattered energy in later time. After signal-to-noise ratio improvements, a time range the range of 11 to 21 ns was chosen for display and the data were read into the GPHYZGPR program, which included a translucent display option for 3D data (Daniels, 2000). Translucence levels applied to data using constructed color mapping effectively emphasized volume features of interest.

SUBSIDENCE DETECTION: DATA EXAMPLES AND DISCUSSION

The following sections present EM-wave velocity tomogram and surface 3D radar data results, along with interpretations regarding subsidence activity and relative future roadway collapse risk, for several regions of the I-70 study area.

Borehole Tomography

Figure 6 shows EM-wave velocity tomograms acquired along the eastbound passing lane between road stations 483+00 and 483+57 (borings GC201 to GC206; see Figure 1). Between wells GC202 and GC203, a region of relatively low EM velocity exists from 14.0 to 16.0 m deep at the bedrock level. This low velocity zone at the bedrock level exists between road stations 483+14 and 483+19 and is interpreted to be the result of increased water content due to subsidence-related fracturing. This interpretation is supported by the drill log GC202 at road station 483+14; as a void was encountered during drilling at a depth of 15.5 m (Figure 7). Wells in this region were not cored to the depths necessary to confirm coal presence or absence. However, these data suggest that the mine workings map, which indicates a supporting coal pillar beneath well GC202 and GC203 locations (Figure 1), has placed the eastern edge of the pillar too far to the east.

Data in Figure 6 indicate that a disrupted and down-dropped bedrock horizon exists between wells GC203 and GC205 (road stations 483+23 to 483+40). Relatively low EM velocities at the surrounding bedrock level suggest an increased secondary porosity due to fracturing and bedrock subsidence. The inter-layering of grout and shale beneath the bedrock surface as mapped by well GC205 has contributed to relatively low velocities at the bedrock and mine levels. Between wells GC205 and GC206 (road stations 483+40 to 483+57) EM-wave velocities at the bedrock level are higher than those to the immediate west. Substantial mineralogic or primary porosity differences are a possible explanation, but this observation and supporting drill log information in the area suggests a relative decrease in bedrock subsidence-related fracture density between GC205 and GC206.

Possible subsidence-related disruption of materials directly beneath the roadway cannot be inferred from Figure 6 due to refraction interference and poor signal-to-noise ratio at shallow depths, which prevented the application of tomography. However, tomographic data demonstrate that mine-related overburden and bedrock horizon disruption has occurred. Because of the close proximity of disrupted bedrock to the roadway, the eastbound passing lane is regarded as having a relatively high potential for future mine-related surface failure in the road station range of 483+14 to 483+40 (Figure 6). This interpretation is supported by shear-wave seismic reflection data (Guy et al., 2003) that indicated the bedrock had been down-dropped along normal faults in this region and by drill log data (Figure 7), which also indicate a bedrock low and voids in this region.
Figure 6. EM velocity tomograms mosaic for borings GC201 through GC206 (16.3 m apart; see Figure 1) located in the eastbound passing lane.
Figure 7. Geologic cross-section constructed from drill logs for borings GC201 through GC206 (16.3 m apart; see Figure 6) located in the eastbound passing lane.
Surface 3D Radar

Shown in Figure 8 is a 3D surface radar block of data acquired along the eastbound lanes between road stations 469+00 and 471+00 (Figure 1). The two-way travel time to the top of the rebar structure occurred at ~5 ns, representing a depth of ~ 0.25 m assuming an $\varepsilon_r$ of 9 for the roadway. A time range of 11 to 21 ns was chosen for display of the data presented in this paper as it enables easier observation of subtle changes within and beneath the rebar structure. Relevant surface features in this road station range (Figure 1) include two previous sinkholes located just north of road station 468+50 (westbound side) and three areas of noted depression in the roadway: 469+50 to 470+50 and 471+00 to 472+50 (eastbound side), and 467+50 to 469+00 (westbound side). Mine workings have been mapped as running underneath the roadway between 468+50 to 470+00. Based on previous subsidence evidence and mapping alone, it appears that this region of the study area, particularly on the western end, is at increased risk for future subsidence-related failure.

Two slump features, anomalies A and B (Figure 8), were imaged using the surface radar data from this section. These features are consistent with what might be expected for data collected on a concrete structure where the base support has decreased due to the slumping of the materials beneath it. The expression of A is most pronounced on the shoulder where there is no rebar re-enforcement in the concrete, thus leaving the roadway structure most susceptible to the slumping of near-surface materials from active subsidence processes. As these anomalies are located just west of a noted pavement depression and directly over the mine workings, this explanation is reasonable.

Contained in Figure 9 is a 3D surface radar block of data acquired along the eastbound lanes between road stations 483+00 and 485+00 (Figure 1). This area is located at the western end of the re-enforcing patch emplaced over the previous collapse site from road stations 483+25 to 483+75 with mine rooms mapped beneath the roadway in the entire station range (Figure 1). Anomaly C, which is a large circular feature, is significant, given its well-defined nature that is consistent with a pit-style subsidence feature, and its location with respect to adjacent areas of observation. Also imaged in Figure 9 is anomaly D, which is located at the western edge of the construction patch. While this anomaly does not necessarily offer conclusive evidence that this area is at a high risk for future subsidence, its proximity with respect to the previous collapse zone and pavement depression suggest that further investigation is required.

Subsidence-related disruption of support materials beneath the roadway structure could not be directly imaged in Figures 8 and 9 due to depth limitation of the radar signal. However, the data indicate such, as structural disruptions in the roadway due to mine-related subsidence processes are clearly shown. Because structure is disrupted immediately beneath the roadway surface (in the roadway structure), the eastbound lanes, specifically the eastbound passing lane, are regarded as having a relatively high potential for future mine-related surface failure in the road station ranges of 469+40 to 469+70 (Figure 8), and 483+40 to 484+00 (Figure 9) respectively. Shallow exploratory probing performed subsequent to the interpretations supports interpretations. For example, probing the area of anomaly A (Figure 8) revealed the existence of near-surface voids directly beneath the roadway and shoulder.
Figure 8. Surface 3D radar block for I-70 eastbound lanes road stations 469+00 to 471+00 (61 m apart). Anomalies A and B result from coal mine-related subsidence disruption of the roadway subsurface; see text for discussion.
Figure 9. Surface 3D radar block for I-70 eastbound lanes road stations 483+00 to 485+00 (61 m apart). Anomalies C and D result from coal mine-related subsidence disruption of the roadway subsurface.
COMPARISON OF METHODS

As expected, the borehole tomography and surface radar data allow inference of different effects from the mine-related subsidence, and have been used together to complete a more effective site characterization. The borehole radar tomography data (road stations 483+00 through 483+57, Figures 5 and 6) indicate changes in bedrock consistent with subsidence-related disruption only the most significant zones of low velocity at depth between borings GC204 to GC206 correlate with surface radar anomalies C and D (Figure 7). Low velocity zones at depths between borings GC202 to GC204 and GC212 to GC213 do not appear to have propagated to the surface as there are no features evident to suggest shallow disruption in the surface radar data. However, the proximity of these low velocity zones to the noted pavement depression suggest that subsidence related activity is not confined to the depression in the pavement or the previous roadway collapse zone. Additionally, anomalies A and B (Figure 8), located between road stations 469+00 to 471+00, indicate the presence of subsidence related activity that was not targeted by the borehole tomography during this investigative phase.

CONCLUSIONS

The results of our study demonstrate that the application of an integrated approach utilizing borehole tomography and surface 3D radar methods can be used to locate areas where subsurface bedrock, overburden, and shallow road fill materials have been disrupted due to mine-related subsidence processes. Borehole radar was shown to be capable of providing insight into the nature and extent of subsidence-related fracturing in saturated, consolidated units existing at depths which were not able to be investigated (due to signal attenuation) using surface-based radar. Surface radar was been shown to be effective for quickly and accurately detecting subsidence-related disruption of the near-surface roadway structure at depths that were not able to be characterized (due to refraction interference and signal attenuation) using cross-hole radar. The two radar methods complimented one another, and can be used together to improve site characterization potential and to locate areas along a roadway having a relatively high risk for future collapse during other mine-related subsidence studies.

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