Detection and characterization of subsurface cavities, tunnels and abandoned mines

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Abstract

Despite decades of effort, detection and characterization of subsurface cavities, tunnels and abandoned mines remains one of the most difficult classes of problems addressed by near-surface geophysics. As geophysical technology has advanced, so have the difficulties of the requirements. Three primary application areas are drivers for development of geophysical technology for cavity and tunnel detection: geotechnical and safety considerations; civilian criminal activities; military considerations. Natural cavities and abandoned mines are safety threats to man and his expanding utilization of land and natural resources, and pose significant design and construction problems for new engineered structures. Tunneling and utilization of existing cavities and mines have long been used for criminal activities such as smuggling, prison escape, robbery, and caches. With discovery of tunnels under international borders, used for human trafficking and contraband smuggling, new and challenging requirements for geophysical detection technology have emerged. In a military context, tunneling and utilization of existing cavities and tunnels have played important roles throughout history for logistics and storage, troop insertions behind enemy lines and across borders, intelligence operations, terrorism, accessing secure installations, and deeply buried facilities. The basic physics of detection haven't changed, and no dramatic technology breakthrough has occurred. However, significant advances in geophysical data acquisition, processing and interpretation capability have dramatically enhanced possibilities for cavity detection and characterization. Following a historical perspective and review of basic concepts, brief case histories illustrate approaches, continuing challenges, and rules of thumb for cavity, tunnel, and abandoned mine detection.

Introduction

The term subsurface cavity is used to refer to all subsurface features that are termed cavities, caves, caverns, tunnels, mines, and other engineered/constructed facilities. Subsurface void refers to a cavity that is air-filled. Subsurface cavities can be natural or manmade. Natural cavities include caves, caverns, tubes, chambers, and pipes that are formed by natural processes. The most common natural cavities are those formed in limestone by dissolution processes, and at least 20% of the earth's land surface has limestone and other solution-susceptible rocks near the surface. Natural cavities can be air-filled, water-filled, or sediment-filled. Manmade cavities include tunnels and mines and may be known or unknown in present day context. Known mines and tunnels include active mines, recently closed mines, and railway, highway and sewer tunnels. Unknown mines and tunnels include abandoned (forgotten or records lost) and ancient tunnels and mines, as well as covert tunnels. Manmade cavities often contain significant quantities of metal (machinery, rails, power lines, etc.) and are often lined and contain other support structures.

Three primary application areas are drivers for development of geophysical technology for cavity and tunnel detection: (1) civilian geotechnical and safety considerations; (2) civilian criminal activities considerations; (3) military considerations. Requirements for detection and characterization of subsurface cavities have resulted in significant investments in formal programs for cavity detection methodology and technology development. The major problems and some of the resulting programs include:

—cavities in karst areas threaten dams, levees, roads, buildings, parking lots, utilities, power plants, beneath paved and concrete structures and general broad-based problems due to population expansion and aging infrastructure; research programs by the United States (US) Department of Transportation, the US Army Corps of Engineers (COE), and the US Nuclear Regulatory Commission were executed during the 1970's and 1980's addressing problems associated with cavities in karst areas, including detection and characterization (e. g., Butler 1977, 1983; Ballard 1982, 1983; Curro 1983; Cooper 1983; Butler et al. 1983; Franklin et al. 1980); interest in aging infrastructure continues (e. g., Llopis et al. 1995)

—use of cavities for covert military activity, including weapons caches and manufacturing, cross-border incursion, subsurface command facilities, etc., have resulted in numerous military programs by various nations for detection, characterization, and concealment of subsurface facilities, at least since the 1960's;

—ground collapse and settlement over abandoned mines, causing damage to infrastructure, has been problematic throughout history; programs and symposia by agencies such as the US Geological Survey, Office of Surface Mines (OSM) and the Mine Safety and Health Administration have addressed this growing problem (e. g., Butler 1984; Butler and Kean 1991; OSM 2003);

—cross-border contraband smuggling tunnels (drugs, weapons, human trafficking, etc.), tunnels for prison escape, terrorism related tunnels, etc., have led to various law enforcement and military programs directed, for example, to counter-drug tunnel detection technology development.

Approaches to a subsurface cavity detection program are widely varied. The most common and often the first approach in a geotechnical context (karst areas, abandoned mines, etc.) is invasive (i. e., drilling). Geophysical methods for detecting and delineating subsurface cavities are all too frequently applied only after drilling has failed or has resulted in a confusing and non-definitive assessment of the problem.. Some interesting trends emerge when publications on cavity detection are reviewed. In the United States the ranking of geophysical methods, in terms of numbers of publications and stated preferences of researchers and practitioners, seems to be (a) electrical resistivity and electromagnetic (EM) methods (including ground penetrating radar, GPR), (b) seismic methods, and (c) gravimetric methods, with 'a' and 'b' nearly equal. In Europe, a similar ranking of methods would be somewhat different: (a) gravimetric methods, (b) resistivity and EM methods, and (c) seismic methods. Military programs often emphasize development of a "silver bullet" methodology, with preferences for airborne or spaceborne technologies. However, as in all near-surface geophysics efforts, no single method should be relied on to optimize detection of subsurface cavities; the most effective approach uses a combination of complementary methods.

The nature of subsurface cavities and their geophysical expression

Subsurface cavities represent an anomaly or departure from the surrounding or "background" geologic conditions. Geophysical surveys detect anomalous responses on the surface or in nearby boreholes that are caused by the subsurface cavity. Fig. 1 illustrates the distinction between the subsurface anomaly (a cavity/tunnel) and a geophysical anomaly detected by measurements along the surface above the cavity. Subsurface cavities are anomalous due to (1) the cavity space itself, (2) secondary effects around the cavity, and (3) materials within the cavity. The anomalies represented by all subsurface cavities have effective diameters larger that the physical dimensions of the cavity space itself, due to item (2); this is called a "halo" effect, and is caused by stress redistribution, cracking and fracturing, subsidence, and induced ground water flow. The effective size of the subsurface cavity anomaly is often larger by a factor of two than the cavity itself. Material within the cavity could be water, clay or other secondary geologic material, and, in the case of mines and tunnels, metal, wood, plastic, motors, power lines, etc. The cavity, its "halo", and material within the cavity is termed the cavity system.

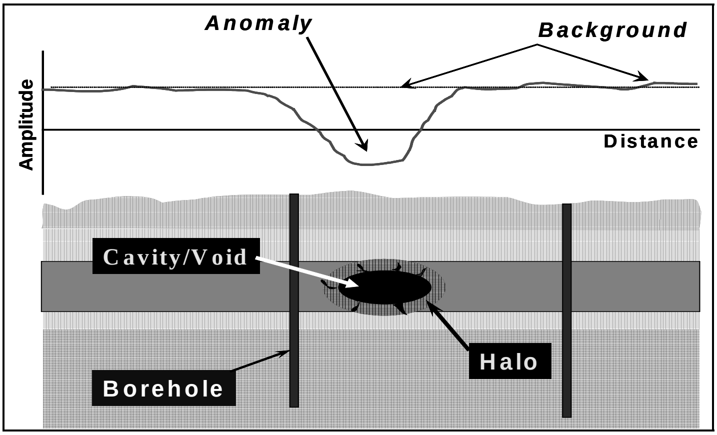


Fig. 1. Illustration of cavity system (cavity with filling materials or void and cavity halo) and surface geophysical anomaly.

What determines if the anomaly caused by a subsurface cavity system is detectable on the surface? Theoretically it might be argued that there will always be a surface anomaly over a subsurface cavity for a given geophysical measurement, but in many cases the anomaly will not or cannot be detected. Whether or not an anomaly will be detected depends on four primary considerations: (1) magnitude and spatial wavelength of the anomaly; (2) noise; (3) sensitivity of the measurement system; (4) depth of investigation of the measurement system. The magnitude of the surface anomaly is determined by the size of the subsurface cavity (including the “halo”), the depth to the cavity, and the physical property contrasts represented by the cavity system. Surface spatial wavelength is dependent primarily on the depth to the cavity and secondarily by the size of the cavity system. Noise sources affecting a set of geophysical measurements can be natural (e. g., wind, micro-seismicity, magnetic, electrical and EM sources, and natural geologic variation or heterogeneity) or manmade. Clearly the anomaly magnitude should be greater than the noise level, and the anomaly frequency and spatial extent (wavelength) should be distinctive from the characteristics of the noise sources. Many geophysical methods have a theoretical and a practical “depth of investigation, “ and if the subsurface cavity is significantly below this depth, the cavity cannot be detected on the surface. Also, the geophysical measurement system must have appropriate measurement sensitivity and accuracy for the parameter magnitude or the anomaly will not be detected. For subsurface cavity systems which cannot be detected from the surface, detection by borehole to surface or cross-borehole measurements may be possible. However, for subsurface cavity systems which cannot be detected from the surface, it is very unlikely that the system can be detected by any type of airborne system.

Basically, the procedure in the detection and delineation of subsurface cavities is first the determination or suspicion of the *presence* of localized anomalous conditions in the subsurface by drilling and/or remote methods (surface and/or airborne geophysics) and then the subsequent delineation or detailed mapping by geophysical and drilling methods of any anomalous conditions found. While airborne imagery, geologic reconnaissance, drilling, dye tracing, historic records, human 'intelligence' (for abandoned and covert cavities, tunnels, and mines), and other techniques, can contribute significantly to subsurface cavity detection and delineation, only surface geophysics, subsurface geophysics, or low-level airborne geophysics can effectively detect and delineate subsurface cavities. The geophysical anomaly produced by a cavity system will depend intimately on its size and the nature of the filling material (air, water, clay, other secondary geologic material, or manmade materials). In order to use geophysical methods for detection of cavities, it is necessary to understand how the physical properties of cavity systems affect geophysical measurements. Fig. 2 assesses the applicability of geophysical methods to various near-surface characterization objectives, and includes cavities.

Example Objectives	Seismic Refraction	Seismic Reflection	Ground Penetrating Radar	Electrical Resistivity	Electromagnetic Induction	Induced Polarization	Microgravity	Airborne Sensing	Magnetic Methods
Geologic mapping	➊	➊	➊	➊	➊	②	②	②	②
Hydrogeology characteristics	➊	②	➊	➊	➊	③	②	③	na
Water table depth	➊	②	②	➊	➊	③	na	②	na
Top of bedrock	➊	➊	③	➊	➊	③	②	③	na
Cavity detection	②	②	➊	➊	➊	③	➊	③	③
Disposal trench mapping	③	②	➊	➊	➊	na	②	②	②
Nature of trench fill	③	na	➊	➊	➊	?	➊	na	➊
Inorganic contaminant plume	na	na	➊	➊	➊	➊	na	②	na
Organic contaminant plume	na	na	②	?	?	?	na	②	na
Disposal container (metal drum)	na	na	➊	②	➊	③	③	na	➊
Underground storage tanks	③	③	➊	②	➊	③	②	na	➊
UXO detection	na	na	➊	➊	➊	na	na	③	➊
Coal "Void" Detection	2	1	2	2	2	3	1	3	3

KEY: ➊ = primary applicability; ② = secondary supporting applicability; ③ = limited applicability; na = no general applicability or not widely used; and ? = area of active research and rapidly evolving technology or questionable application.

(NRC 2002)

Fig. 2. Geophysical methods applicability based on nature of target and experience (adapted from NRC 2000 and NRC 2002).

Case histories

Large diameter metal pipelines

A large diameter (- 1 m or larger) metal pipeline is an example of the simplest category of "reinforced tunnels" to detect with geophysics. Clearly, at shallow depths (e. g., < 3 m), a large metal pipe can be easily detected with most of the geophysical methods (e. g., GPR, EM induction, electrical methods, microgravity, magnetometry (for steel pipes)). A practical example of detection of a large diameter pipeline is shown in Fig. 3. In this example, a 1.2-m diameter pressurized gas pipeline was buried at a nominal depth of 2 m along a right of way that crossed numerous wetlands. A geophysical survey program was conducted to accurately locate and determine the depth of the pipe, in order to assess the legal compliance of the construction techniques with wetlands preservation requirements. The geophysical survey program consisted of two steps: (1) location of the pipeline and determination of its approximate azimuth using EM induction (see the next case history for an example of this procedure) and (2) conducting a GPR survey approximately perpendicular to the pipeline azimuth determined in step one to determine depth to top of the pipe. Immediately on completion of the geophysical location and depth determination, the ground was mechanically excavated to within approximately 0.2 m of the estimated depth, and the final excavation was done by hand methods.

Cross-border intrusion tunnel

Examples of tunnels crossing international borders include the spectacular tunnels through massive granite under the demilitarized zone in Korea and more recently tunnels in soil under the Israel-Egypt border for weapons smuggling and tunnels in soil under the Mexico-US border for drug smuggling. These tunnels are as shallow as 10 m for some of the weapons and drug smuggling tunnels to 150 m for the Korean tunnels, and range from non-reinforced for tunnels in compacted soil and massive rock to reinforced with wood planking and concrete lining. A particularly high profile example of a drug smuggling tunnel under the Mexico-US border is the Otay Mesa Tunnel near San Diego, California. The Otay Mesa Tunnel was approximately 425-m long, ranged from 11-m deep on the northern end to approximately 20-m deep at the southern entrance, and nominally was 1.5-m in diameter. The compacted soil was an ideal tunneling media and was non-reinforced except for the last 120 m on the northern end, which was lined with a reinforced concrete. The Otay Mesa Tunnel Site was selected as a tunnel test site, and approximately 20 different geophysical systems were evaluated for detection capability. Only electrical resistivity (dipole-dipole array) methods were capable of reliably detecting the air-filled section of the tunnel, while both electrical and EM induction methods could detect the reinforced, concrete-lined section. Results of EM induction surveys across the concrete-lined section are shown in Fig. 4, at a location where the tunnel depth is approximately 13 m. Electromagnetically lossy soil conditions prevented GPR from detecting of the tunnel from the surface, even at 50 MHz center frequency.

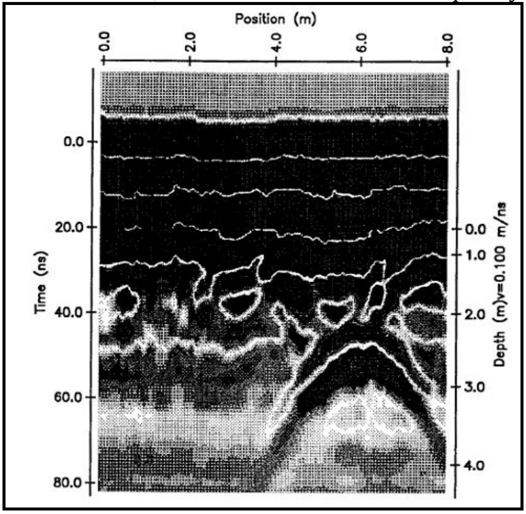


Fig. 3. GPR record over a 1.2-m diameter gas pipeline at a nominal depth of 2 m. Time-depth conversion using mean, measured near-surface EM propagation velocity.

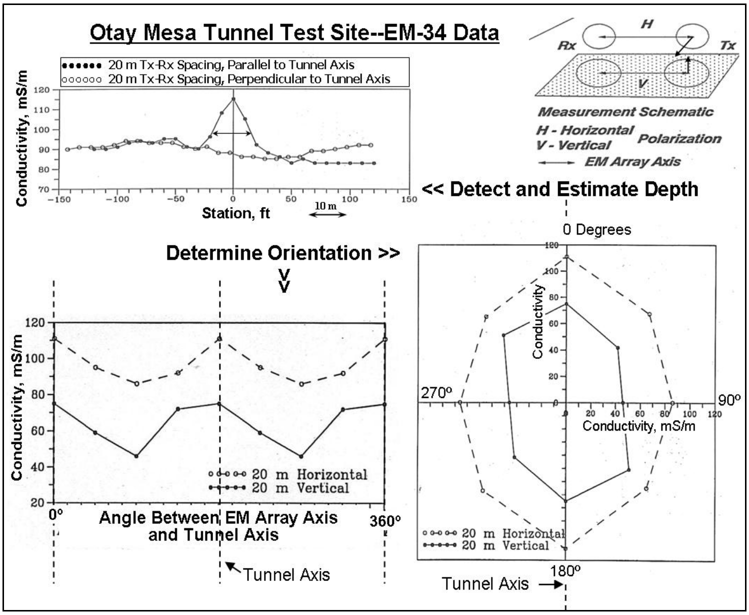


Fig. 4. Results of EM induction surveys to locate, determine orientation and approximate depth of the Otay Mesa drug intrusion tunnel.

Natural cavities in karst areas

No problem in near-surface geophysics presents such diverse and complex challenges as detecting and characterizing cavities and associated features in karst areas (Yuhr 1993; Benson et al. 2008). The references by Franklin et al. (1980), the five report series by the COE, and Butler (1994) summarize the state of art through approximately 1990, while the reports by NRC (2002) and OSM (2003) continue the developments through approximately 2000. The requirements for knowledge of local geology include sinkholes, known cavities, soil depths to top of soluble formations, lineaments, springs and seeps, and exposures in roadcuts and surface mining operations. Electrical resistivity, EM induction, GPR and microgravity are the primary geophysical methods used to detect and characterize karst features, including cavities. Of all the geophysical methods, microgravimetry comes closest to allowing a positive statement regarding the presence or absence of subsurface cavities. For any particular microgravimetric anomaly, it is not possible in general to identify a unique source, although knowledge of the geology considerably restricts the possibilities. However, the absence of gravity anomalies in a site survey has considerable significance, and the presence of negative anomalies suggests the presence of cavities. For any hypothesized cavity (filled or unfilled) that might be considered to pose a threat to foundation bearing capacity in subsequent site use, it is always possible to calculate the minimum depth at which the cavity can exist without being detected. Even considering reasonable experimental errors in the data, such calculations are generally conservative, since experience shows that gravity anomalies due to cavities in karst regions are greater generally by a factor of two or more than those calculated on the basis of cavity dimensions, due to increased porosity (decreased density, caused by fracture and solution in the rock around the cavity (the 'halo'; Butler 1994, Yule et al. 1998). An example microgravity survey profile correlated to known geology is shown in Fig. 5 (Butler 1984b). As a rule of thumb, using modern gravimeters and exacting field procedures, air-filled cavities can be detected to a depth of 8 – 10 times the effective diameter of the cavity (a similar rule of thumb holds for electrical resistivity and EM methods).

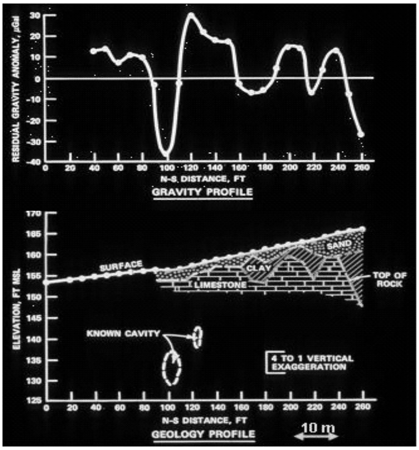
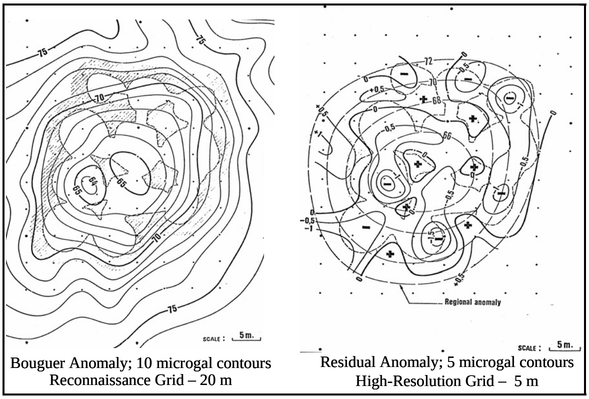


Fig. 5. Microgravity survey profile correlated to closely-spaced drilling results and knownsubsurface, air-filled cavity characteristics.



Bouguer Anomaly; 10 microgal contours
Reconnaissance Grid – 20 m

Residual Anomaly; 5 microgal contours
High-Resolution Grid – 5 m

Fig. 6. Room-and-Pillar Mine (– 5 m Depth) Detected by Reconnaissance Microgravity Survey (left) and Delineated (right) by Follow-on High-Resolution Survey: + anomaly—pillar; – anomaly—”room”

Abandoned mines

Results of a high-resolution microgravity survey of an anomaly discovered during a reconnaissance microgravity survey is illustrated in Fig. 6, where a subsurface quarry system is shown to be well-defined in plan (Butler 1994). To add depth information to the results shown in Fig. 6 would require borehole information for any of the negative regions of the contour plot or depth computations based on assumptions regarding geometry and rock density. Microgravimetry can be applied to cavity detection at sites where no other method, even drilling, can be successfully or safely applied. Such a difficult site for geophysics and drilling is a powerplant switchyard, where ground vibrations, stray EM fields and ground currents, and overhead structures, make the use of all geophysical methods except microgravimetry virtually impossible, and drilling is extremely hazardous and should be undertaken only at specific anomaly locations (Butler and Yule 1984; Yule et al. 1998).

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