GUIDELINES FOR
GEOPHYSICAL INVESTIGATIONS
OF MINES UNDER HIGHWAYS

MINE RESEARCH PROJECT - GUE 70 - 14.10

PID No. 18459

Report to

OHIO DEPARTMENT OF TRANSPORTATION

Prepared by

BBC&M ENGINEERING, INC.
and
SOFTEARTH ASSOCIATES, INC.

DUBLIN, OHIO

Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

June 2003

BBC&M ENGINEERING, INC.
6190 Enterprise Court, Dublin, Ohio 43016-7297
Phone (614) 793-2226 Fax (614) 793-2410

June 27, 2003
011-07000-130

Ms. Monique Evans, Administrator
ODOT, Office of Research and Development
1980 West Broad Street, 2nd Floor
Columbus, Ohio 43223

Re: Guidelines for Geophysical Investigations of Mines Under Highways
Phase III Report - Mine Research Project GUE 70 - 14.10

Ms. Evans:

BBC&M Engineering, Inc. is herewith submitting the final report for Phase III of the GUE 70 14.10 Mine Research Project. The document has been titled "Guidelines for Geophysical Investigations of Mines Under Highways". The report was prepared as a cooperative effort between BBC&M Engineering Inc. and our Geophysical Sub-consultant Dr. Jeff Daniels of SoftEarth Associates Inc.

If you have any questions regarding the work completed, please do not hesitate to contact our office.

Respectfully submitted,
BBC&M ENGINEERING, INC.

Christopher K. Hall
Senior Geologist, BBC&M

Jeffery J. Daniels, Ph.D.
The Ohio State University
SoftEarth

Timothy A. Van Echo, P.E.
Executive Vice President, BBC&M

CKH/ckh
submitted: 60 copies
120 copies of Executive Summary
2 copies Compact Disc with Report in PDF format
2 copies Compact Disc with Report in WordPerfect Format

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/OH-2003/007-1		

4. Title and subtitle.	5. Report Date
Guidelines for Geophysical Investigations of Mines Under Highways Mine Research Project GUE 70 - 14.10	June 2003
	6. Performing Organization Code
7. Author(s) Mr. Timothy A. Van Echo, P.E. Mr. Christopher K. Hall Dr. Jeffery J. Daniels, PhD	8. Performing Organization Report No.
	10. Work Unit No. (TRAIS)
9. Performing Organization Name and Address BBC&M Engineering, Inc. 6190 Enterprise Court Dublin, Oh 43016-7297	11. Contract or Grant No. State Job No. 45041(0)
	13. Type of Report and Period Covered Final Report
12. Sponsoring Agency Name and Address Ohio Department of Transportation 1980 W Broad Street Columbus, OH 43223	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

It is estimated that approximately 8,500 abandoned underground mines are present in Ohio and mine-related subsidence has been a problem dating back to the 1920's. Many investigative methods have been utilized with varying degrees of success in an attempt to characterize the mines and the stratigraphy above the mined intervals. The primary objective of the research was to provide an overview of and guidelines for the implementation of geophysical investigations of sites where highways are constructed above mines.

The geophysical methods tested as part of the project included: surface seismic reflection; spectral analysis of surface seismic waves; cross-hole seismic measurements; surface ground penetrating radar (GPR); side-looking GPR; cross-hole GPR; resistivity, and borehole geophysical logging. Based on the work completed, it is believed that surface GPR, resistivity, surface seismic reflection using shear waves, geophysical logging, and cross-hole GPR can be valuable supplements to the investigation of mines beneath highways.

It is noted that abandoned mine sites cannot be fully characterized by use of geophysical methods alone. The characterization and evaluation should also include: a review of available data; a site reconnaissance by personnel familiar with mine subsidence; site characterization by drilling and sampling; and, intrusive investigation of specific areas of high concern. Furthermore, interpretation of geophysical data is an iterative process between the drilling program and the geophysical investigations. The drilling data improves the interpretation of the geophysical data, and the improved interpretation should be applied to re-direct the drilling progam.

17. Key Words	18. Distribution Statement
geophysical, ground penetrating radar, GPR, resistivity, surface seismic reflection, shear waves, cross-hole, borehole geophysical logging, abandoned underground mines, spectral analysis of surface seismic waves, subsidence.	No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

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SECTION 1 - SCOPE AND OVERVIEW

1.1 Purpose of Document

This document discusses the results of geophysical investigation methods conducted along Interstate Route 70 (IR-70) under a contract with the Ohio Department of Transportation (ODOT). The specific site conditions, as determined by the investigations that were conducted, are not presented in this document. Those findings were reported in the document entitled "Site Investigation Report - Mine Research Project GUE 70 - 14.10". However, a brief description of the scope of the IR-70 field project is included to establish the overall scope and focus of the project.

1.2 Motivation for the Study

The Study Area is a 2,100-foot long section of IR-70 (between Stations 467+00 and 488+00) located between Cambridge and Old Washington in Guernsey County, Ohio. In the Study Area, IR-70 crosses over underground mine workings that are part of the abandoned Murray Hill No. 2 mine complex. During March of 1994, a mine-related collapse pit was recognized by ODOT in the median just east of Station 478+00 and two additional subsidence pits were identified adjacent to the shoulder of the westbound lanes. Drilling conducted at this time encountered voids beneath the roadway and debris in the mined zone, indicating that collapse of the mine roof had occurred at several locations. A collapse of the eastbound lanes of IR-70 occurred during March of 1995 between Stations 483+00 and 484+00; the collapse resulted in a pit roughly 10 feet in diameter.

Immediately subsequent to the recognition of collapse areas along the roadway during 1994, an aggregate material was used to fill depression features, and the areas were then patched with asphalt. Following the 1995 collapse, the roadway was closed for 4 months, during which time a mine remediation project was constructed. This work consisted of drilling and grouting within the Project Area to fill mine voids and rock fractures, and to construct land bridges (composed of reinforced concrete) along the westbound lanes. After the roadway reopened, grout settlements at borehole locations developed during the spring of 1996, at which time exploratory drilling revealed voids in several locations where grouting had been previously performed. A second phase of grouting was then conducted from May through September of 1997. During the two phases of grouting, approximately 1,800 grout injection boreholes were drilled along the roadway in a grid pattern.

Shortly after the completion of the mine remediation work at the site, ODOT decided that the entire Project Area should be studied to determine if the post-construction subsurface conditions were remaining in a stable condition. ODOT recognized that geophysical investigative methods that were found to be effective in studying the Project Area might also be effective for use at other similar roadway locations. A research team comprised of individuals from academia and industry were chosen to test several different investigative methods at the Project Area.

The methods were tested in two phases. The first phase of the testing (Phase I) consisted of testing most of the conventional geophysical methods over a limited area (200 linear feet of the eastbound lanes). The methods consisted of techniques that have been utilized in mining and engineering applications over the past few decades. The second phase of the study (Phase II) consisted of applying the most promising techniques, as determined by Phase I testing, over the entire 2,100-foot length of highway.

1.3 Geophysical Methods

The methods discussed below were evaluated during the project.

1.3.1 Surface Ground Penetrating Radar (GPR)

Surface GPR is a technique that utilizes the fact that high frequency electromagnetic waves propagate in the subsurface at a velocity that is directly related to the electrical dielectric constant of the material. If the wave encounters a change in dielectric constant as it propagates into the subsurface, then some of the energy is refracted into the lower medium, while the remainder of the energy is reflected back to the surface. The energy that is reflected (or diffracted in the case of sharp boundaries) returns to the surface where its arrival time and energy distribution are mapped. These measurements of the energy that is reflected back to the surface become “records”, or maps of the distribution of boundaries between materials of different velocities. Since the velocities are related to the dielectric constant, and the dielectric constant is related to the density, GPR records can be interpreted as two dimensional cross sections of the density distribution. Under some circumstances, GPR may directly map voids in the near surface.

Photograph 1: Surface GPR Data Acquisition Equipment

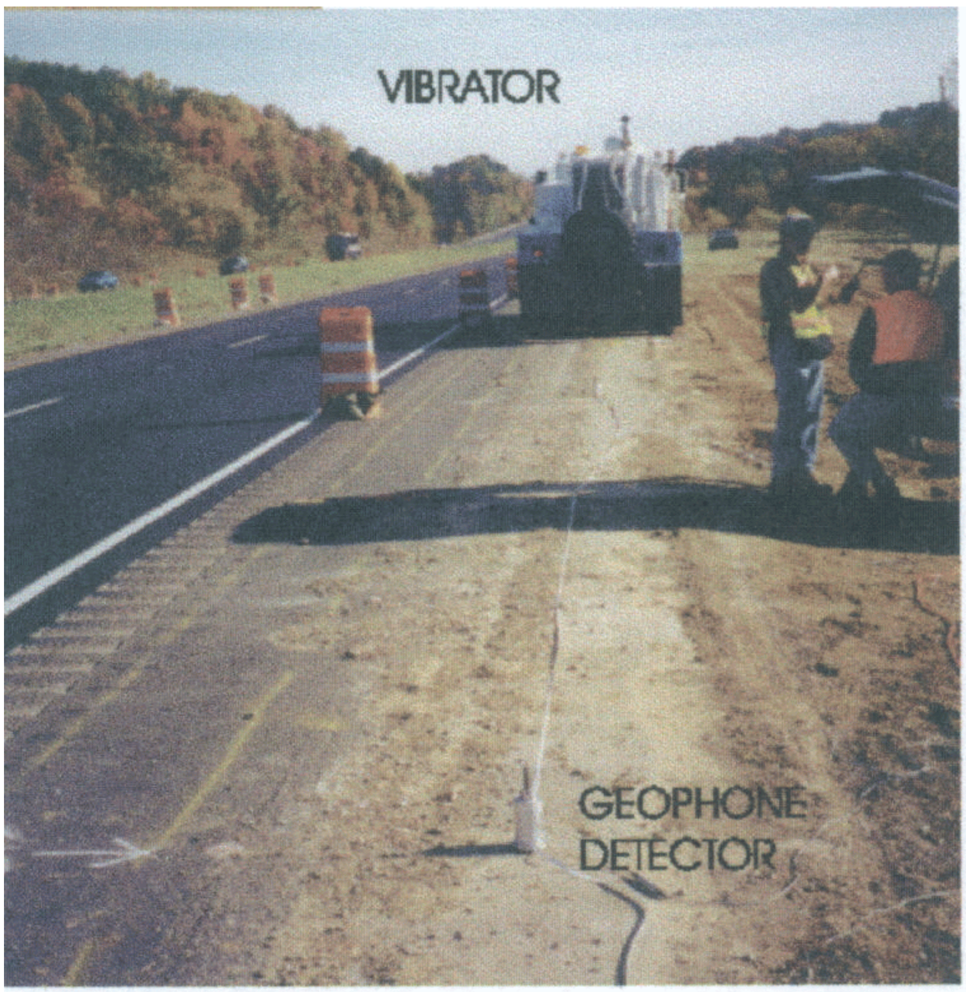
1.3.2 Surface Seismic Reflection

Surface seismic reflection is a proven technology which provides a reliable cross section of the subsurface along a line of measurements on the surface. The seismic reflection method and the associated data processing techniques are used routinely in the petroleum industry to explore geologic features for the potential of locating oil and gas deposits. Recently the petroleum industry has been investigating the use of shear waves (S waves), rather than compressional waves (P waves), for subsurface imaging. The tests on IR-70 included the use of both P and S waves. S waves have the advantage of having a different direction of motion than the traffic on the highway. S waves also have the advantage of being much slower (usually around 1/3 slower) than P waves. This is important for near-surface studies where the distance from the surface to the targets of interest in the subsurface is very short. Seismic methods can provide a cross-sectional map of subsurface geologic features which may indicate the presence of near surface voids.

Photograph 2: Seismic Geophones on 1-foot Spacings

1.3.3 Spectral Analysis of Surface Waves (SASW)

Spectral analysis of surface waves (SASW) is a technique that measures the dispersion (frequency dependent velocity) of seismic surface waves. SASW techniques have been developed over the past thirty years to investigate the near-surface velocity of seismic waves. It can be shown that these velocities are related to the mechanical properties of the near surface materials. Objects in the near surface that cause an increase in the porosity of materials (e.g., voids and slumps) also cause a decrease in the velocities interpreted from SASW measurements.



Photograph 3: Field Operations for SASW

1.3.4 Side Looking Underground Radar (SLUR)

The SLUR method utilizes the same basic principles of surface GPR. However, with the SLUR method, the measurements are made along a sloped surface, whereby the sloped surface is a trench cut into the ground parallel to the buried feature that is being investigated. This arrangement provides an angled side view of the buried object, rather than a vertical view as is obtained using conventional surface GPR.

Photograph 4: SLUR Data Acquisition with Antennas in Co-pole Orthogonal Configuration

1.3.5 Resistivity

Direct current resistivity is an established electrical method that measures differences in the spread of electric current in the subsurface. The differences are caused by variations in the electrical resistivity that are related to changes in lithology and/or porosity. The most commonly used configuration for the measurement of resistivity is a dipole-dipole arrangement. Resistivity has traditionally been considered a labor intensive technique, but new technologies have provided a means to obtain resistivity data inexpensively. Results of a resistivity survey are presented in the form of subsurface cross section (called a pseudo-section) that can be interpreted to represent a cross-sectional slice of the earth. Data are interpreted using a mathematical inversion procedure, and the results of a resistivity survey are inherently non-unique, but in some cases resistivity can provide a rapid non-intrusive means to detect large voids and fracture zones in the subsurface.

Photograph 5: Sting Resistivity System

1.3.6 Cross-hole Ground Penetrating Radar

Cross-hole GPR is a technique that applies the basic theory and principles of surface GPR to provide an image of the materials between two boreholes. The theory is sound, since it is identical to propagation theory that has been developed to describe surface GPR measurements. Cross-hole GPR should be able to provide an excellent high resolution two dimensional image of changes in the velocity of propagation of a high frequency electromagnetic wave between two boreholes. The velocity of propagation is directly related to the relative electrical dielectric constant (sometimes called the dielectric constant), which in-turn is related to the density of material. Therefore, cross-hole GPR should be a good indicator of voids, slumps, and other low density features related to mine collapse. Cross-hole GPR can be utilized in cross-hole-velocity or cross-hole-tomography mode, as discussed below for the cross-hole seismic method.

Photograph 6: GPR Transmitter and Receiver being Lowered into Boreholes

1.3.7 Cross-hole Seismic Methods

There are two modes of operation for cross-hole seismic methods:

1) cross-hole seismic velocity; and

2) cross-hole seismic tomography.

Both approaches place a seismic source in one borehole and a receiver in another borehole, with the objective of sensing and imaging variations in the seismic velocity and/or the bulk density of the material between the boreholes. Cross-hole seismic velocity measures the velocity of propagation of a compressional wave between two holes. By making measurements at different levels in the boreholes, a vertical profile of the velocity variations between the two boreholes can be established. The seismic velocity can then be related to the porosity of the material. Seismic tomography is an inverse imaging technique that has the goal of providing a two dimensional image of changes in the velocity of propagation of a seismic wave between two boreholes. Propagation and measurement of S waves and P waves provides the potential of measuring the full propagation tensor matrix (three orthogonal transmission directions, and three orthogonal measurement directions), which increases the likelihood of obtaining an improved image of the velocity distribution between the boreholes. Seismic tomography should be a good indicator of voids, slumps, and other low density features related to mine collapse.

Photograph 7: Set-up for Cross-hole Seismic Shear Wave Measurements

1.3.8 Down-hole Geophysical Borehole Logging

Geophysical borehole logs provide a detailed analysis of the physical properties within the immediate vicinity of the borehole wall. The logs provide a continuous record of the physical properties and indicate the details of the physical property changes. The geophysical borehole logging evaluated for this project included a natural gamma ray and a conductivity (inverse resistivity) logging. Borehole geophysical measurements can in some cases replace many of the standard testing methods that have been traditionally utilized for the analysis of physical and geologic properties in boreholes.

SECTION 2 - EVALUATION OF TECHNIQUES

2.1 Evaluation Summary

Geophysical methods were tested extensively in Phase I over a limited Test Area, with the most promising methods being applied to the entire IR-70 Study Area. The results are summarized in this section. Based on the analysis of the Phase I results, it was recommended that

- surface GPR should be used to try to detect any features that might be located directly beneath the roadbed;
- seismic reflection should be used to detect fracturing in the bedrock above the mine;
- cross-hole methods should be utilized to help image specific features identified by the surface work; and,
- borehole geophysical logging measurements should be used to help define the geologic features in individual boreholes.

A summary of the techniques tested at the IR-70 site are presented in Table 1 on the following page.

Table 1: Summary of Geophysical Methods Evaluated During the Project

Method	Type *	Brief Explanation and Rationale for Application	Phase Tested	General Results of I-70 Tests	Pros and Cons
Resistivity	S	Measures variations in conductivity of ground. Open voids have a conductivity of zero.	II (unique test)	Results generally correlated with known locations of anomalies.	Technique is widely accepted and used. Results are non-unique, but may provide general location information. Dipole-dipole configuration appears to be most effective.
Seismic Reflection (S-Wave)	S	Measures changes in the propagation of seismic shear waves.	I and II	Good discrimination of stratigraphy above the bedrock.	Good technique for identifying stratigraphy and shallow bedrock fractures. Resolution and depth of penetration limited. Expensive.
Seismic Reflection (P-Wave)	S	Measures changes in the propagation of seismic compressional waves.	I and II	Did not provide as good of results as S-wave measurements.	Good for locating very deep features. Affected by highway noise. Expensive.
SASW	S	Measures changes in the spectral content of surface waves.	I	Did not provide high resolution results, only overall layering revealed.	Technique has proven effective elsewhere. Affected by highway noise, and the interpretation provides a non-unique solution.
GPR	S	Measures changes in the dielectric constant. Voids and earth materials have a high contrast.	I and II	Detected anomalies that could be associated with slump features. Some anomalies unrelated to slumps or voids.	Technique is widely accepted and used. Results may provide a pseudo-3D image. Depth of penetration can be highly restricted in some cases to 1.5 feet. Results are very dependent upon site conditions.
Gamma Ray	B	Borehole logging technique that can determine stratigraphy.	I and II	Good results.	Good general use method that can be used in place of sampling for general determination of stratigraphy.
Conductivity/ Resistivity	B	Borehole logging technique that can determine stratigraphy and/or voids.	I and II	Good results.	Good general use method that can be used in place of detailed sampling for general determination of stratigraphy. Good for identification of voids and fractures. Not as good as gamma ray for stratigraphy.
Cross-hole Radar	X	Utilizes principles of surface GPR to investigate objects between boreholes.	I and II	Good results.	Measurements are time consuming and require closely spaced boreholes.
Cross-hole Seismic Tomography	X	Utilizes principles of seismic wave propagation to investigate objects between boreholes.	I	Potential of the method for success is high. Current equipment is not adequate.	Method has potential for the future. More research is needed to develop reliable and easy-to-use sources and detectors of S-waves in dry holes.
Cross-hole Seismic Velocity	X	Utilizes principles of seismic wave propagation to investigate objects between boreholes.	I and II	Results were difficult to evaluate.	(See comments on cross-hole seismic tomography.)
Side Looking Underground Radar (SLUR)	S	Utilizes principles of surface GPR to investigate objects from the surface at an angle.	I	Difficult to evaluate and implement. Theory sound, but not practical for routine roadway application.	Produces good results under ideal ground conditions. Otherwise the penetration depth is very limited. Requires construction of trenches with a road grader or bulldozer.

* Legend: Type S: Surface Measurements
Type B: Borehole Measurements
Type X: Cross-hole Measurements

2.2 Summary of the Phase II Geophysical Studies

The Phase II studies established the usefulness of an integrated geophysical testing approach that makes use of GPR for very-shallow investigations, seismic shear wave reflection surveys for determining fracturing and voids in the bedrock above the mined interval and establishing the continuity of the subsurface geology, and cross-hole GPR for determining the presence of void space and other low density features between boreholes. In a few cases, the seismic shear wave reflection surveys can be used to map block failures in the bedrock. The GPR, seismic shear wave measurements, and cross-hole GPR measurements should be interpreted in a composite form (see Figure 1 on the next page), and in all cases the interpretation of the composite geophysical data should be conducted in connection with existing geologic and hydrogeologic information.

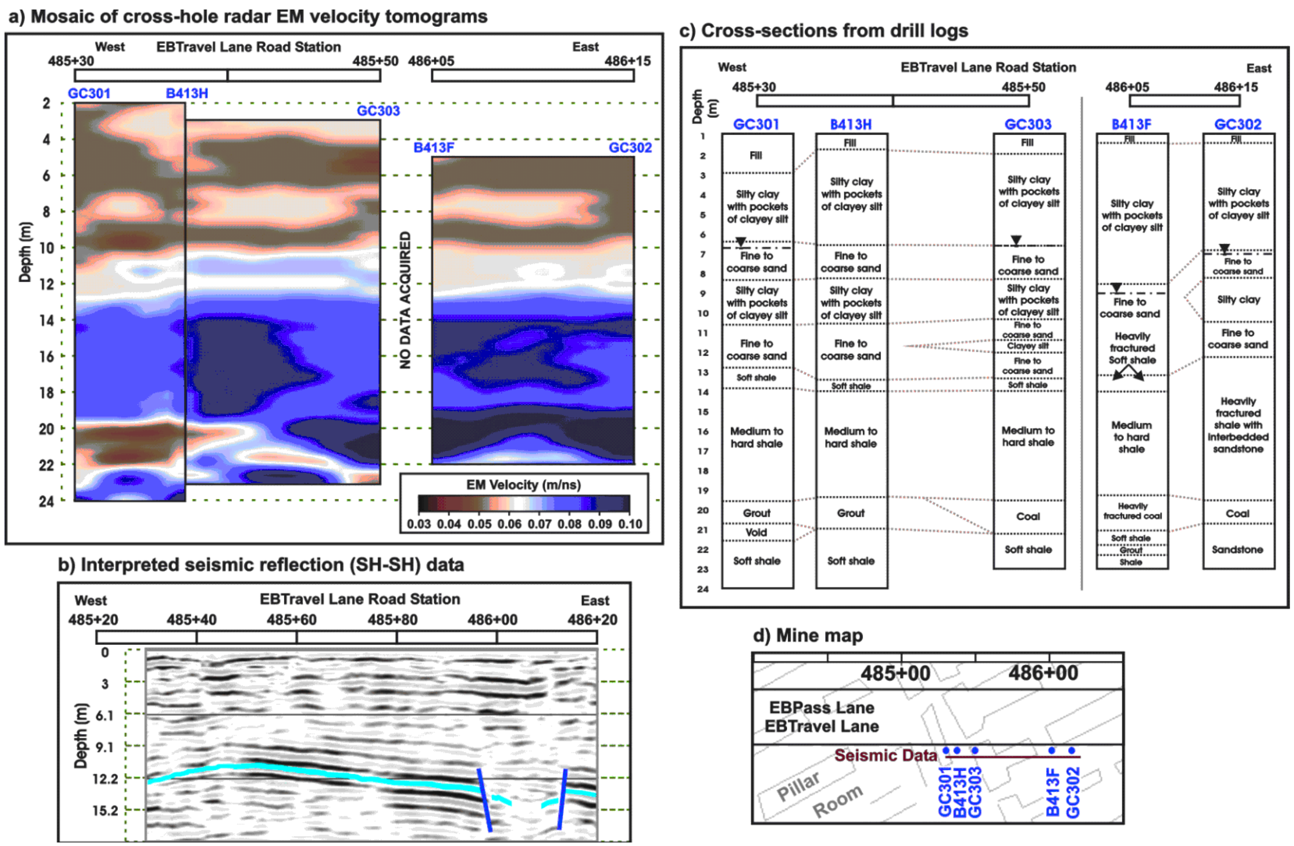


Figure1: Composite of Interpreted Data. IR-70 eastbound travel lane Station 485+30 to 486+20: (a) EM-wave velocity mosaic, (b) S-wave reflection data, (c) geologic cross-sections from logs, and (d) approximate locations of mine workings. Velocities (a) suggest that the coal pillar beneath the road (Stations 486+05 to 486+15) actually extends farther south than mapped in (d), and that the seismically imaged subsidence feature (b) resulted from bedrock collapse into the mine room located just south of this pillar.

SECTION 3 - RECOMMENDED PROCEDURES FOR APPLICATION OF GEOPHYSICAL METHODS

The selection and sequential application of geophysical methods is important. The following general recommendations are made concerning the integration of geophysical methods into investigations of potential mine subsidence under highways:

1) All sources of site information, including ODOT construction and maintenance records, mine maps, existing boring and well logs, geologic and water resource maps, existing mine permits and maps, and any other available information should be reviewed during the earliest stages of an investigation (see ODOT Abandoned Underground Mine Inventory and Risk Assessment Manual (AUMIRA) Section 3.1, 3.2, and Appendices C & D).
2) A detailed site reconnaissance should be performed by personnel with experience in evaluating and remediating mine subsidence (see AUMIRA Section 3.3).
3) Surface GPR measurements should be conducted on the driving lanes and shoulders to detect voids or slumping that might be present in the immediate vicinity of the surface. GPR can be used to identify suspect areas that have little or no apparent disturbance at the surface. In general 2D GPR should be attempted initially because it is quicker and the lower frequencies used may provide greater depth of penetration (compared to 3D GPR). 3D GPR should be attempted to delineate the horizontal and vertical extent of anomalies at suspect locations identified by the 2D GPR. The use of 3D GPR requires close line spacings and higher frequencies, which may limit the depth of penetration. An antenna range of 0.2 to 1 meter (0.7 to 3.2 feet) with a centerband frequency range of 500 HHz to 12 GHz can be expected to be most affective in paved areas for shallow investigations. In non-paved areas the most affective antenna frequency will vary depending upon the soil type, 0.5 to 10 meters (1.6 to 33 feet) at 50 MHz to 500 MHz for sandy soils and 0.1 to 0.5 meters (0.3 to 1.6 feet) for sandy/clayey soils. Generally speaking lower frequencies provide deeper depths of penetration. In all cases, a range of antennas should be tested at

the site to determine the optimum antenna arrangement.

4) A drilling program should be planned and implemented which investigates any anomalies detected by the GPR and includes the general characterization of the site. The drilling should include standard penetration testing at regular intervals, the collection of undisturbed samples (if appropriate), and recovery of bedrock samples via coring methods. Estimates of the vertical drops of the drilling tools should be recorded to estimate the extent of voids. It is noted that voids can occur within the soil, overburden bedrock, or at the mined zone (see ODOT Specifications for Subsurface Investigations Manual).

5) For cases where mine dewatering is believed to have been a contributing factor to the subsidence, a hydrogeologic investigation should be performed. The investigation should include the installation of groundwater monitoring wells or piezometers, in-situ and/or laboratory permeability testing, and estimates of lateral and vertical groundwater movement. The lowering of the groundwater level in abandoned mines can significantly increase the effective loading on the mine roof, and result in subsidence. At a minimum, at least three monitoring wells should be installed in each significant water-bearing formation encountered, including the abandoned mine.

6) Resistivity may be useful in the early stages of an investigation to help define the boundaries of the larger slump regions and regions of fracturing in the near surface. The work completed for this Project used capacitively coupled and direct coupled dipole-dipole arrays.

7) Where there is a high probability of the presence of collapse features at the soil - bedrock interface, a seismic reflection survey using shear waves is recommended. The best component combination identified by this research is an SH-SH configuration in which the source and detector orientation is orthogonal to the line direction.

8) Confirmation drilling and sampling of the soil and bedrock should be conducted in areas where anomalous data has been gathered and in areas of suspected abandoned underground mines. Conventional borehole geophysical log measurements should be made in each borehole. These measurements serve as a continuous record of the lithology; can be used to verify the presence of voids; and, can be correlated to determine the continuity of near-horizontal geologic features.

9) Seismic cross-hole velocity and tomography measurements proved to be difficult to implement above the water table. However, these investigations showed the usefulness of cross-hole GPR measurements. These measurements proved to be a high-resolution compliment to surface seismic and surface GPR measurements. Cross-hole GPR was a successful tool to determine the vertical location and extent of fractured zones that may be present between boreholes.

Interpretation of data is an iterative process between the drilling program and the geophysical data. The drilling data will improve the interpretation of the geophysical data, and the improved data interpretation should be applied to re-direct the drilling to a conclusive result. All geophysical methods are interpretive, and the interpretation improves as more subsurface information becomes available.

SECTION 4 - PITFALLS OF APPLYING GEOPHYSICAL METHODS

In terms of subsurface physical properties, some sites have significant variability that makes it difficult to conduct geophysical surveys in a normal manner. The geologic variability (heterogeneity of the physical properties) can lead to ambiguity in the interpretation of the geophysical measurements. This situation may be improved in the future with sophisticated models that help to account for the spatial variability of the subsurface materials. At present, the effect of the geologic variability on the geophysical measurements can only be determined by performing confirmatory drilling and sampling at the locations of the anomalies to assist in the interpretation of the results.

Other major factors that affect the geophysical measurements along highways are the effect of passing traffic on the measurements, as well as traffic control, and above and below ground utility effects and constraints. In addition to the obvious factor of workers safety, the subsurface vibrations induced by the flow of traffic can significantly affect the geophysical measurements. Because of these affects, the data must be interpreted by personnel with the knowledge and experience to differentiate between the “noise” and genuine subsurface features. It should be noted that the IR-70 Study did prove that high resolution surface seismic reflection can be used effectively along a busy highway by measuring shear waves rather than the compressional waves.

A major hindrance at the present time to the general acceptance of geophysical techniques is the level of technical competence needed for routine application. There are no instruments which are currently available that can be used by the field engineer or geologist without specialized training and/or consultation with geophysicists. Additionally, economically-viable, rapid acquisition systems such as GPR may not be used frequently enough by a highway department to warrant the equipment costs and training needed for the reliable collection and interpretation of data. These problems are difficult to overcome and are compounded by the unknown variability of the subsurface conditions of sites with limited available information. On this basis, collection of data and interpretation of the data by trained geophysicists is recommended.

SECTION 5 - REFERENCES

ASTM Standards

D 420 Guide to Site Characterization for Engineering, Design, and Construction Purposes

D 653 Terminology Relating to Soil, Rock, and Contained Fluids

D 4428/D 4428M Test Methods for Cross-hole Seismic Testing

D 5753 Guide for Planning and Conducting Borehole Geophysical Logging

G 57 Test Method for Field Measurement of Soil Resistivity Using the Wenner dipole-dipole Method

D 6429 Standard Guide for Selecting Surface Geophysical Methods

ODOT Manuals

Manual for Abandoned Underground Mine Inventory and Risk Assessment

Specifications for Subsurface Investigations

ODOT Report

PID No. 18459 Site Investigation Report: Mine Research Project - GUE 70 – 14.10

Books (author, title)

Parasnis, Principles of Applied Geophysics

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