Detection of Underground Voids in Ohio by Use of Geophysical Methods

By Jens Munk and Rodney A. Sheets

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16. Abstract

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Results of ground-penetrating radar surveys at three highway sites indicate that subsurface penetration varies widely with geologic material type and amount of cultural interference. Two highway sites were chosen over abandoned underground coal mines in eastern Ohio. A third site in western Ohio was chosen in an area known to be underlain by naturally occurring voids in limestone. Ground-penetrating radar surveys at Interstate 470 in Belmont County, Ohio, indicate subsurface penetration of less than 15 feet over a mined coal seam that was known to vary in depth from 0 to 40 feet. Although no direct observations of voids were made, anomalous areas that may be related to collapse structures above voids were indicated. Cultural interference dominated the radar records at Interstate 70, Guernsey County, Ohio, where coal was mined under the site at a depth of about 50 feet. Interference from overhead powerlines, the field vehicle, and guardrails complicated an interpretation of the radar records where the depth of penetration was estimated to be less than 5 feet. Along State Route 33 in Logan County, Ohio, bedding planes and structures possibly associated with dissolution of limestone were profiled with ground-penetrating radar. Depth of penetration was estimated to be greater than 50 feet.

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
inch (in.)	2.54×10^{1}	millimeter
foot (ft)	3.048×10^{-1}	meter
mile (mi)	1.609×10^{0}	kilometer
centimeter (cm)	3.937×10^{-1}	inch
meter (m)	3.281×10^{0}	foot
	Area	
square centimeter (cm^2)	1.076×10^{-3}	square foot
	Volume	
cubic centimeter (cm^3)	6.102×10^{-2}	cubic inch
cubic meter (m^3)	3.531×10^{1}	cubic foot
	Force	
newton (N)	2.248×10^{-1}	pound
	Mass	
gram (g)	3.527×10^{-2}	ounce avoirdupois
kilogram (kg)	2.205×10^{0}	pound avoirdupois
	Velocity	
foot per second (ft/s)	6.818×10^{-1}	mile per hour
foot per second (ft/s)	3.048×10^{-1}	meter per second
meter per second (m/s)	3.281×10^{0}	foot per second
	Gravity	
milligal (mgal)	1.0×10^{-5}	meter per second squared

Abbreviated geophysical units used in this report: Time is given in seconds (s), and frequencies are given in hertz (Hz). Electrical resistivity is given in ohm-meters (ohm-m); electrical conductivity, the reciprocal of resistivity, is given in siemens per meter (S/m).

Prefixes and abbreviations for multiples and submultiples:

giga (10^9)	G
mega (10^6)	M
kilo (10^3)	k
centi (10^{-2})	c
nano (10^{-9})	n

Other abbreviations used in this report:

EM	Electromagnetic induction method
GPR	Ground-penetrating radar
IT	Infrared themography
MLF	Multiple low frequency
SP	Spontaneous/self potential
VLF	Very low frequency

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ABSTRACT

Geophysical methods are generally classified as electrical, potential field, and seismic methods. Each method type relies on contrasts of physical properties in the subsurface. Forward models based on the physical properties of air- and water-filled voids within common geologic materials indicate that several geophysical methods are technically feasible for detection of subsurface voids in Ohio, but ease of use and interpretation varies widely between the methods. Ground-penetrating radar is the most rapid and cost-effective method for collection of subsurface data in areas associated with voids under roadways. Electrical resistivity, gravity, or seismic reflection methods have applications for direct delineation of voids, but data-collection and analytical procedures are more time consuming. Electrical resistivity, electromagnetic, or magnetic methods may be useful in locating areas where conductive material, such as rail lines, are present in abandoned underground coal mines. Other electrical methods include spontaneous potential and very low frequency (VLF); these latter two methods are considered unlikely candidates for locating underground voids in Ohio.

Results of ground-penetrating radar surveys at three highway sites indicate that subsurface penetration varies widely with geologic material type and amount of cultural interference. Two highway sites were chosen over abandoned underground coal mines in eastern Ohio. A third site in western Ohio was chosen in an area known to be underlain by naturally occurring voids in limestone. Ground-penetrating radar surveys at Interstate 470 in Belmont County, Ohio, indicate subsurface penetration of less than 15 feet over a mined coal seam that was known to vary in depth from 0 to 40 feet. Although no direct observations of voids were made, anomalous areas that may be related to collapse structures above voids were indicated. Cultural interference dominated the radar records at Interstate 70, Guernsey County, Ohio, where coal was mined under the site at a depth of about 50 feet. Interference from overhead powerlines, the field vehicle, and guardrails complicated an interpretation of the radar records where the depth of penetration was estimated to be less than 5 feet. Along State Route 33 in Logan County, Ohio, bedding planes and structures possibly associated with dissolution of limestone were profiled with ground-penetrating radar. Depth of penetration was estimated to be greater than 50 feet.

INTRODUCTION

Underground voids from abandoned mines or natural dissolution of rock material can result in the collapse and subsidence of overlying material. Effects of such collapse or subsidence can range from alteration of surface and subsurface drainage to rupturing of gas lines and roadway collapse.

Abandoned underground coal-mine voids are an important source of water supply for some communities in eastern Ohio (Crouch and others, 1980). In other areas, acid mine drainage from mine voids affects water quality and stream biota. Collapse or subsidence of mine voids may drastically affect ground-water or surface-water supplies.

Hazards that might be associated with abandoned underground coal mines or natural voids under highways are of particular interest to the Ohio Department of Transportation (ODOT) and the Federal Highway Administration (FHA) because collapse of the material over these voids can sometimes result in surficial expressions that are devastating to roadways and vehicles. In March 1995, material over an abandoned coal mine in eastern Ohio collapsed into a void, resulting in damage to several vehicles and closure of an interstate highway for a period of several months.

Cost-effective techniques to locate underground voids would not only aid in averting hazardous conditions but also might help water purveyors or regulators locate additional sources of water supply or sources of acid mine drainage. In summer 1996, the U.S. Geological Survey (USGS), in cooperation with ODOT, began a study to address these concerns.

Purpose and Scope

The purpose of this report is to evaluate surface geophysical techniques that might prove useful in remotely characterizing voids or void-related subsidence features under roadways in Ohio. Selected techniques are described, and the results of model and field investigations are presented in the report.

Previous Investigations

Geophysical techniques have been widely used for investigations of underground voids and void-related features. Techniques to characterize subsurface voids peaked in the 1960's with U.S. Government efforts to locate tunnels in Vietnam. Efforts in recent years have focused on U.S. highway construction, water supply, mine planning, and hazard reduction (Dobecki and Romig, 1985; Colorado School of Mines, 1984). A wide variety of techniques can be employed to map these features and several techniques often are used in combination because of their complementary nature (Hauser and Jessop, 1995; Hensel and Dalton, 1995; Pawlowski and others, 1995). Specific references on the application of selected techniques to void detection can be found later in this report.

Acknowledgments

We acknowledge the assistance of Jim Graham, George Beiter, Steve Kramer, and Rick Ruegsegger of the Ohio Department of Transportation for supplying the necessary highway information and field support needed to safely complete this work. We also thank American Aggregates, Inc., for access to their quarry near the Logan County site.

EVALUATION OF SELECTED GEOPHYSICAL METHODS FOR DETECTION OF UNDERGROUND VOIDS

Physical properties of underground voids and void-related features, such as collapse structures, can contrast dramatically with those of the surrounding rock. Geophysical measurements of the contrasts in physical properties can help define locations of these features. The following sections describe several commonly used geophysical methods and detail the use of individual geophysical methods to delineate voids or void-related features in areas of

Ohio where underground voids are common. In many cases, the use of a single geophysical method may not adequately delineate voids or void-related features, and a combination of methods may be more appropriate.

The effectiveness of geophysical methods relies on physical property contrasts in the subsurface, which cause variations in the associated energy field. These methods can be classified into three broad categories, based upon the physics behind the techniques: electrical (electromagnetic), potential (gravitational and magnetic), and seismic (acoustic). Each type of field responds uniquely to a given physical property, which may be electrical conductivity, relative dielectric permittivity, density, magnetic susceptibility, or seismic wave velocity. Selected physical properties for typical Ohio rock and soils are listed in table 1, along with properties of air and water.

Table 1. Summary of selected physical properties of typical Ohio rocks and minerals, air, and water

[Modified from Heiland, 1963; Dobrin, 1960; Guyod and Shane, 1969; L. G. Stolarczyk, oral commun., 1996; electric conductivity = 1/electric resistivity (in ohm-meters); S/m, siemens per meter; g/cm^3, grams per cubic centimeter: cgs, centimeter-gram-second; m/s, meter per second]

	Electric conductivity (S/m)	Relative dielectric permittivity (no units)	Density (g/cm^3)	Magnetic susceptibility (cgs x 10^6)	Seismic wave velocity (m/sec)
Limestone	10^{-7} to 0.02	8-12	1.93 to 2.90	3.8	4,000 to 6,400
Sandstone	10^{-9} to 1	4.7-12	1.61 to 2.76	16	1,400 to 4,900
Shale	10^{-4} to 0.5	7	1.70 to 3.20	44	2,100 to 5,200
Coal	2x10^{-4} to 0.05	7 to 43	1.20 to 1.50	<2	1,340
Clay	0.01 to 1	8 to 12	1.30 to 2.46	20	1,000 to 2,800
Air	0	1.0	0.00	0	332
Water (fresh)	0.001 to 0.003	81	1.00	0	1,460

Making use of the physical properties given in table 1, a forward model can be used to estimate variations in the measured field quantities due to voids in the subsurface. A forward model is used to generate synthetic data, assuming that the appropriate physical properties are known. Although anomalous features are typically complex structures, their properties can often be modeled using simple cylindrical and spherical bodies. Air and (or) water-filled voids are considered most susceptible to collapse and are modeled herein as simple bodies. The magnitude of the field variations is analyzed with respect to the sensitivity of the measuring device, effect of cultural disturbances, noise, and the presence of subsurface anomalies not of interest to the survey. These concerns are especially important with regard to data collection on or near highways. A final consideration is the speed and ease by which data can be obtained for a particular method. Results of forward models are included in the following sections if forward-modeling computer programs are available for the respective techniques.

Electrical Methods

Electrical methods represent the most diversified group of techniques in surface geophysics (Dobrin, 1960; Heiland, 1963; Keller and Frischknecht, 1966; Telford and others, 1990). Electrical methods vary greatly with respect to their methodology and frequency of electrical field. Low-frequency techniques involve a slowly varying electric field, whereas high-frequency electrical methods involve a rapidly varying field. In addition, the electrical energy to be evaluated can be either naturally occurring or artificially generated. The effectiveness of a particular electrical method depends on various factors, including the difference in the electrical properties between the anomaly and the surrounding medium and the size and depth of the anomaly.

In electrical prospecting, the important electrical properties of earth materials are electrical conductivity or resistivity and dielectric permittivity. These properties relate directly to the atoms and molecules that make up the material. Generally, all materials contain both free and bound electrical charge, where free charge refers to electrons that move unrestricted from molecule to molecule and bound charge refers to electrons that are confined to their molecules.

Conductivity or its inverse, resistivity, is a measure of the amount of free charge (electrons) of a material. These electrons move under the influence of an applied electric field, generating an electric current that in turn produces a secondary electromagnetic field. The magnitude and orientation of the secondary field is related to the conductivity of the material.

The dielectric permittivity is a measure of the polarizability of a material, or the extent to which a material's molecular structure distorts when subjected to an electric field. When a material composed of molecules with bound electrical charge is subjected to an electric field, a slight displacement occurs between the negative and positive charges of the molecular structure. This displacement results in a secondary electromagnetic field, which can then be measured (Kraus, 1992).

Electrical Resistivity

The electrical resistivity method typically employs a direct current (DC) or a very low frequency current (<10 Hz), which is applied by placing a pair of electrodes in contact with the ground (Dobrin, 1960; Heiland, 1963; Keller and Frischknecht, 1966; Telford and others, 1990). The voltage potential is then measured between a second pair of electrodes. A number of possible patterns of electrodes can be used, depending on the depth of penetration needed and the resolution desired. A mathematical combination of the measured current and potential and the geometry of the electrode array yields the apparent resistivity of the subsurface. The true resistivity and the apparent resistivity are the same only when the subsurface is perfectly homogeneous to a depth equal to the depth of exploration.

Resistivity measurements are used to measure lateral or vertical changes in the resistivity of the subsurface. To investigate the variation of resistivity with depth, electrode spacings are increased or decreased; the greater the spacing, the greater the depth of penetration. A fixed electrode separation typically is maintained along a profile line to determine lateral variations.

Electrical resistivity methods are commonly used to map electrically conductive ground-water (for example, saltwater or waste plumes), lateral and vertical changes in lithology, and depth to bedrock. The utility of the method is wholly dependent on the depth and size of the target and the differences between its electrical resistivity and the resistivity of the rock surrounding the target.

Apparent resistivity can be easily calculated for a three-dimensional void by taking advantage of the analogy between voltage potential and hydraulic-pressure differences; this analogy permits use of a ground-water flow model developed by the USGS for analysis of resistivity data (McDonald and Harbaugh, 1988; Jansen and Taylor, 1995). For example, the apparent resistivity resulting from a 5- by 2-m rectangular tunnel in a coal layer can be calculated by assigning resistivities of 50, 150, and 100,000 ohm-m for the limestone, coal, and void, respectively, in a conceptual forward model employing the dipole-dipole and Wenner arrays (Robinson and Coruh, 1988, p. 462, figures 13–15; Zohdy and others, 1974, p. 10–13). Results of the forward modeling, shown in figure 1, indicate that an anomaly of approximately 15 ohm-m would result if dipole-dipole resistivity data (an n-spacing of 2 m; see fig. 1) were taken over a 5- by 2-m air-filled void at a depth of 5 m. As the n-spacing is increased, the resulting anomaly broadens and decreases in magnitude. In general, the electrode spacing is determined from the depth and size of the expected anomaly where relatively small electrode spacings are needed to define shallow targets. Ambient noise levels — resulting from natural variations of earth resistivity, cultural interference, and lateral inhomogeneities in the subsurface — may limit recognition of these anomalies, but the electrical responses are sufficient to warrant further investigation. The forward modeling results of the Wenner-array data indicate that relatively small anomalies would result from this array configuration over the void. Recognition of anomalies from the Wenner-array data would be difficult, given the expected noise levels.

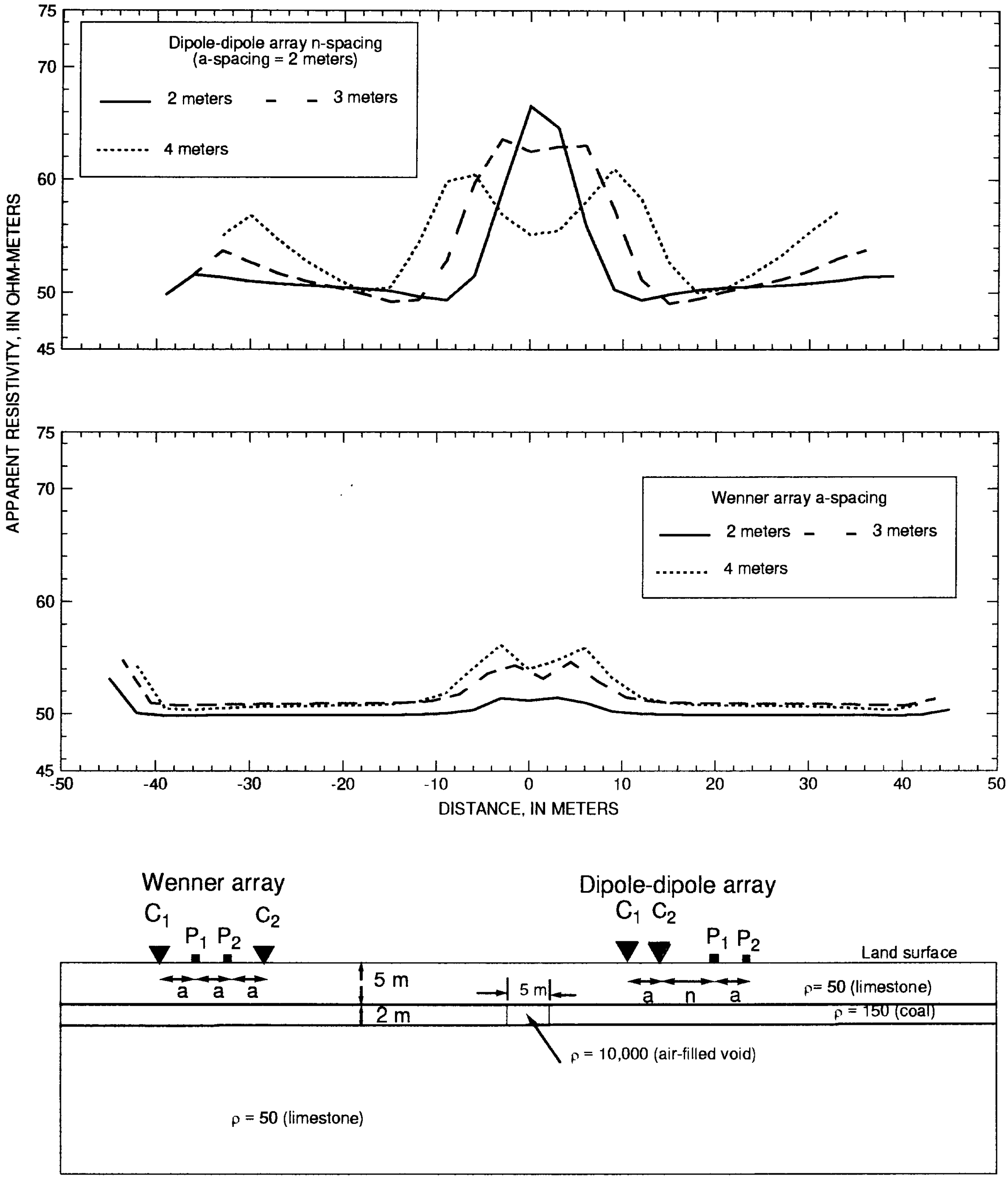

Figure 1. Modeled apparent resistivity over a 5- by 2-meter air-filled void in a coal seam. (Dipole-dipole and Wenner resistivity array results are shown. $C_{1,2}$ and $P_{1,2}$ indicate current and potential electrodes; ρ is resistivity, in ohm-meters.)

Electromagnetic Induction

The electromagnetic induction method (EM) is based on the variations measured in a secondary electromagnetic field produced when a primary field is generated by inducing a current through coils. The EM method is typically used to obtain horizontal profiles and depths of conductive layers. The effectiveness of the method depends on the target size and depth and differences between its electrical resistivity and that of the surrounding rock. Two

EM techniques, time domain and frequency domain, are described below (Dobrin, 1960; Heiland, 1963; Keller and Frischknecht, 1966; Telford and others, 1990).

The frequency-domain EM technique measures the magnitude and phase of an induced electromagnetic current that is altered by the conductivity of the underlying soil and rock. With the frequency-domain technique, an electromagnetic field is generated by passing an alternating current at a frequency ranging from 100 to 5,000 Hz through a conductive wire loop. The current applied to the wire loop sets up a primary magnetic field that, when placed on or near conductive materials, results in current flow within the conductive body. These secondary currents establish a secondary magnetic field that has the same frequency as the primary, but a different phase and direction. The resulting secondary magnetic field is detected by measuring the induced voltage in a second loop of wire, the receiver. The phase and directional differences between the primary and secondary magnetic fields are used to infer the conductive properties of the underlying ground.

The time-domain EM technique measures the conductivity of soil and rock by inducing pulsating currents into the ground by use of a transmitting coil and by monitoring their decay over time with a separate receiver coil. The current pulse applied to the wire loop sets up a primary magnetic field that, when placed on or near conductive materials, results in current flow within the conductive body. These secondary currents establish a secondary magnetic field that is detected by measuring the induced voltage in a second loop of wire, the receiver. The time and amplitude differences between the primary and secondary magnetic fields are used to infer the conductive properties of the underlying ground.

The EM method has been widely used to explore for base-metal ores, which generate strong secondary fields resulting from their high electrical conductivities. This also makes the method a good candidate for detecting tunnels containing rails, electrical wires, or other long conducting bodies, provided that the host material is itself not highly conductive (Hill, 1988; Stolarczyk, 1988). The effective depth at which these bodies can be detected depends on the electrical properties of the earth, the frequency of electromagnetic waves, and the spacing between the transmitter and receiver loops (Keller and Frischknecht, 1966).

Owing to the low conductivities of voids and coal alike, the EM method would have limited applicability in locating abandoned-mine voids containing no rails or other conducting bodies. Limestone also has a very low conductivity, and similar results can be expected. Because this method is effective at locating conducting bodies, it is particularly susceptible to interference from cultural artifacts such as powerlines, guardrails, and buried pipes. This interference can overwhelm the data and obscure the small anomalies that may be of interest. In general, EM surveys lack the resolution of resistivity surveys, but they can be done more rapidly and cheaply because they require no intrusive contact with the ground.

Ground-Penetrating Radar

Ground-penetrating radar (GPR) represents one of the newest geophysical methods and, consequently, it is not included in most geophysics references; however a large number of journal references pertaining specifically to GPR are available. GPR employs high-frequency electromagnetic waves to produce a continuous profile of the subsurface. In the method, a transmitting antenna is used to generate an electromagnetic pulse, and a receiving antenna is used to measure the response. This response consists of electromagnetic reflections resulting from electrical discontinuities or inhomogeneities in the subsurface, which are due to variations in the dielectric permittivity and the electrical conductivity of the underlying material. These inhomogeneities affect the velocity and attenuation of the transmitted electromagnetic pulse.

GPR surveys are done with the antennas in either a monostatic or bistatic mode. If the same antenna is used to both transmit and receive, the configuration is called monostatic; the use of separate transmitting and receiving antennas is called bistatic. Typical GPR systems accommodate various antennas ranging in frequency from 20 MHz to 2 GHz, where the choice of antenna depends on the resolution or depth of penetration needed for the survey. Generally, the use of a high-frequency antenna improves resolution of subsurface features, but depth penetration is limited. GPR surveys are done by moving the antenna over the region of interest and measuring the response (voltage) at the receiving antenna. The pulses can be triggered using either a constant-time or distance-based mode.

The effectiveness of GPR is influenced by several factors, the most important being the signal attenuation of the return electromagnetic wave. The attenuation results in part from the spherical spreading of the transmitted signal, but it is also affected by various electrical properties of the ground, most importantly the electrical conductivity. In order to compensate, the received signal is typically amplified with respect to time; however, the received signal eventually becomes too weak to distinguish from the surrounding ambient noise. Although not essential, a dielectric probe can be inserted into the ground to determine the dielectric permittivity and electrical conductivity of the ground at a given depth.

Publications on various types of shallow subsurface investigations with GPR include the following: tunnel detection (Gourry and others, 1995; Hauser and Jessop, 1995), ground-water mapping (Beres and Haeni, 1991; Rea and Knight, 1995), detection of hydrocarbon spills (Maxwell and Schmok, 1995; Olhoeft, 1992), detection of unexploded ordnance (Pawlowski and others, 1995), and archaeological surveys (Bauman and others, 1995). Although the relative ease of data collection makes GPR particularly advantageous for many applications, care must be taken when doing a survey. Specifically, careful attention must be given to the environment above the ground because the receiving antenna cannot distinguish between above- and below-ground artifacts. Therefore, powerlines, guardrails, or other large reflective objects need to be carefully noted in an interpretation of GPR data.

Radar in a borehole configuration has been studied by numerous authors with specific applications to tunnel detection (Greenfield, 1988; Lytle and others, 1976; Moran and Greenfield, 1993). One method is to lower the transmitter and receiver in the same borehole. Another method entails measuring a received electromagnetic pulse as the depths of the transmitter and receiver are varied in separate boreholes; a tunnel or collapsed feature between the two boreholes could presumably be detected by interpreting variations in amplitude phase of the received signal. This interpretation often entails employing tomography (Frank and Balanis, 1988; Shope and Greenfield, 1988) in an attempt to construct an image of the ground properties between the two boreholes. The time and expense associated with borehole radar precluded it from consideration in this study.

To help understand how an anomalous feature such as a void may appear in GPR data, the authors used a forward model (Powers, 1995) to generate synthetic radar records. The model employs ray-tracing methods with an antenna operating in a monostatic mode, and only the primary reflection ray path (no multiple reflections) is considered. With ray-tracing methods, only surfaces oriented perpendicular to the direction of the incident electromagnetic pulse are detected. The model allows only two-dimensional variations in the underlying material properties; however, three-dimensional effects of the antenna are included.

A synthetic radar record for three 0.5-m-radius cylindrical voids in a homogeneous, nonconductive medium is shown in figure 2. The distances from the surface to the center of the voids are 1, 5, and 10 m. The relative dielectric permittivities for the void (ε_r=1) and the surrounding medium (ε_r=9) are indicative of air and limestone, respectively (table 1). The cylindrical voids appear as hyperbolae, and the depth to the anomalies is directly related to the time at which they appear on the record. The shape and magnitude of the reflections are affected by the depth of the target, the hyperbolae becoming broader as the target depth increases.

A synthetic radar record for three voids of radii 0.5, 1.5, and 3 m with the top of the voids at 5 m below land surface is shown in figure 3. The relative dielectric permittivity of the surrounding, nonconductive medium is representative of limestone (ε_r=9). The three hyperbolae have virtually the same shape and magnitude, despite the differences in the respective void radii; however, as the radius increases, a subtle reflection from the bottom of the void becomes increasingly evident.

Figure 4 shows a simulated radar record of a 2-m-thick horizontal coal layer (ε_r=14), buried 5 m below land surface, that contains an air-filled cylindrical void (ε_r=1) at a depth of 5 m. A nonconductive limestone (ε_r=9) is above and below the coal layer. The boundary of the horizontal structure appears as two horizontal reflectors spanning the entire record. A hyperbolic reflection from the void is evident in the synthetic radar record, but its magnitude appears less than in previous examples because of interference from reflected waves from the horizontal structure. The effect of differing conductivity of the surrounding media is shown in figure 5. The geometry is the same as in figure 4; however, the horizontal structure and surrounding media of figure 5 have electrical conductivities of 10 and 5 mmho, respectively. The most notable difference between the two records is the significantly reduced reflection from the bottom of the horizontal structure, a result of the additional attenuation of the electromagnetic wave as it travels in the conductive media.

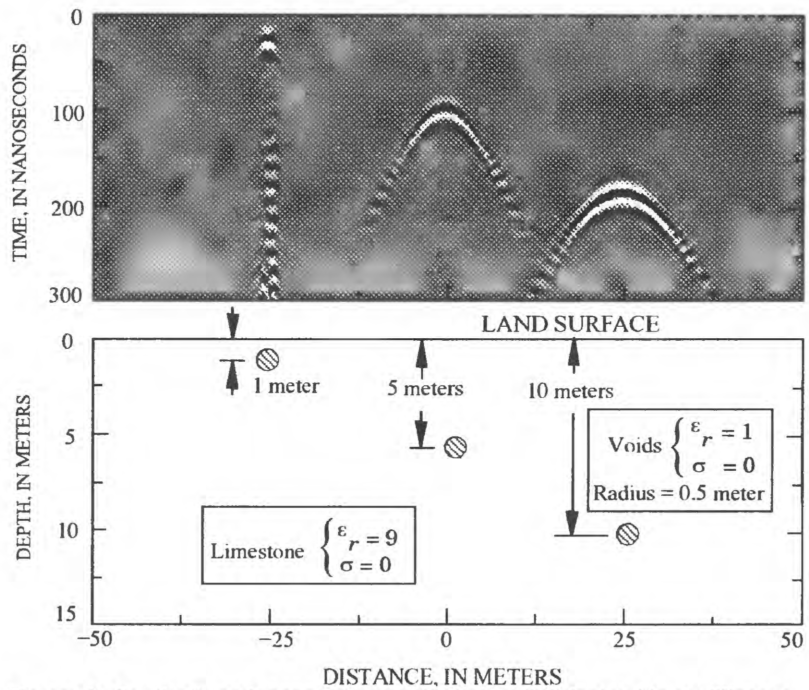

Figure 2. Synthetic radar record over air-filled cylindrical voids at different depths. ε_r and σ denote relative dielectric constant and electrical conductivity, respectively.

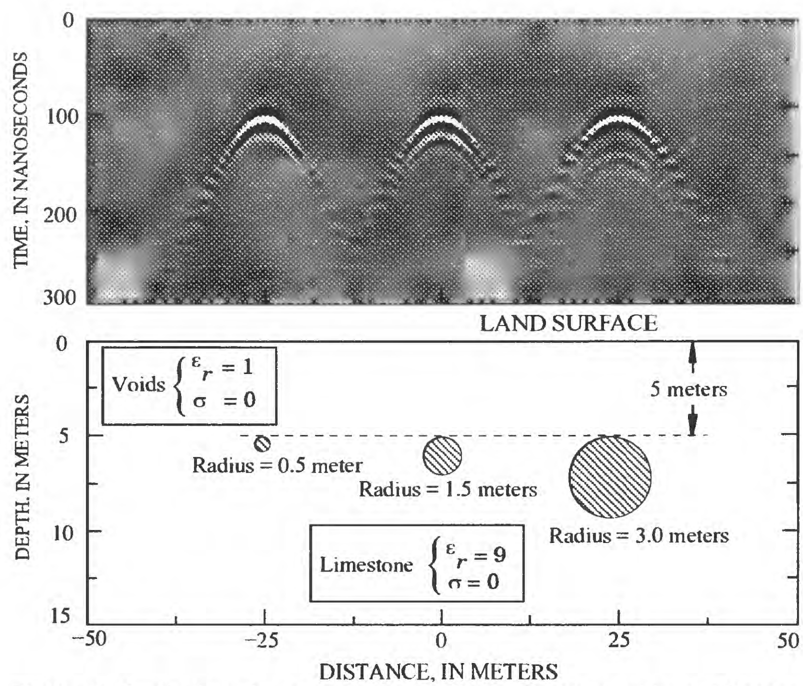

Figure 3. Synthetic radar record over air-filled cylindrical voids of different radius, at 5 m depth. ε_r and σ denote relative dielectric constant and electrical conductivity, respectively.

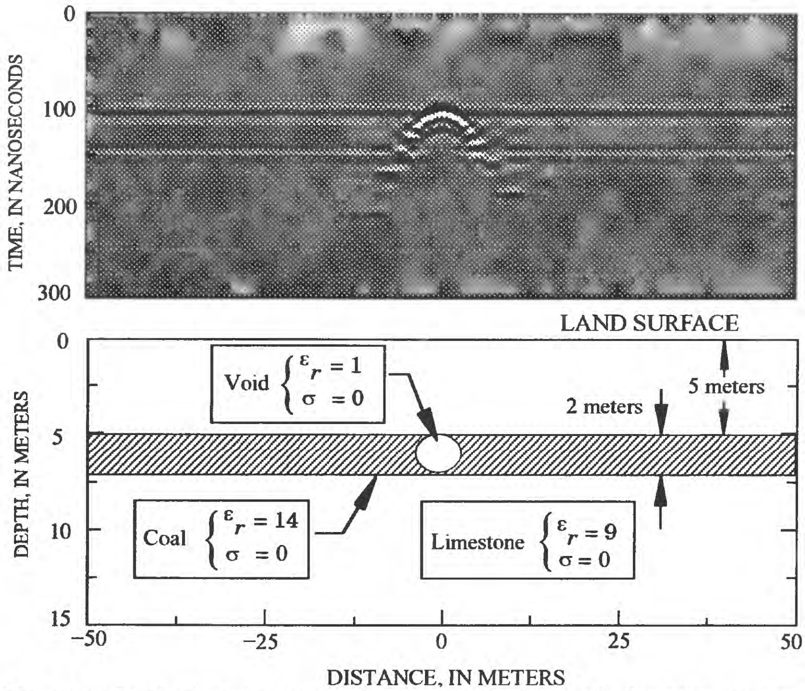

Figure 4. Synthetic radar record over an air-filled cylindrical void located in a horizontal geologic structure with no conductive loss. ε_r and σ denote relative dielectric constant and electrical conductivity, respectively.

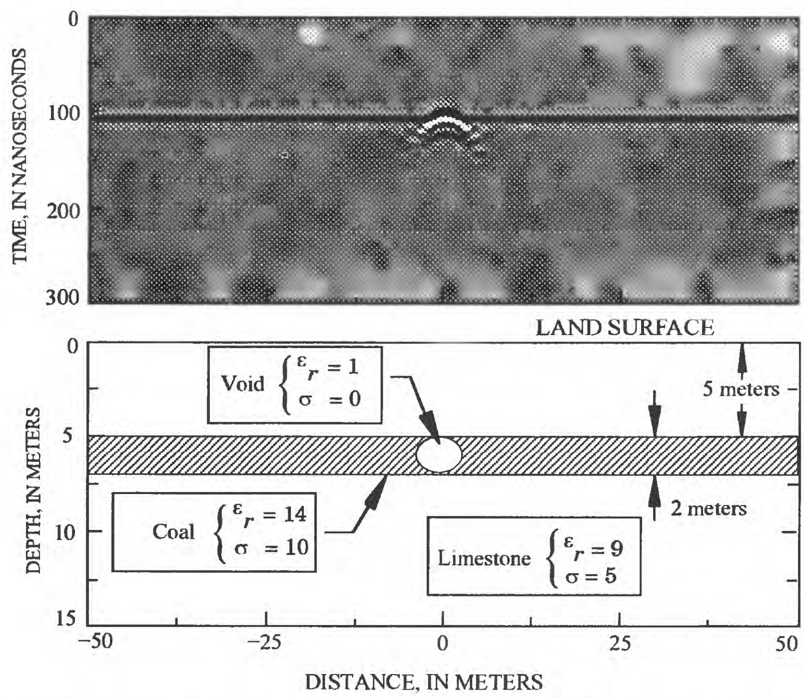

Figure 5. Synthetic radar record over an air-filled cylindrical void located in a horizontal geologic structure with conductive loss. ε_r and s denote relative dielectric constant and electrical conductivity, respectively.

The radar record can be converted from time to distance provided that the relative dielectric permittivity of the host material is known. The velocity, v (in meters per second), of an electromagnetic wave traveling in a material is given by

$$v = \frac{c}{\sqrt{\varepsilon_r}} ,$$

where c is 3×10^8 m/s (speed of light) and ε_r is the relative dielectric permittivity of the host material, as given in table 1. For a reflector located at a depth d (in meters), a radar record image can be determined by use of

$$d = \frac{1}{2} v t ,$$

where v is the electromagnetic wave velocity in the host material (meters per nanosecond) and t is the two-way traveltime between the antenna and the reflector (nanoseconds).

Spontaneous Potential

The spontaneous-potential (SP) (also known as self-potential) method involves two electrodes placed on the ground to measure natural voltage differences in the subsurface (Dobrin, 1960; Heiland, 1963; Telford and others, 1990). Natural voltage differences are typically associated with differences in conductivity that can result from geochemical reactions associated with mineral composition or flowing water.

SP anomalies are usually on the order of hundreds of millivolts in magnitude and are usually measured along profiles with electrode pairs maintained at uniform separation. Typically, the gradients, as opposed to the actual potential differences, are mapped. Equipotential lines (contours with the same relative voltage) are sometimes mapped by maintaining one electrode in a fixed position and finding the contour along the surface for which no voltage difference between it and a movable probe is observed.

The SP method is typically used in locating ore bodies that may be in contact with solutions of different composition, resulting in an electrochemical reaction. The method has proven effective in locating sulfide bodies at shallow depths, where they are partially submerged below the water table. The strongest potentials are measured in ores such as pyrites and in a number of minerals such as pyrrhotite and magnetite.

Although SP measurements are easy to make, neither coal nor limestone are electrochemically active; therefore, this method would be ineffective for the intended application. The method may be potentially useful for locating clay-filled voids; however, the threat of a void collapse would be greatly diminished in this case. The small magnitude of the electric field observed for typical anomalies makes the method particularly susceptible to interference from stray currents resulting from natural or cultural features.

Very Low Frequency

The very low frequency (VLF) method is based on existing military radio transmissions operating in the 10–30 kHz range; measurements are made of distortions of the radio waves created by local changes in the underlying electrical conductivity of the earth. VLF transmitters are located throughout the world, and three of them are in the continental United States. The transmitted VLF field consists of vertical and horizontal electrical components and a horizontal magnetic field. Variations in the underlying electrical conductivity produce a secondary magnetic field, which is then compared to the primary field (Geonics, Ltd., 1979).

A VLF survey is typically done in a traverse or grid with interval spacing based on the size and depth of the suspected anomalies. At each station, the VLF receiver measures the horizontal and vertical component of the electric field at a specified frequency. Variations in the ratio of the two electric (or magnetic) field components are then related to lateral variations in the underlying conductivity.

VLF measurements are primarily used in mapping the extent of sedimentary basins (limestones, sandstones) to define gross lithology (Telford and others, 1977), mapping vertical and lateral lithologic or water-quality changes in glacial aquifers (Haeni, 1986), and locating vertical faults containing water, clay, or other conductive materials (Stewart and Bretnall, 1986).

The VLF technique is most effective at locating electrically conductive bodies surrounded by a relatively nonconductive host material. In an abandoned coal mine that does not contain conductive material (rails or other conducting bodies), the method would be of minimal value because neither the coal nor the void would be particularly electrically conductive, and conductive contrast would be minimal. This is also true of limestone voids, where again both the limestone and the void have low electrical conductivities.

Because the VLF method is effective at locating conducting bodies, it is also particularly susceptible to cultural noise, such as that from powerlines, guardrails, and buried pipes. These noise sources can overwhelm the data and obscure the small anomalous contributions that may be of interest when one is trying to delineate the presence of voids or collapsed structures under roadways.

Potential-Field Methods

Potential fields are slowly varying, naturally occurring force fields; they include the Earth's gravitational and magnetic fields. Local variations in the measured potential field can be due to subsurface rock or material properties (Dobrin, 1960; Heiland, 1963; Telford and others, 1990).

For near-surface anomalies, potential fields are typically measured in traverses or gridded surveys at the surface. For the gravity and magnetic methods, depth to anomaly estimates can be made by doing the survey at several altitudes over the area of interest. Changes in the measured anomaly as a function of measurement altitude are then used to infer the depth of the anomaly. For regional (large) anomalies, measurements are usually made from airborne or satellite stations.

Potential-field methods, specifically the gravity method, have been widely used in void detection (Hinze, 1990). Because potential fields rely on measurements of naturally occurring earth fields, they do not require a device that generates energy, such as a transmitter. As a result, the measurement equipment is portable and relatively easy to use.

Gravity

In the gravity method, precise measurements of the Earth's local gravitational field are used to infer changes in the underlying rock densities. The gravitational field varies with local changes in the density of the subsurface resulting from either geological or cultural features. The applicability of the gravity method depends on differences in density between target bodies and their surrounding material. Because all masses exert an attraction upon one another, any method designed to measure the gravitational field will invariably determine the influence of all nearby masses and therefore lack the depth control inherent in some other methods.

Measurement spacing of a gravity survey varies considerably depending on the size and depth of the anomaly under investigation. Typically, ground-based measurements are taken on the order of tens to thousands of feet apart, whereas data obtained from satellites are less dense. For sufficient resolution, small targets at shallow depths require much smaller grid spacing, often on the order of 1 ft.

Typical uses of gravity surveys are locating buried valleys and igneous intrusions in bedrock. Microgravity surveys, however, can be used to locate voids. The method is most effective for relatively large anomalies with large density contrasts in relatively homogeneous host material.

An abandoned coal mine can be modeled as a cylindrical shape, whereas a limestone void can be modeled as a sphere. The measured vertical gravity anomalies that result from a spherical void (g_s) and cylindrical tunnel (g_c) are given by Nettleton (1942):

$$g_s = \frac{4}{3}\pi R^3 G\rho \frac{z}{(x^2 + z^2)^{\frac{3}{2}}},$$

and

$$g_c = 2\pi R^2 G\rho \frac{z}{x^2 + y^2},$$

where G is the universal gravitational constant (6.6732 X 10^{-11} Nm^2/kg^2); z is the depth to center of tunnel (meters); x is the lateral location over tunnel (meters); R is the radius of tunnel (meters); and ρ is the density contrast (kilogram per cubic meter).

The computed gravity anomalies for a cylindrical void in coal and a spherical void in limestone at various depths are shown in figure 6. The anomalies indicate that air- or water-filled voids have sufficient density contrast to result in a recognizable gravity anomaly, but only if the void is large relative to the depth of burial. In the case of an air-filled spherical void in limestone, a 2-m-radius void at 5 m depth would be recognized in the field only under ideal field conditions. Abandoned mine voids, which often have a long horizontal dimension equivalent to a horizontal cylinder, would have a larger anomaly due to the added void, as shown by figure 6. However, the anomalies due to the spherical or cylindrical voids are sometimes minor compared to other lateral or vertical inhomogeneities in the subsurface.

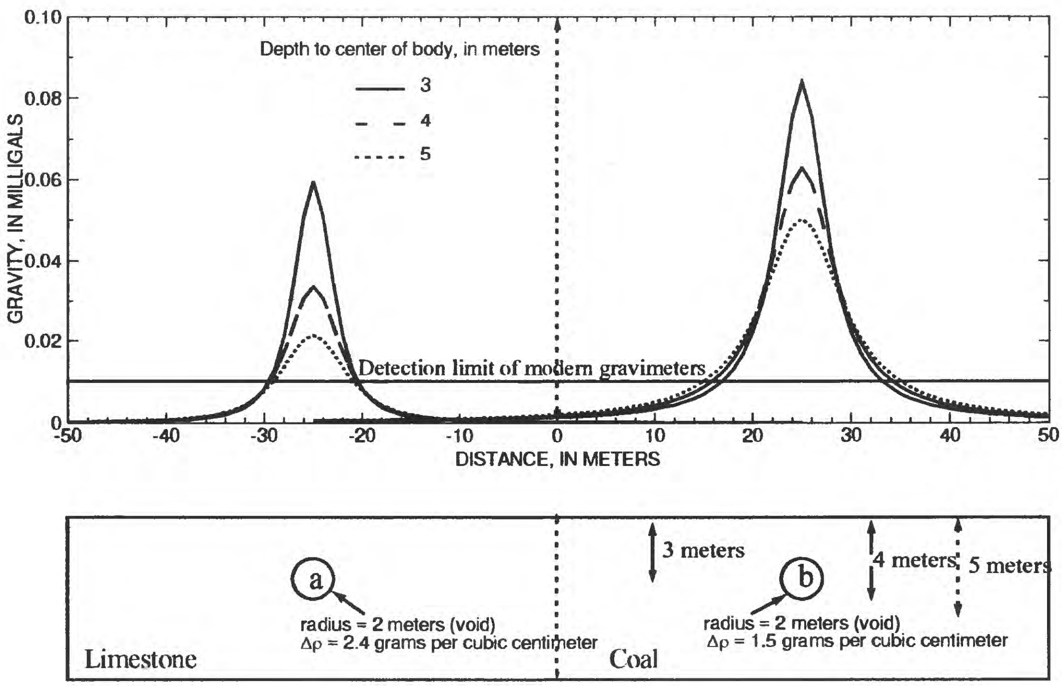

Figure 6. Calculated gravity response over (a) spherical and (b) cylindrical bodies at varying depth. The density contrasts ($\Delta\rho$) are representative of (a) air-filled spherical voids in limestone and (b) water-filled cylindrical voids in coal-bearing strata (mine voids).

Current state-of-the-art gravimeters are able to measure variations of 0.01 mgal, which is on the order of 10^{-9} of the Earth's gravitational field. The limiting factor, however, is not the gravimeter but the ability to discern very small anomalies from their inhomogeneous surroundings. Sites of interest in engineering studies tend to involve small density variations and small volumes, resulting in minor anomalies compared to extraneous components produced by other sources. As a result, gravity methods require high precision topographic and gravity surveying. Microgravity surveys, which have been used to locate voids, typically require altitude controls to 0.01 ft and station spacings of one-fourth to one-third the expected target size. In addition, the sensitivity of the gravimeter requires slow and tedious field procedures, as well as a base station for the purpose of drift corrections (Hinze, 1990). The instruments are also particularly susceptible to human induced vibrations (for example, moving vehicles) and natural vibrations (for example, wind).

Magnetics

Measurements of the Earth's local magnetic field are used to infer ferrous properties of the subsurface material. The effectiveness of the method depends on sufficient differences in the magnetic susceptibilities of anomalies with respect to the surrounding material. The magnetic susceptibility is a measure of the response of a material to an external magnetic field. Materials with high magnetic susceptibilities have a relatively large composition of magnetic dipoles, which tend to orient themselves according to the external magnetic field. Generally, the order of magnetic susceptibility of rocks (from most to least magnetic) is igneous, metamorphic, and sedimentary. Ranges and average magnetic susceptibilities of some selected materials in Ohio are listed in table 1.

Owing to the dynamic nature of the magnetic field of the Earth, careful field procedures are required for a magnetic survey. Specifically, the magnetic field of the Earth varies periodically with the rotation of the Earth as a result of the Sun's own magnetic field or "solar wind." This effect, referred to as the "diurnal," can be removed from the data by employing an additional stationary magnetometer as a calibration reference. Diurnal effects can be many times the order of that of the anomalous field.

Magnetic surveys are useful in locating ferrous materials that may be cultural or geologic in origin. Magnetic surveys have been used in locating manmade objects such as oil drums and utility pipes. They are even useful for locating areas of archeological interest, where the station spacing is quite small (< 1 m). Geological applications include locating ore and mineral deposits and mapping the extent of igneous contacts in bedrock. The spacing of measurements for these types of studies are on the order of tens to hundreds of meters. The number of magnetic measurements per unit area is determined by the size and depth of the assumed anomalous object.

An abandoned coal mine or tunnel can be modeled as a cylindrical shape, whereas a limestone void can be modeled as a spherical shape. The following equations give the vertical magnetic response (in gammas) for spherical (V_s) and cylindrical (V_c) bodies, respectively (Nettleton, 1942):

$$V_s = \frac{4}{3}\pi R^3 Hk \frac{(2z^2 - x^2)}{(x^2 + z^2)^{\frac{5}{2}}},$$

and

$$V_c = 2\pi R^2 Hk \frac{(z^2 - x^2)}{(x^2 + z^2)^2},$$

where H is vertical component of the Earth's magnetic field (gammas); k is magnetic susceptibility contrast; z is depth to center of tunnel/sphere (meters); x is lateral location over tunnel/sphere (meters); and R is radius of tunnel/sphere (meters).

Calculated magnetic anomalies for a cylindrical air-filled void in a coal seam and a spherical void in limestone at various depths and radii are shown in figure 7. The small susceptibilities of both limestone and coal preclude the use of the magnetic method in locating voids. However, ferrous materials, such as rails, in coal mines may contribute to a magnetic anomaly, so the magnetic method may be useful in this situation. Because magnetic fields are strongly influenced by disturbances resulting from steel pipes, vehicles, fences, buildings, light posts, and so on, it is often difficult to discern cultural anomalies from buried materials in areas of cultural activity. New and developing technologies, such as recent advances in magnetometer design, may decrease these problems and increase the chances of locating anomalies of interest.

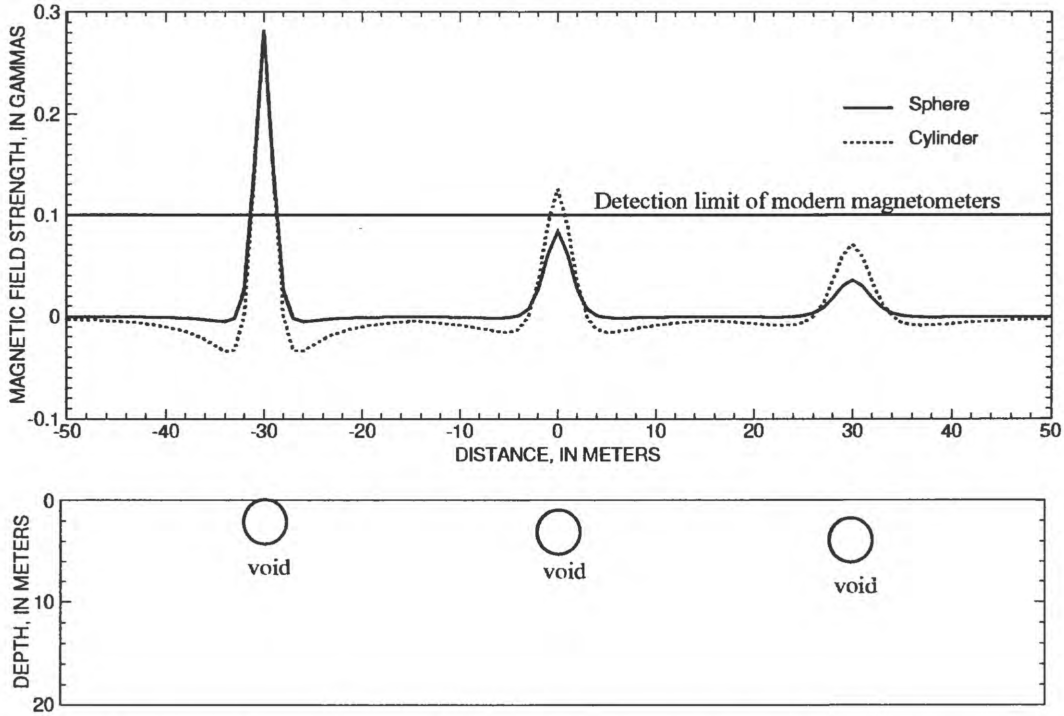

Figure 7. Calculated magnetic response over a shallow sphere and cylinder. The magnetic susceptibility contrast is equivalent to an air-filled void in shale (45 x 10^{-6} centimeter-gram-seconds).

Seismic Methods

Seismic methods employ a mechanical impulse, such as a hammer or explosive device, to generate an acoustic wave that travels into the ground and returns to the surface, where sensitive vibration detectors called geophones are used to measure the response. The measured response results from reflections, refractions, and diffractions of the generated impulse wave due mainly to differences in seismic-wave velocity among various earth materials (Clay, 1990; Dobrin, 1960; Heiland, 1963; Telford and others, 1990).

In seismic surveying, an array of geophones is placed in the ground at spacings defined by the required depth of penetration. Several impulses are generated in this configuration and then the entire array is moved, with some overlap of the first array. The spacing of the geophones can vary from <1 to 10 m for very shallow exploration (<100 m) to >100 m for very deep exploration (<100 km). Seismic methods have been used extensively by the petroleum industry to investigate deep (< 500 m) geologic structures that might contain oil or gas. Modifications of these techniques have been used for shallow (< 100 m) investigations of geology and hydrology. These modifications include scaling down the survey (decreasing the geophone spacing), increasing the high-frequency content of the generated waves, and improving data-collection and data-processing technology. Of the two dominant seismic methods, seismic reflection has proved to be most useful for detection of shallow voids or cavities in the subsurface.

Seismic Reflection

The seismic reflection method measures the elapsed time of an acoustic wave from initiation at the source to reflection by a geologic discontinuity to detection by geophones. This reflection results from differences in the seismic velocity of different earth materials. By moving the relative positions of the geophones and source, characteristics of an underground anomaly can be determined. An array of 24, 48, or more geophones placed 2 to 5 m apart, depending on the desired resolution, is typically used in conjunction with several source locations to collect the traveltime information. Several sources are used for each geophone array, then the array is moved to obtain continuous coverage of the subsurface. Accurate vertical and horizontal locations of each geophone and source locations are needed to determine the location of the subsurface anomaly. Although any estimate depends on the depth of investigation and site conditions, Lepper and Ruskey (1976) estimated that a 1,200- to 1,600-m shallow seismic reflection line can be covered each day, under normal operating conditions. The detailed and labor-intensive data reduction and analysis required to adequately interpret seismic reflection data are not considered in this estimate.

Seismic reflection is used primarily for determining the depth and thickness of geologic strata. It is also effective in locating isolated bodies that may be either of geological or cultural origin. Generally, higher frequencies (100–200 Hz) of the generated waves are used for anomaly detection within 100 m of land surface. Seismic reflection has been used successfully for depths of exploration between 10 and 100 m and thickness of target bodies of less than 1 m.

Researchers using the seismic reflection method for void detection cite three phenomena for evidence of a void: free oscillations of resonance of the void walls, anomalous amplitude attenuations in the reflected signal, and delay in signal arrival times (Cook, 1965; Watkins and others, 1967; Fisher, 1971). Application of the seismic reflection method to discriminate a subsurface void from the undisturbed material around it depends largely on the dominant frequency of the energy source. Abandoned coal mines and limestone voids require a source with sufficiently high frequency content to achieve meaningful resolution. The minimum resolvable void is one-fourth the wavelength of the recorded energy (Widess, 1973), where the relation between velocity (v), frequency (f), and wavelength (λ) is given by

$$v = \frac{f}{\lambda} .$$

Sources capable of producing frequencies in excess of 200 Hz include the 30.06 rifle and a 50-caliber gun (Miller and others, 1986). Improved signal-to-noise ratios can be achieved by giving careful attention to geophone placement, minimizing extraneous noise, and effectively controlling the air-coupled wave from the seismic source (Steeples and Miller, 1988, 1990). Some natural and cultural acoustic noise (wind, rain, motion of trees, vehicle traffic) greatly reduces the signal-to-noise ratio. More recently, a step-frequency source (Narbutovskih and others, 1995) operating from 10 to 550 Hz has been employed, and an improved signal-to-noise ratio was reported.

Seismic Refraction

The seismic refraction method involves use of geophones to measure the traveltime of an acoustic wave traveling down to and along an interface of differing seismic velocities and back up to the geophones. The refracted wave propagates along the so-called critical angle until it reaches a discontinuity, where it travels horizontally along the interface separating the two materials. The critical angle is determined from the velocities v_1 and v_2 that a transverse acoustic wave will attain in the respective materials. The seismic refraction method also requires the use of several geophones and source locations, but the geophone spacings are necessarily greater than for seismic reflection because of the refracted wave path. Analysis of refraction data generally takes less time than analysis of reflection data. As with other seismic methods, seismic refraction is used primarily for determining the depth and thickness of geologic strata. For example, it can be used for determining depth to water table and depth to bedrock. Seismic refraction is capable of resolving multiple layers if seismic velocities of these layers increase with depth (Haeni, 1988).

The seismic refraction method works best and produces more easily interpretable data where seismic velocities increase with depth. Air-filled voids have a lower seismic velocity than the geologic material surrounding them (table 1), therefore precluding the use of standard seismic refraction techniques for void location. Water-filled voids commonly have a lower acoustic velocity than the surrounding geologic material, limiting the use of seismic refraction to directly map void areas. Even in the unusual cases where the velocity increases in the presence of a water-filled void, discerning the presence of a water-filled void as opposed to saturated rock material of equivalent velocity would be difficult, if not impossible. Ferland (1969), however, used a modified seismic refraction array to locate and map air-filled voids and subsidence features in dolomite and limestone. With this method, seismic sources were located within the suspect horizon, and delays in traveltimes were measured to map the extent of the anomalous area. Very accurate horizontal and vertical positions of the geophones were required to accurately locate the void areas.

Other Methods

The previously discussed geophysical methods represent the most commonly used for detection of underground voids; however, several methods cannot be categorized under the above. Specifically, methods have been proposed in which ground-water level monitoring is used to infer transient changes in the subsurface, such as subsidence (Cahn and others, 1988; Patton and Smith, 1988). In addition, the injection of low-level radioactive tracers into the ground water can provide information regarding the subsurface, a typical application being the location of rock fractures (Benson and others, 1982).

Anomalous fluctuations in ground-water levels can result from tunnel-related activities (Cahn and others, 1988; Patton and Smith, 1988). A meaningful interpretation of these fluctuations requires monitoring of water levels in boreholes close to the area of interest. Because the method is used to monitor changes in ground-water activity, it provides only relative and not absolute information; however, the method could be used in a long-term monitoring program. A radiometric scheme could also be used to periodically monitor changes in the migration of radioactive tracers.

Infrared thermography (IT) measures variations in the surface temperature resulting from differences in the thermal conductivity and heat capacity of the underlying earth material, by use of a thermal infrared detector. The method has been employed to locate fractures, caves, tunnels (Gourry and others, 1995), and seeps and to map contaminants floating on water; it has been used with some success in the detection of unexploded ordnance. The use of IT has been combined with GPR (Gourry and others, 1995), where the authors report that IT outperformed GPR at detecting very small (0- to 10-cm) surface anomalies. For intermediate depths (0.1–1m), the two methods were found to be complementary; for depths greater than 1 m, GPR was found to be far superior. Thermal-detection methods can prove most effective for shallow targets, but they would be of limited use in locating collapsed structures or voids at depths greater than 1 m. The IT method could prove useful for detecting cracks in roadbeds or for other similar applications, owing to its excellent resolution.

USE OF GROUND-PENETRATING RADAR TO DETECT UNDERGROUND VOIDS

Geophysical methods can be used to evaluate areas of Ohio where voids or void-related structures are common. Because it was the most promising method and because of its ease of use and portability, only GPR was used during this study. The following sections briefly describe the use of GPR at three highway sites in Ohio.

Description of Three Highway Sites

Three sites were chosen to test the effectiveness of GPR in detecting voids or void-related structures at highway sites in Ohio. Two of the three sites were in the coal-mining area of eastern Ohio, and one was in the limestone terrane of western Ohio. The sites were chosen because void-related subsidence has occurred in or near these areas.

Belmont County

The Belmont County site is on Interstate 470 (I–470) (fig. 8). Here, the highway is underlain by the Pittsburgh (No. 8) coal seam, which dips about 18 ft/mi towards the southeast. The highway is at about a 4 percent grade toward the Ohio River. This coal seam crops out at the southern edge of the study site and is 25 ft or less below land surface. The Pittsburgh coal seam is the basal unit of the Monongahela Formation and is overlain by the Redstone Limestone Member (Berryhill, 1963). The Redstone Limestone Member consists of four or more massive beds of 3- to 4-ft-thick limestone. Each limestone bed is separated by a 6- to 8-in.-thick layer of claystone or soft shale. Where the Redstone Limestone crops out, the limestone beds range from hard and resistant to soft and crumbly and often contain shale partings within the beds. At the base of the Redstone Limestone member is a 3- to 4-ft-thick shaley claystone. The Redstone Limestone member contains traces of clay, silt impurities, and small amounts of siderite (Berryhill, 1963). The Fishpot Limestone member overlies the Redstone Limestone member and is similar in composition. This member is present only in the western part of the study area. The Fishpot Limestone is more evenly bedded than the Redstone Limestone but is generally more argillaceous. Several slump features (approximately 1–2 m diameter; fig. 8) were recognized near I–470 during this investigation. These depressions were thought to be surface expressions of collapsing coal-mine voids.

Guernsey County

The Guernsey County site is on Interstate 70 (I–70) (fig. 9). Most surface rocks of the county belong to the Pennsylvanian Conemaugh Group, a repetitive sequence of thick sandstones, mudstones, and sandy shales, and thin beds of coal, clay, and marine and nonmarine limestone (Crouch and others, 1980). The Upper Freeport (No. 7) coal, the uppermost unit of the Allegheny Group, has been mined under the site at a depth of approximately 50 ft. Overlying the Upper Freeport coal are thinly bedded limestones and shales (Condit, 1912). Shale directly overlies the Upper Freeport coal in most areas, but there are areas where a channel sandstone cuts into the coal (Crouch and others, 1980). Mine maps of the area do not indicate this channel sandstone in the immediate area of the site. No surface expressions of void collapse were mapped in the field, but a collapse of roof material into mine voids had occurred within 2 mi of the site.

Logan County

The Logan County site is on a newly constructed section of State Route 33 (fig. 10). The site is underlain by the Columbus Limestone, which is mined for aggregate at a nearby quarry. At this site, the thickness of the limestone ranges from 90 to 100 ft. The Columbus Limestone is a massive, fossiliferous limestone with bedding planes spaced approximately 2 to 3 ft, some containing detrital clay. Here, topography is dominated by fractures and karst features, including sinkholes. During construction of this section of highway, several sinkholes and clay-filled fractures were found (fig. 10).

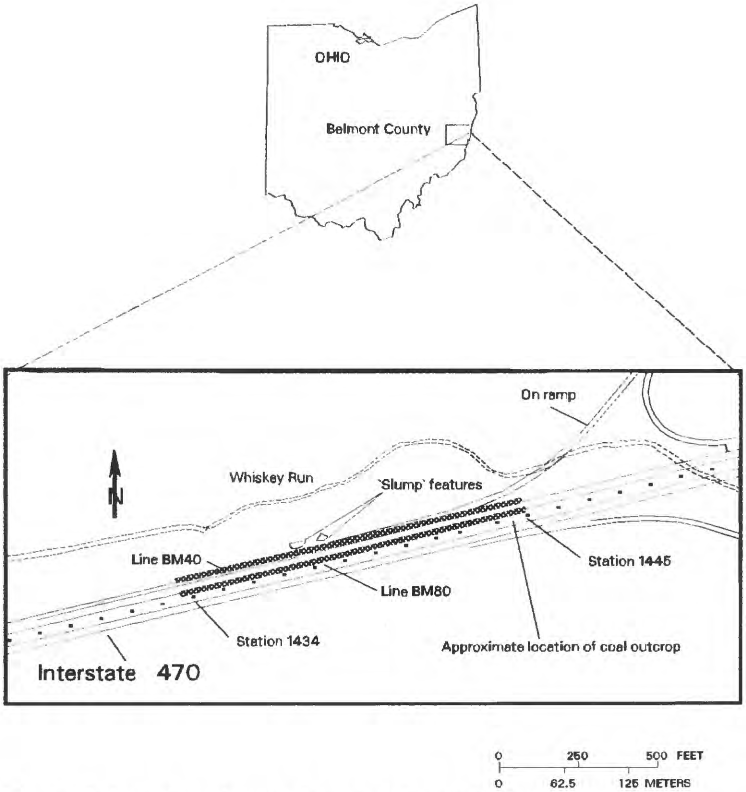

Figure 8. Location of ground-penetrating-radar survey lines and surface features, Interstate 470, Belmont County, Ohio.

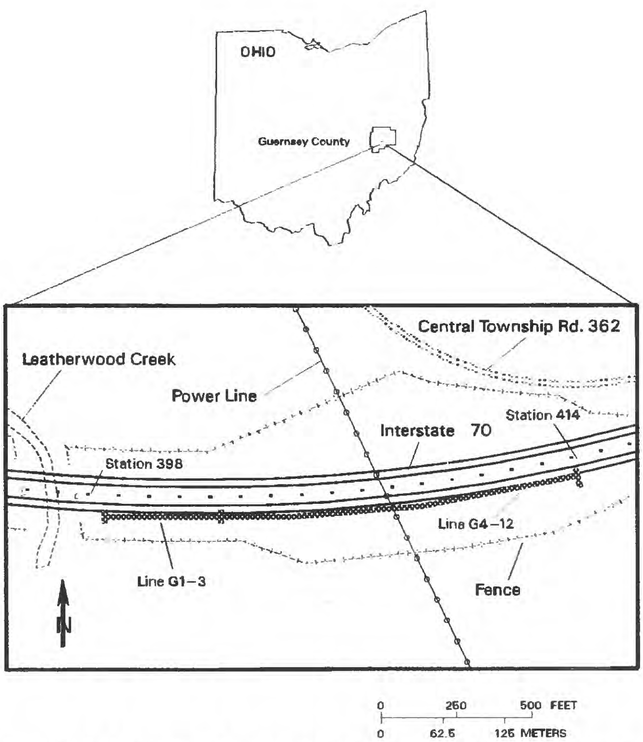

Figure 9. Location of ground-penetrating-radar survey lines and sources of possible cultural interference, Interstate 70, Guernsey County, Ohio.

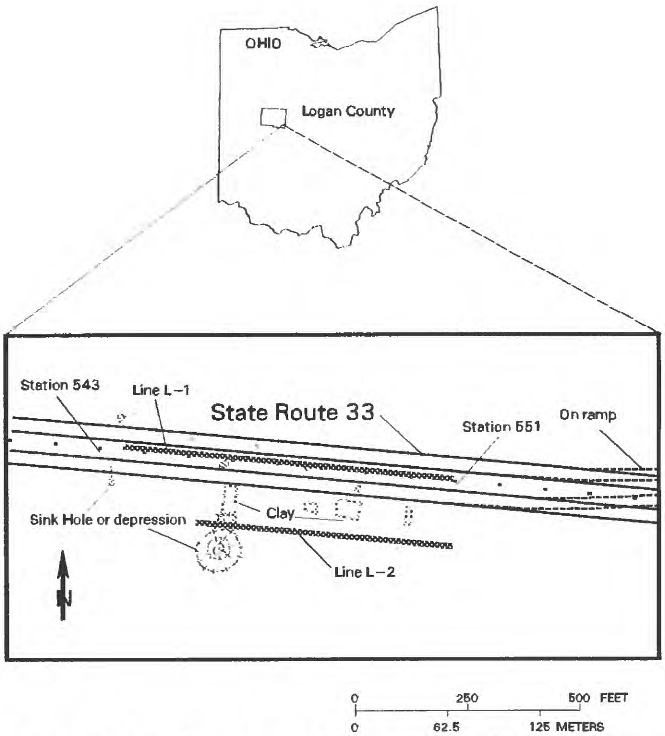

Figure 10. Location of ground-penetrating-radar survey lines and surface features found during excavation of roadway, State Route 33, Logan County, Ohio.

Survey Procedures

A Geophysical Survey Systems (GSSI) SIR–10 radar unit was used to collect GPR records at the three sites. Several antenna configurations were employed at each site in order to examine the relation between resolution and depth of penetration. The antennas used were the GSSI 80 MHz monostatic antenna and the GSSI multiple low frequency (MLF) 25–120 MHz adjustable-frequency bistatic antenna. Employing lower frequencies improves the depth of penetration and decreases resolution. In addition to the differences in the monostatic and bistatic configurations, the 80-MHz antenna has a bow-tie-shaped antenna element, whereas the MLF antenna consists of dipole (tubular) elements. Bow-tie antennas are more broadband than linear antennas, and they typically produce less "ghost" or multiple reflections in the radar record (Balanis, 1990).

Field data were obtained in time-based and distance-based modes. In the time-based mode, traces are taken at fixed time intervals and thus require movement of the antenna at a constant velocity to obtain evenly spaced traces. Data can be collected in the distance-based mode by use of a special distance wheel to trigger uniformly spaced traverse marks on the record. The GPR parameters used for collecting data at each of the three field sites are listed in table 2.

Table 2. Ground-penetrating radar setups and estimated penetration depths for field sites

[MHz, megahertz; MLF, multiple low frequency]

Field site	Local geology	Antenna frequency	Trigger mechanism	Time-length of radar trace (nanoseconds)	Estimated depth of penetration (feet)
I-470 in Belmont County	Shaly limestone, coal	80 MHz MLF, 40 MHz	Time Distance	300 480	10 15
I-70 in Guernsey County	Limestone, sandstone, shale, coal	80 MHz	Time	300	<5
SR-33 in Logan County	Limestone	80 MHz MLF, 60 MHz	Distance Distance	500 300	40 >50

Results of Data Collection and Analysis

Belmont County

The Belmont County data were collected on two separate occasions approximately 1 month apart. The 80-MHz antenna and a time-based trace triggering mode were used in collecting the initial GPR records at this site. The antenna was towed 130 ft behind the van containing the SIR–10 radar unit. The separation between the van and antenna ensured that radar reflections from the van were minimized. Each trace consisted of 512 discrete samples; the time-length of each trace set to 300 ns.

The record, shown in segmented frames (fig. 11), covers a total distance of 1,125 ft over the westbound lane of I–470 beginning at station 1445. Station numbers are in hundreds of feet from an arbitrary datum. Several features — most notably the sharp evenly spaced anomalies at approximately 40 ns — appear throughout the radar record. These anomalies result from reflections very near the road surface and correspond to seams or contraction joints in the underlying concrete base at a 20-ft spacing. The hyperbolic feature with its apex at approximately 100 ft is due to a light fixture just to the right of the shoulder. The apex of the hyperbola corresponds to the shortest distance between the light fixture and the antenna.

GPR records were also obtained using the MLF antenna in its 40-MHz configuration, and a distance-wheel trace triggering device was used to obtain evenly spaced radar traces. Approximately 1,200 ft of GPR record were obtained over the center of the westbound lane, beginning at station 1450 (fig. 12). Each trace consisted of 512 discrete samples; the length of each trace was set to 480 ns. The record shows anomalous features at traverse distances of 75 ft, 440 ft, and 975 ft, as indicated by circles in figure 12. Near-surface anomalies, indicated by ellipses, appear near 710 ft, 750 ft, and 825 ft, as evidenced by their vertical orientation in the radar record. The large hyperbolae, seen in several parts of the record and spanning approximately 300 ft, are due to cultural interference from light fixtures. Both GPR records, and especially the 40-MHz data, contain horizontal banding caused by antenna "ringing" resulting from antenna resonance (a characteristic of the antenna), and this pattern should not be interpreted as the result of anything geological. The resonance is consistent throughout all traces, resulting in the appearance of horizontal features in the GPR record. This artifact can be greatly reduced by using "average trace subtraction," where an average trace is obtained from part or all of the GPR record and is subsequently subtracted from each individual trace.

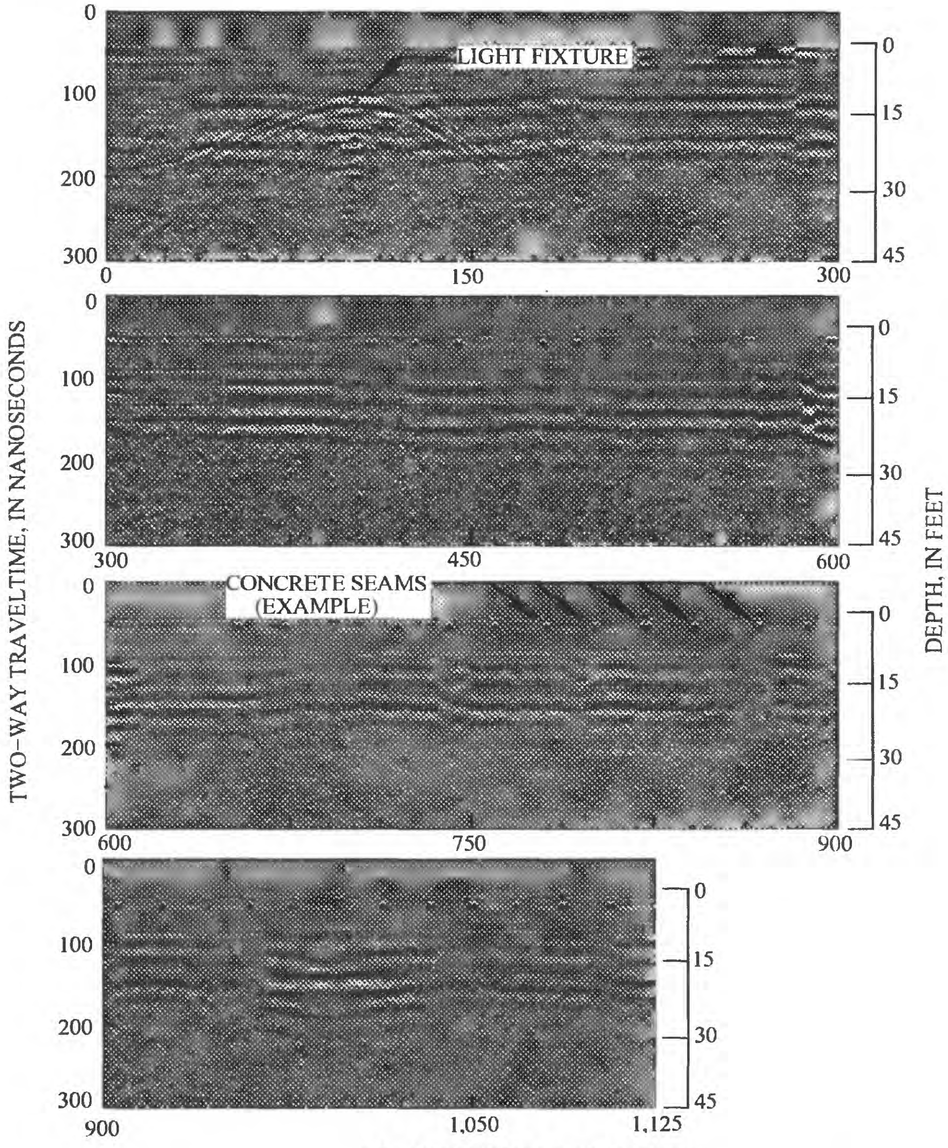

Figure 11. Ground-penetrating-radar section of 80-megahertz data, Interstate 470, Belmont County, Ohio. Data shown were processed using average-trace subtraction.

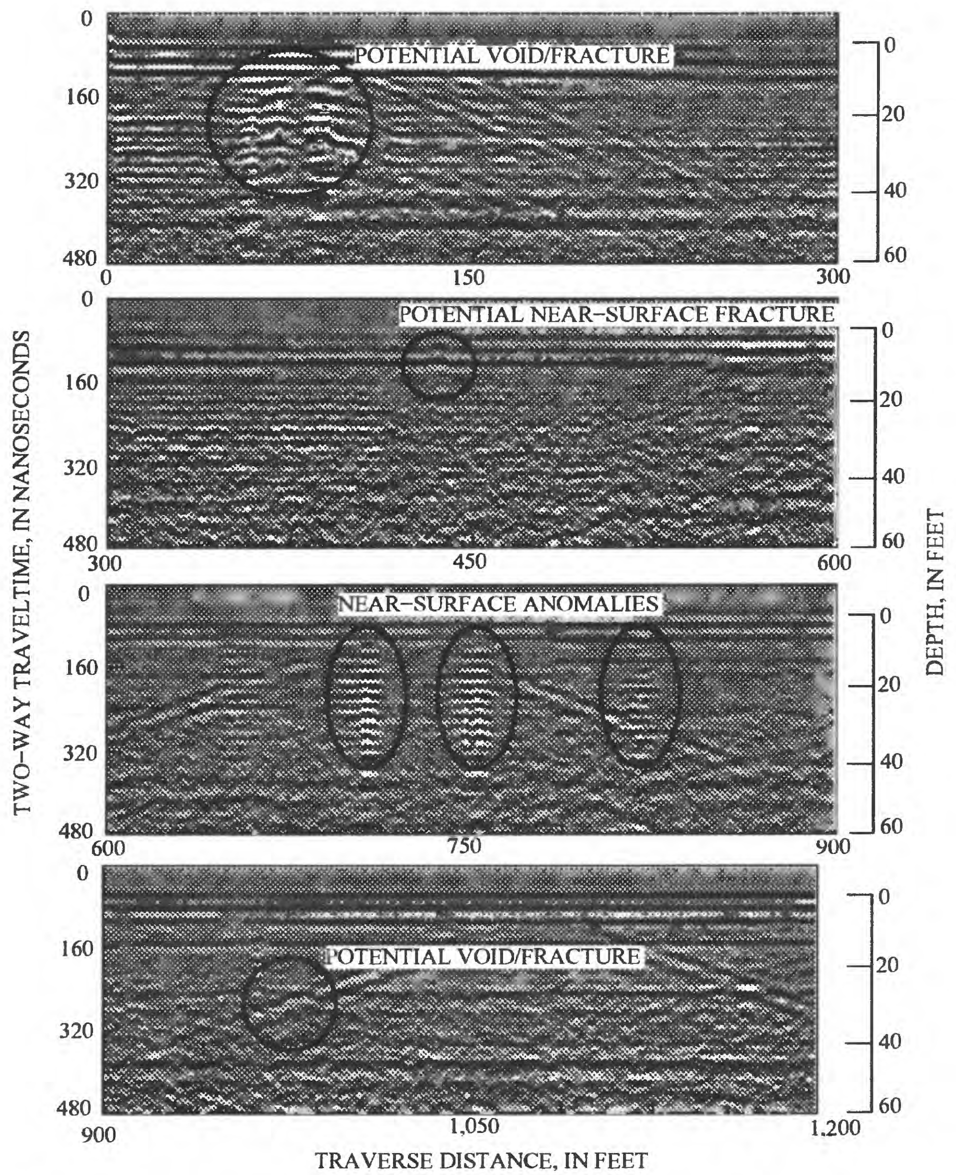

Figure 12. Ground-penetrating-radar section of 40-megahertz data, Interstate 470, Belmont County, Ohio. Data shown were processed with average-trace subtraction.

Guernsey County

The 80-MHz antenna in a time-based trace triggering mode was used to traverse approximately 1,140 ft along I–70. Data were obtained by manually pulling the antenna at a constant velocity towards the SIR–10 radar unit, which was in a stationary field vehicle. Each trace consisted of 512 discrete samples, the time-length of each trace being set to 300 ns.

The data, shown in segmented frames (fig. 13), contain no features that seem to be related to voids or collapsed structures; it does, however, exhibit several notable features. Specifically, the data illustrate the inability of the antenna to distinguish whether the objects are above or below ground. Each of the nine individual GPR records exhibit long, linear features increasing from left to right in the data. These features are due to signal reflections from the field vehicle and move up the record with respect to time as the antenna is moved towards the vehicle. Several hyperbolic shapes are apparent, resulting from above ground scatterers. The very strong signal at approximately 250 ns with its apex at 600 ft of transverse corresponds to reflections from an overhead powerline. The rough appearance from 1,040 to 1,140 ft in the radar record is due to reflections from a guardrail. Reflections resulting from above-ground features are not attenuated by the conductivity of the ground, tend to be very strong, and hence dominate the radar record. This illustrates the importance of careful attention to above-ground features to avoid data misinterpretations.

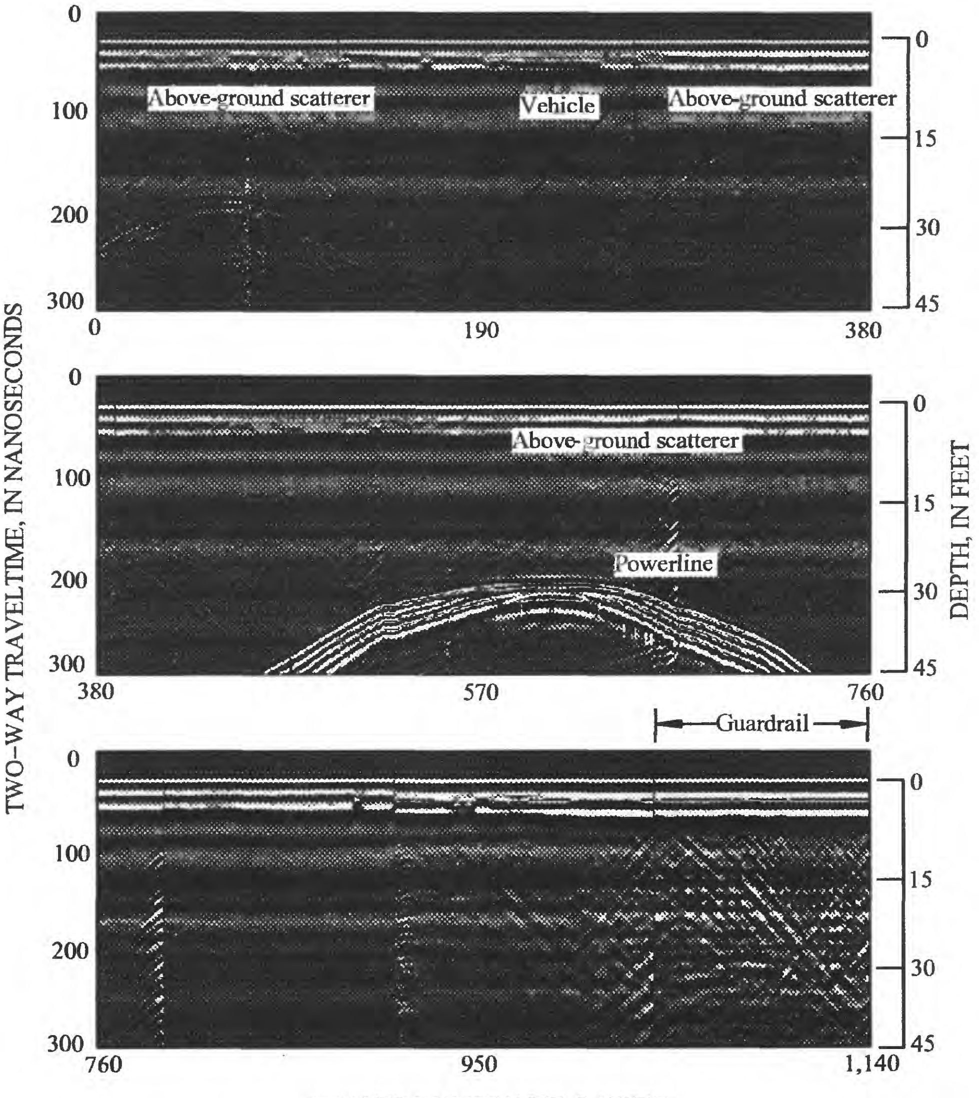

Figure 13. Ground-penetrating-radar section of raw 80-megahertz data, Interstate 70, Guernsey County, Ohio.

Logan County

GPR data were collected in the median between the eastbound and westbound lanes of State Route 33, starting at station 551 and traversing west for 1,000 ft. The effects of different antenna frequencies were examined by use of the MLF antenna in a 60-MHz and a 40-MHz configuration. Additional data were obtained above the road cut along line L-2 (fig. 10), with the 40-MHz antenna. The distance-wheel triggering device was used is all instances. Individual traces consisted of 512 discrete samples, the time-length of each trace being set to 500 ns.

Comparisons between the 40- and 60-MHz antennas showed data to be very similar; the slight differences were mostly in resolution. Figure 14 shows the 60-MHz data along line L-1, where subsurface anomalous features, possibly related to karst features or fractures in the limestone, have been highlighted. The radar record shows excellent penetration to more than 40 ft (250 ns). The data set is a good example of the penetration that can be expected in a low-conductive rock such as limestone.

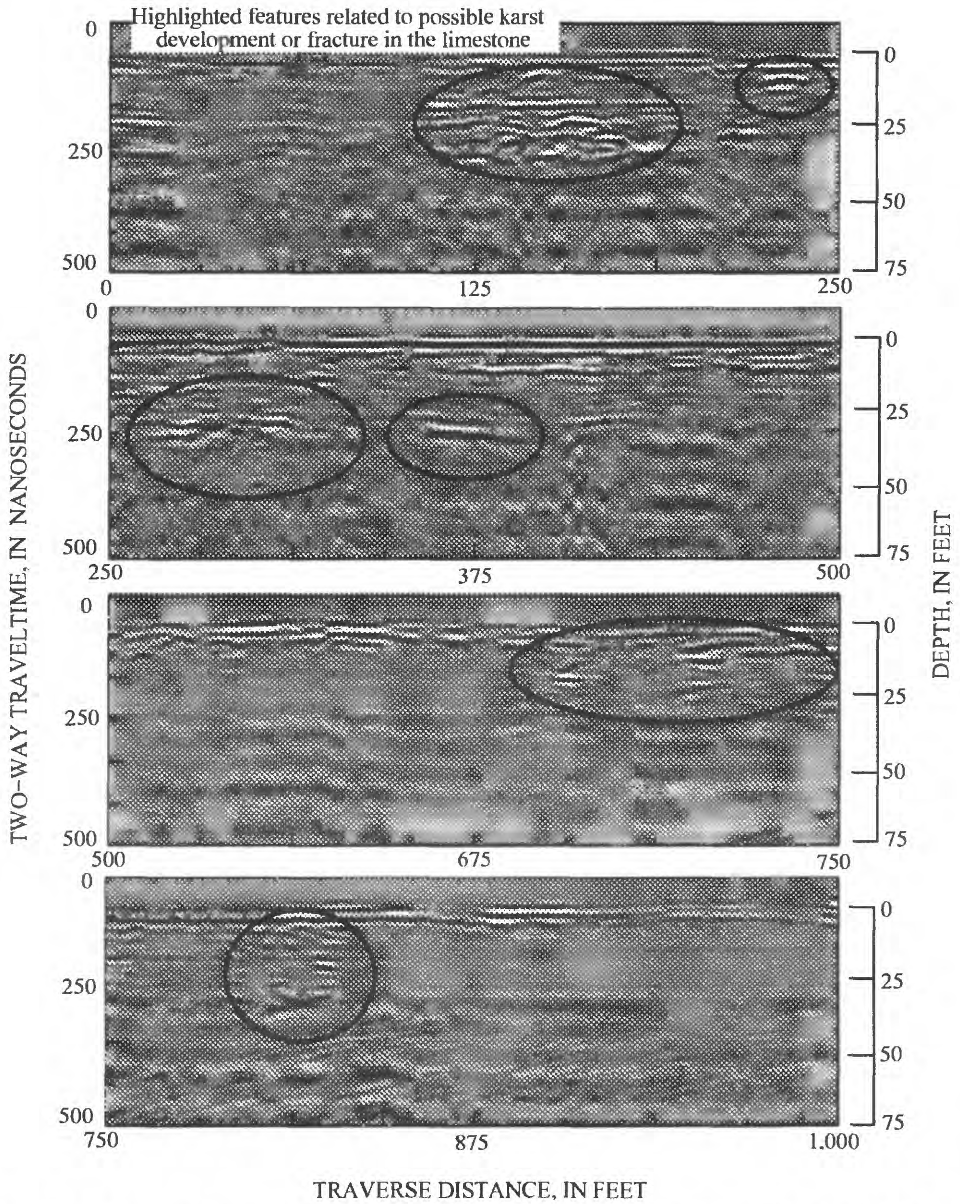

Figure 14. Ground-penetrating-radar section of 60-megahertz data, State Route 33, Logan County, Ohio. Data shown were processed with average-trace subtraction.

An entrance ramp to a new section of State Route 33 under construction also was examined using GPR, and the results are shown in figure 15. With the overburden removed during construction, the data were obtained directly over the limestone by use of the 80-MHz antenna. Data were obtained beginning at marker 16+0 and terminating on marker 13+0, corresponding to a distance of 300 ft. The data show excellent penetration over the entire 300-ns range, corresponding to a depth of more than 50 ft (based on an assumed relative dielectric of 9). This is evident by the horizontal features, assumed to be l mestone bedding, that appear throughout the radar record. In addition, several circled anomalous features may be related to karst features or fractures in the limestone.

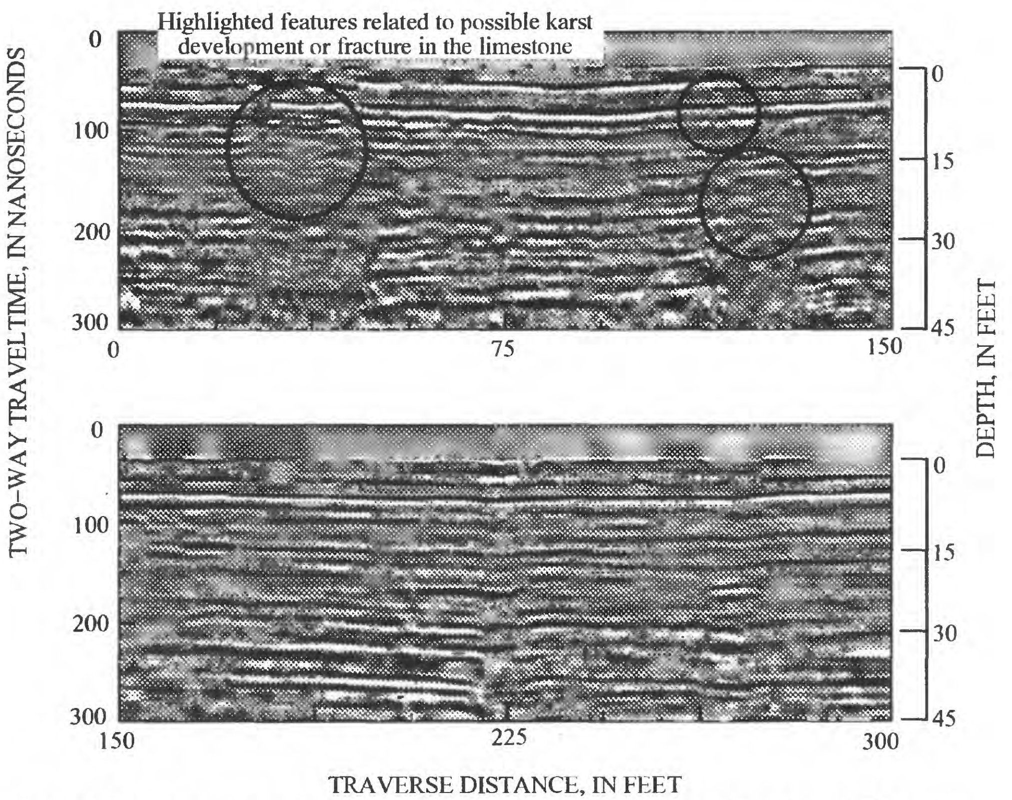

Figure 15. Ground-penetrating-radar section of 80-megahertz data, State Route 33, Logan County, Ohio. Data shown were processed using average-trace subtraction.

Summary of Field Investigations

GPR data were obtained and analyzed for three highway sites in Belmont, Guernsey, and Logan Counties, Ohio. The effectiveness of GPR was shown to be dependent on the method of operation and the environment in which the data were obtained. The most important factors affecting the surveys were the properties of subsurface materials and effects resulting from cultural interference. The Belmont and Guernsey County data illustrate the difficulty encountered in a culturally noisy environment, whereas the Logan County data illustrate the depth of penetration that can be expected in a relatively low-conductivity limestone environment with little environmental noise.

SUMMARY AND CONCLUSIONS

The use of geophysical techniques to characterize or identify locations of subsurface voids was investigated through literature reviews of theory and practical applications, numerical modeling, and field investigations. The geophysical methods examined in this study are grouped into four general categories: electrical, potential field, seismic, and other. Techniques for specific methods are presented in regard to their theoretical background and typical applications. Field applications by other investigators and forward models and field applications of selected methods are discussed in this report. Forward models using resistivity, GPR, gravity, and magnetics were evaluated. The ease and speed of data collection for a particular technique were also considered.

Apparent resistivity measurements were modeled using a ground-water flow model, because of the similarity in theories between water flow and electrical current flow. Synthetic data were generated using Wenner and dipole-dipole configurations for resistivities typical of coal, limestone, and air. The dipole-dipole configuration yielded a larger response to a given anomaly; however, for both configurations, detection of these anomalies would be difficult given cultural effects and lateral inhomogeneities. Resistivity measurements are labor intensive and slow because they require the insertion of conducting rods, which must be moved and reinserted for each new data point. EM surveys lack the resolution of resistivity surveys but can be done more rapidly and with less expense because EM surveys require no intrusive contact with the ground.

Synthetic GPR data were generated under various assumptions regarding the depth, size, and surrounding media of various voids. The voids were easily detectable in all of the examples provided; however, influences such as ground clutter and cultural interference were not considered. The effectiveness of GPR is almost entirely dependent on the electrical properties of the underlying ground. For highly conductive materials, the method has limited application; however, in limestone and other resistive material, penetration of more than 25 ft can be expected. As a result of the high-frequency of operation, GPR allows excellent resolution of anomalous features, providing a reasonable image of shallow subsurface features. In addition, the GPR method can be the most time efficient of the geophysical methods considered.

Two other electrical methods, the SP and VLF methods, were discussed. Although SP measurements are easy to make, the electrical properties of materials at the three highway sites would make the method ineffective in locating voids. The method may have utility in locating clay filled voids, but the threat of a void collapse would be greatly diminished in this case. The VLF method is effective at locating conducting bodies; however, it is particularly susceptible to cultural noise, such as from powerlines, guardrails, and buried pipes. At the three highway sites considered, the noise would likely overwhelm anomalous contributions resulting from voids or collapsed structures under roadways.

Gravity and magnetic anomalies were modeled by plotting the analytic solutions to spherical and cylindrical voids in material having properties typical of coal and limestone. Although the calculated anomalies were above the threshold of current state-of-the-art gravimeters and magnetometers, the small size of the anomalies would require extreme care in obtaining field data. This is especially true of gravity measurements, where a single data point would require 5 to 15 minutes of setup for the gravimeter. In addition, the scale of these anomalies would require that the data be sampled at relatively short distance intervals, requiring many data points. Other factors such as cultural interference and clutter were not considered and could easily adversely affect the data.

The effectiveness of seismic methods is dependent on having a source capable of producing the high frequencies necessary to achieve sufficient resolution. Both seismic reflection and refraction require geophone plants, which are slow and labor intensive. To achieve sufficient resolution, the spacing between geophones is necessarily small, and hence time consuming. Finally, obtaining good data in a highway environment would be especially difficult given the extraneous noise.

From the above considerations, GPR was evaluated as the most effective technique for the detection of voids and collapsed structures in Ohio. GPR measurements were made at three highway sites in Ohio, where subsurface voids have already been discovered or where surface features indicated subsurface void collapse. These sites include a section of I–470 in Belmont County, a section of I–70 in Guernsey County (both in the coal mining area of eastern Ohio), and a newly constructed section of State Route 33 in Logan County, in the limestone terrane of western Ohio. The Belmont and Guernsey County data illustrated the effects of cultural interference on radar data where the estimated depth of penetration was less than 15 and 5 ft, respectively. At the Belmont and Guernsey County sites, the most prominent features in the record were attributed above-ground scatterers such as overhead powerlines, guardrails, and the field vehicle. Excellent data were obtained at the Logan County site, where the maximum depth of penetration into the limestone was estimated to be greater than 25 ft. The data show numerous anomalous features, possibly related to karst features or fracturing in the limestone. Where the overburden was removed, horizontal bedding in the underlying limestone was clearly evident in the radar record.

The technical feasibility of selected geophysical methods to detect voids and void related features (collapsed structures) in Ohio have been demonstrated using numerical models, simple calculations, and field applications. Results of this report demonstrate the difficulties associated with locating anomalous features given the size of the anomalies combined with clutter and cultural interference. The geophysical methods evaluated are susceptible to cultural noise; however, techniques such as electromagnetics are particularly susceptible to the types of interference experienced on open roadways. Some of the techniques not tested in the field could prove more valuable in less noisy environments, such as new roadways under construction.

Although no single method will succeed in all instances, the likelihood of locating subsurface voids and collapsed structures is increased by incorporating as much information as is reasonably available, from as many techniques as possible. This multisensor philosophy has been suggested in the detection of abandoned mines, shallow landfills, and unexploded ordnance.

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