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DETECTION OF VOIDS UNDERGROUND AND UNDER PAVEMENTS

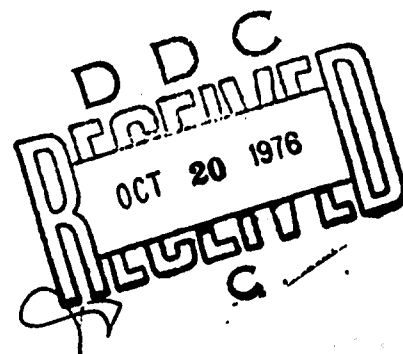
By

M. C. Hironaka, R. D. Hitchcock, and J. B. Forrest

August 1976

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Field investigations using the above three methods are recommended to provide quantitative evaluations of accuracy, reliability, and cost under various site conditions. Based upon the results of these field investigations, development of advanced acoustic holographic methods may be warranted.

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There is no one method capable of accurately locating and defining voids under all circumstances. However, either one or a combination of these three methods appear to be the most promising: (a) earth resistivity, (b) seismic techniques, and (c) subsurface radar. The effectiveness of these methods in detecting voids depends on soil properties, surface material properties (e.g., type of pavement), ground surface geometry, and accessibility with respect to the detecting equipment.

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CONTENTS

	Page
INTRODUCTION	1
TECHNIQUES FOR VOID DETECTION	6
Magnetic Intensity Determinations	8
Gravity Variations	9
Electromagnetic Waves	11
Earth Resistivity Measurements	15
Seismic Surveys	20
Load-Deflection Methods	23
Nuclear Detection	25
Acoustic Holography	27
DISCUSSION	29
CONCLUSIONS	33
RECOMMENDATIONS	34
REFERENCES	35

LIST OF ILLUSTRATIONS

	Page
Figure 1. Surface impression due to a cavity - Dock 3 at Port of Hueneme	2
Figure 2. Evidence of burrowing animal inhabiting cavity - Dock 3 at Port of Hueneme.	2
Figure 3. Undermining of walls beneath dock - Port of Hueneme	3
Figure 4. Surface cavity at runway edge - NOLF San Nicolas Island.	3
Figure 5. Tunnels due to erosion near the main runway - NOLF San Nicolas Island.	4
Figure 6. Schematic representation of voids	5
Figure 7. Anomalies for geological bodies at various orientations and different inclinations of the field (from Reference 3).	10

List of Illustrations (continued)

	Page
Figure 8. The effect of water content on the conductivity of two specific soils (after Reference 8).	13
Figure 9. Relative dielectric constant versus water content P-Band 297 MHz (from Reference 8)	13
Figure 10. Example of record obtained by electromagnetic profiling at Philadelphia NSY (from Reference 9). . .	14
Figure 11. Schematic diagram of a resistivity instrument (from Reference 11).	16
Figure 12. Vertical cross section of an idealized material showing electric field lines (solid lines) and equipotential surfaces (dashed lines) (from Reference 11).	16
Figure 13. Plan view of an idealized material showing electric field lines (solid lines) and equipotential lines (dashed lines) (from Reference 11)	17
Figure 14. Simplified example of graphical solution for anomaly location (from Reference 12)	19
Figure 15. Earth resistivity test over 10-inch-thick (25 cm) reinforced concrete roadway slab (from Reference 13).	20
Figure 16. Idealized vertical cross sections through the subsurface to illustrate direct, refracted, and reflected wave paths (from Reference 14)	21
Figure 17. Idealized seismogram and solution cavity showing expected results (from Reference 16)	24

LIST OF TABLE

Table 1. Methods for Detecting Subsurface Voids	7
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INTRODUCTION

Voids beneath and adjacent to pavements and other engineering structures have resulted in serious problems at various Naval and other military and civilian installations. A few examples of situations wherein suspected voids have caused problems to military activities are:

Philadelphia Naval Shipyard - voids behind quay walls undermine a busy thoroughfare

Naval Air Station, Brunswick, Maine - voids around a culvert under an aircraft parking apron impair the integrity of the structure

Naval Construction Battalion Center, Port Hueneme, California - suspected voids beneath loading docks prohibit their use

Mare Island Naval Shipyard, California - large voids beneath paved surface near the drydocks and deterioration of grout beneath portal crane rails present operational hazards

Commissary Parking Lot, Long Beach Naval Shipyard, California - voids created by decomposition of buried garbage present a serious maintenance problem

Shemya Air Force Station, Alaska - voids caused by subsurface erosion of fine material result in ground surface subsidence [1]

NOLF San Nicolas Island - formation of tunnels under main runway due to subsurface erosion presents a continuing threat

Surface impressions created by collapsing of subsurface cavities at Port of Hueneme are shown in Figures 1 and 2. Further damage to the surface area created by burrowing animals is shown in the second figure. Development of the subsurface voids leading to these surface impressions is attributed to erosion of material beneath the structure, as suggested by Figure 3. Voids on a much larger scale were suspected at NOLF San Nicolas Island. Figure 4 illustrates one of several large depressions along the edge of the runway. Figure 5 shows openings to a large system of erosion tunnels which lead away from the airfield towards the ocean.

Voids occurring beneath ground surface and beneath pavement are shown schematically in Figure 6. The pavement is generally constructed of asphaltic concrete, portland cement concrete (reinforced or unreinforced), or some combination of the two.



Figure 1. Surface impression due to a cavity - Dock 3 at Port of Hueneme.

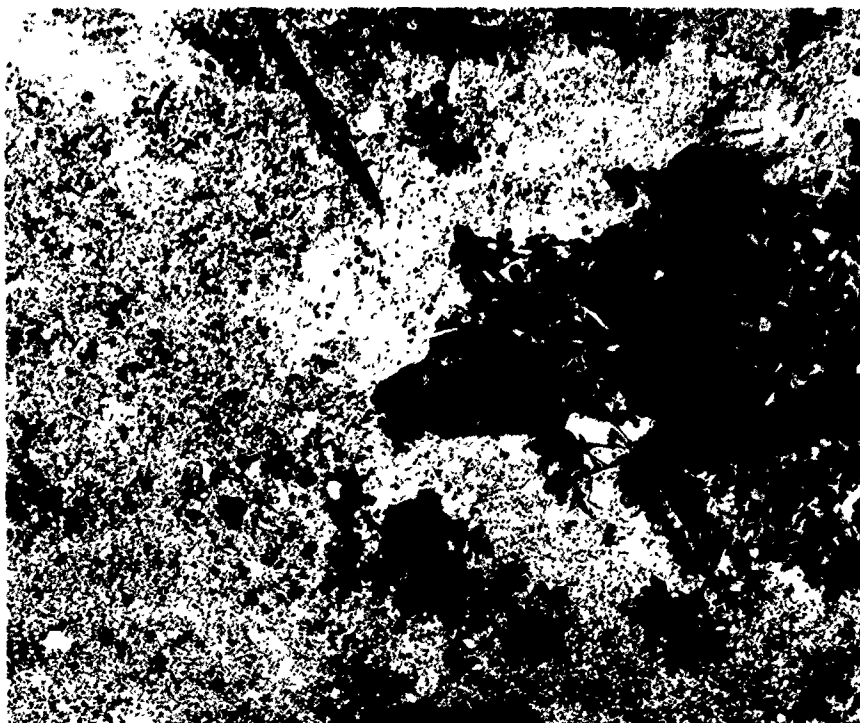


Figure 2. Evidence of burrowing animal inhabiting cavity - Dock 3 at Port of Hueneme.



Figure 3. Undermining of walls beneath dock - Port of Hueneme.



Figure 4. Surface cavity at runway edge - NOLF San Nicolas Island.

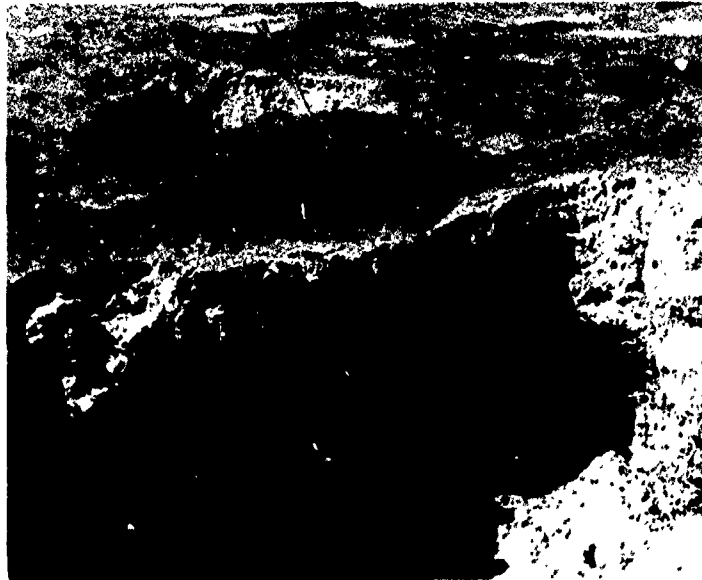


Figure 5. Tunnels due to erosion near the main runway - NOLF San Nicolas Island.

The voids may contain air, water, or some weak deposit such as mud. They may vary from less than an inch (2-3 cm) in size to many feet (meters), may have any irregular cross section, and may be located near the surface or at great depth. The voids may or may not create surface impressions indicating their presence.

Because of the problems that voids create to Naval structures, the Civil Engineering Laboratory (CEL) has undertaken this study to identify and evaluate present techniques, procedures, and equipment for rapidly and nondestructively determining the existence and location of voids underground and under pavements. For purposes of the study, a void is considered to be any anomaly in the soil profile that could impair the function of a supported structure. Although the significance of void size and location may vary, depending upon the nature of the surface structure, this study is generally concerned with situations wherein the ratio of void equivalent radius to depth below surface is in the range of 1 to 0.1 (i.e., $1 \geq \text{radius/depth} \geq 0.1$). Based on the findings from this study, recommendations for void detection by the Navy are presented. Further research and development work are suggested where it is deemed necessary.

The following sources were consulted for literature pertaining to void detection methods applicable to this study: The Engineering Index, Defense Documentation Center, Smithsonian Science Information Exchange, National Technical Information Service, and State of the Art Patent Search. Personal contacts were made with manufacturers of void detection equipment and with users who have applied such equipment to detecting voids in actual field problems. The information obtained was evaluated as to the applicability to solving the problem of void detection with particular attention to Naval Shore Establishment problems.

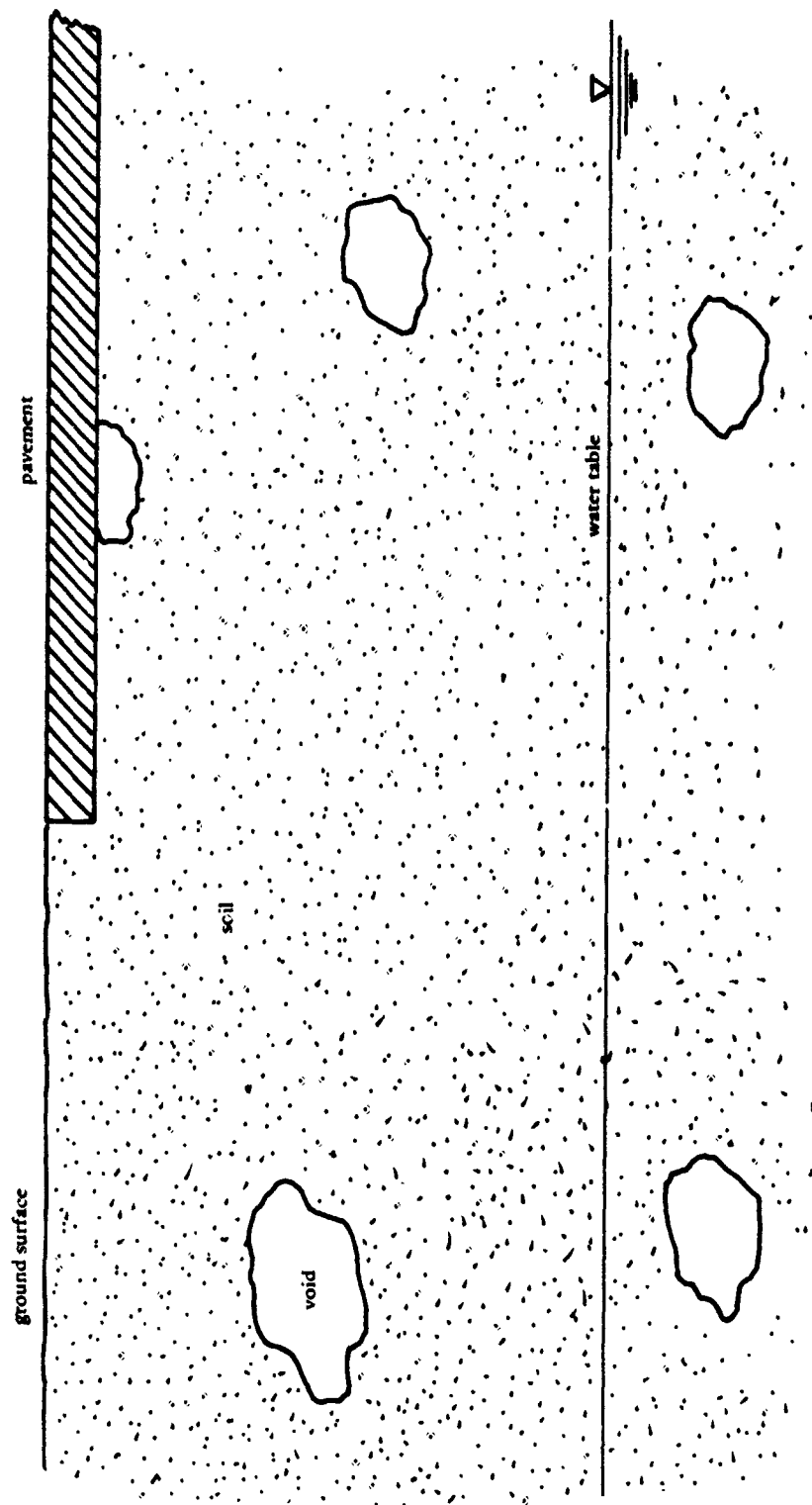


Figure 6. Schematic representation of voids.

TECHNIQUES FOR VOID DETECTION

Void detection approaches fall into three classes based on their utilization with respect to the ground surface: (1) remote sensing, (2) ground surface methods, and (3) direct location methods. Remote sensing methods assess the effect of a void beneath the ground surface from some distance above the surface, generally from an aircraft. Examples of remote sensing methods include aerial infrared surveys, aerial photographs, and microwave surveys. Although these methods offer the advantage of covering large areas rapidly, they are primarily limited to those subsurface cavities that show impressions at the ground surface. These methods are generally used in reconnaissance surveys and are sometimes effective in detecting large cavities occurring beneath the ground surface that cause detectable anomalies at the surface. To detect voids of the sizes and locations of interest to this study, remote sensing methods can be considered totally ineffective. These methods will, therefore, not be discussed further in this report.

Ground surface nondestructive void detection methods include those procedures performed at the ground surface that measure a property which is related to the presence of a void and, thus, do not require physical access to the void. Examples of such methods include the use of the following principles: sonic wave velocity, electrical resistivity, electromagnetic propagation, gravity anomalies, and nuclear transmission and reflection. These methods are not equally effective in detecting voids. Properties of the overlying pavement and of the ground itself greatly influence the effectiveness of particular methods described above. None of these methods can absolutely detect all voids beneath pavements and ground surfaces. As conditions change one method that has been effective under particular circumstances may be ineffective in another. In many cases, it is necessary to use direct location methods to confirm or disprove areas suspected of containing voids.

Direct contact methods include borings, soundings, or excavations into the void or cavity. The exclusive use of these methods require many closely spaced probings or extensive excavations and are very expensive. Direct methods can also be unreliable in that they overlook voids occurring throughout any unexcavated or unbored areas. Thus, the most economical use of direct methods is in support of the indirect methods in confirming suspected voids. Since direct contact methods are common procedures in foundation investigations, these methods will not be discussed further in this report. This report concentrates on ground surface void detection methods. The bulk of these (Table 1) are based upon monitoring some form of energy propagation or force field. Although the electromagnetic spectrum is primarily utilized in remote sensing [2], the basic concepts are also applicable to detecting voids under circumstances of interest herein. The interaction of energy waves with the pavement and soil and with the targets to be sensed governs the frequencies and wavelengths used. The relationship between frequency and wavelength in linear systems is described by:

Table 1. Methods for Detecting Subsurface Voids

Method	Quantity Measured	Measurement Equipment	Effectiveness For Void Detection	Void Size and Depth Location Determinable	Surveying Speed	Reference
Magnetic intensity	anomalies in the earth's magnetic field	proton precession magnetometer (sensitivity - <1 gamma in total earth's field of 50,000 gammas)	low	no	portable, vehicular- or aircraft-mounted	3
Gravity variations	change in acceleration of gravity	gravimeter	low	possible	50 ft ² /hr (5 m ² /hr)	5, 6, 7
Earth resistivity	voltage, current, and distance between electrodes	earth resistivity meter	good	possible	1,000 ft/day (300 m/day)	11, 13
Electromagnetic waves	transmission characteristics of reflected electromagnetic waves	subsurface looking radar	good	possible	portable and towable at several miles/hour (km/hr)	8, 9, 10
Seismic surveys	compressional wave velocities	seismographs, acoustic profilers	fairly good	possible	portable, speed similar to earth resistivity method	14, 15, 16
Load-deflection	magnitude and slope of surface deflections	nondestructive static and dynamic plate-bearing devices	variable	no	2-4 minutes/test location (for dynamic)	19, 20, 21
Nuclear detection	number of counts of backscattered radiation	nuclear-particle counter; pulse-height analyzer	low	possible	50 ft ² /hr (5 m ² /hr)	4, 22, 23
Acoustic holography	phase and amplitude of acoustic wave	coherent acoustic-wave generator; hydrophone array	good	possible	100 ft ² /hr (10 m ² /hr)	24, 25, 26 27, 28

$$f = c/\lambda$$

where f = frequency
 c = wave speed
 λ = wavelength

In the case of the electromagnetic propagation, for example, if the frequency is very high, the interaction of the waves with atoms and nuclei is very large, causing scattering and absorption of the waves. If the frequency is very low, attenuation of the waves will also be low, but resolution* of the target will be poor since an object reflects coherently only waves comparable to itself or smaller. The resolution and effectiveness of other methods are similarly affected by frequency and wavelength. Thus, the selection of the sensing radiation is limited to wavelengths larger than atoms and smaller than targets.

Although different forms of energy propagation may have a similar overall basis, different medium properties affect their propagation. For example, in the case of electromagnetic propagation, the dielectric constant and the conductivity of the medium are important factors affecting propagation. In sonic applications the elastic properties and the density of the medium are the important factors.

Magnetic Intensity Determinations

The use of magnetic intensity measurements for detecting subsurface voids is based upon the presence of anomalies in the magnetic field of the earth. Anomalies represent local disturbances in the earth's magnetic field due to local changes in magnetization (magnetization contrast, see References 3 and 4). These anomalies can be either positive or negative. In field applications, a proton precession type magnetometer is used to monitor the component of the anomaly of the earth's magnetic field. The effectiveness of this method for detecting voids depends on the presence of magnetic material, such as magnetite, surrounding the void and, therefore, shows up as an anomaly. Sedimentary rocks or their metamorphic equivalents, salt or freshwater, or air do not alter magnetic anomalies in any way, because their magnetic permeabilities are the same (unity).

The factors that impair magnetic intensity measurements include:

- (1) a large magnetic field gradient greater than 200 gammas/foot, (600 μ T/m) which sharply degrades the signals from the magnetometer;
- (2) nearby AC electrical power, which can lower the signal-to-noise ratio;
- (3) effects of changes in the magnetic field of the earth due to diurnal variations, micropulsations, and magnetic storms;
- (4) man-made structures containing magnetic material, such as buildings and railroads;
- and (5) the distance between the magnetometer and the object being detected.

* Resolution has dimension of length; "poor" resolution means that only large units of length are detectable, whereas "good" resolution means the capability to discern details within small units of length.

Since the effectiveness of monitoring magnetic intensity to detect subsurface voids depends on the voids being surrounded by magnetic material, the applicability for detecting voids by this method is low. Soils are generally nonmagnetic. If voids occur in magnetic rocks, however, it is possible that these could be detected. Figure 7 illustrates some geological features that are the source of common magnetic anomalies. With experience, it might be possible to interpret similar data for voids. Assuming the geological structures shown in the figure are replaced by voids and the surrounding media by magnetic material, the voids should show up as anomalies similar to those shown in Figure 7 but of opposite magnitudes.

Gravity Variations

The mapping of variations in subsurface density by means of gravity measurements is done routinely in geophysical surveying. However, the purpose of these surveys is nearly always to obtain a relatively large-scale gravity map and not to detect small voids. An underground void, of course, represents a maximum change in density and, hence, in principle, can be detected by observing the resultant change in the force of gravity in the neighborhood of the void. Unfortunately, the gravity force is extremely small compared to electromagnetic forces and requires highly sensitive force-measuring devices with their attendant problems of extracting signals from noise.

The instrument commonly used in geophysical gravity surveys is the gravimeter. This is a device in which the gravitational force on a mass is balanced by the tension in a spring. One particular gravimeter [5] uses a horizontal beam supported by torsion and ligament springs and constrained by these springs to move in a vertical plane about the horizontal axis of the torsion spring. A variation in the vertical acceleration, either because of gravity changes or motions of the support platform, will deflect the beam; the magnitude of the deflection is measured by a light beam reflecting from a small mirror attached to the mechanical beam. Gravimeters can measure changes in the acceleration of gravity with a precision of 0.005 mgal* [6]. This high precision, however, usually requires a large number of measurements. A single scan of the surface region will not detect a subsurface void unless the resultant change in gravity is greater than about 0.01 mgal [7].

A quantitative relationship for void size and depth is derivable from the basic equation for gravitational force:

$$F = Gm_1m_2/r^2 \text{ dynes}$$

where G is the gravity constant ($6.7 \times 10^{-8} \text{ dyne cm}^2/\text{gm}^2$), and m_1 and m_2 are the masses (grams) separated by a distance, r (cm).

If the detectable change in the quantity, F/m_1 , is 0.01 mgal, then

$$\rho_2 V_0 / r^2 = 1.5 \times 10^2 \text{ gm/cm}^2$$

* 1 mgal = 10^{-3} cm/sec^2 .

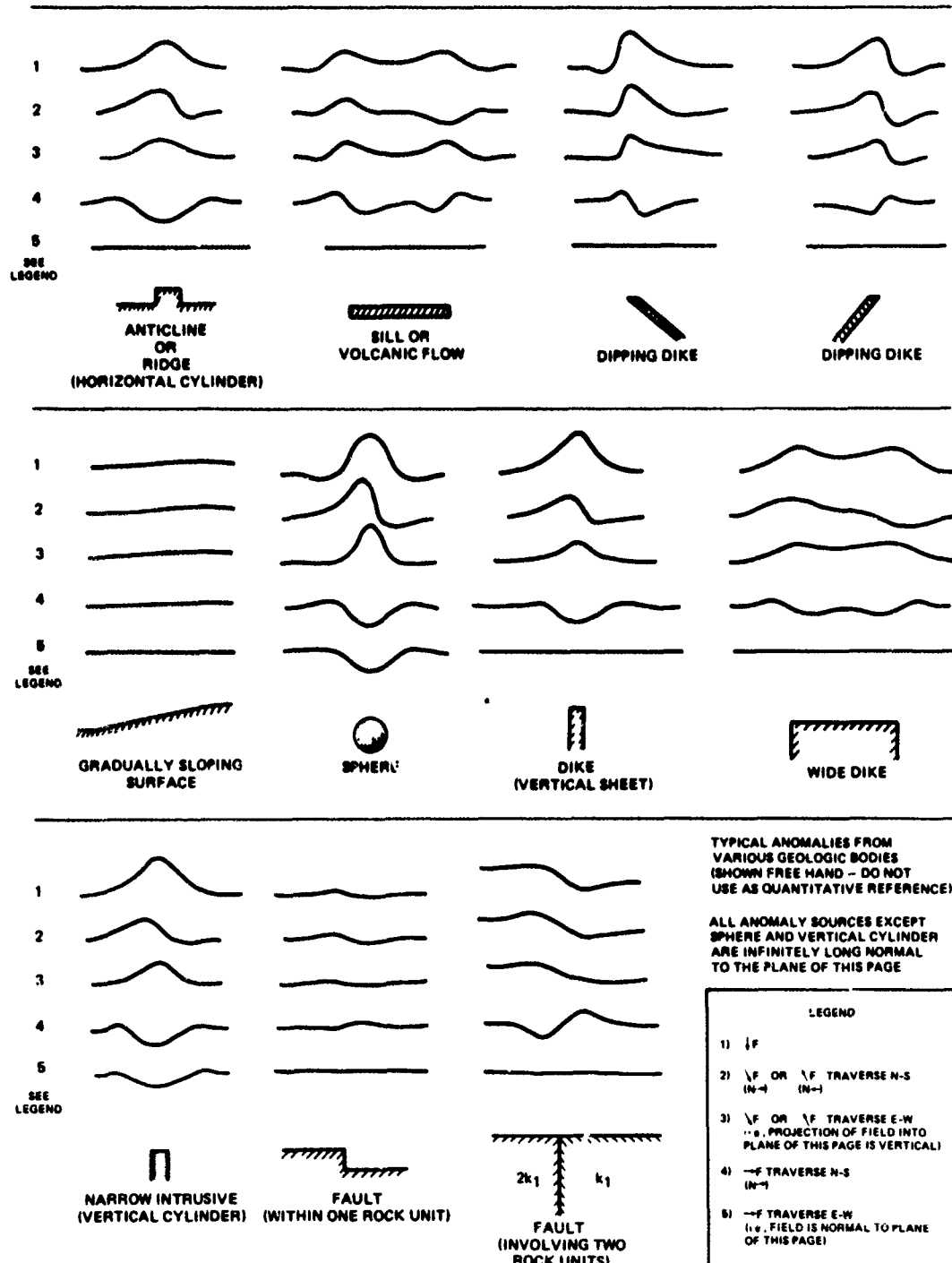


Figure 7. Anomalies for geological bodies at various orientations and different inclinations of the field (©Used by permission. Geometrics [3]).

where ρ_2 is soil density (gm/cm^3) V_0 is the void volume (cm^3), and r is the distance (depth) to the center of the void, assumed to be spherical. If ρ_2 is 2.7 gm/cm^3 , then

$$r = 2.7 r_0 \sqrt{r_0} \text{ meters}$$

where r_0 is the void radius (meters). Thus, for a void of 1 meter radius, the detection distance to the top of the void is 2.2 meters.

Detection, unfortunately, is only the first step. The location and the measurement of the size of void require many measurements and relatively complex data processing and interpretation [7]. One problem with force-field measurement is that the measured quantity does not separate void size and void depth. The same variation in gravity force can arise from a large density anomaly at great depth or a small anomaly close to the surface. Furthermore, above-surface structures and natural formations will complicate the situation. In general, the suspected area must be repeatedly scanned along several widely separated tracks, and the measurements carefully analyzed to determine whether a subsurface localized density anomaly exists. The next step is to determine whether the magnitude of the anomaly is sufficient to indicate a void.

Another problem in gravity techniques is that small accelerations of the instrument platform must be separated from the gravity measurements. Fortunately, the frequency of platform accelerations is usually such that state-of-the-art electronic filtering methods will perform the needed separation. Filtering, however, can be expensive and the only alternative, platform stabilization, is usually equally expensive. The physical size of the gravimeter presents no problem. The gravimeter, as well as simpler types of self-leveling devices, will fit into oil-well boreholes for below-surface surveying [7].

In summary, gravity detection of voids has no upper limit on depth as long as the void is large enough. If time is available for repeated scans of the surface over a relatively wide area (at least ten times the square of the void diameter), and if suitable signal processing equipment and data analysis methods are available, voids can be detected, and their depth and dimensions investigated. However, the costs of signal processing and data analysis do not compare favorably with those for resistivity or seismic surveys.

Electromagnetic Waves

The electromagnetic method for performing subsurface surveying involves video pulses and is a result of advanced radar technology [8]. A short video pulse composed of low frequency radio waves is propagated through the overburden and subsurface materials. These materials can include vegetation, soil, and pavement. Anomalies and interfaces within the soil properties reflect the propagated signals, which are recorded as a function of time. By appropriate calibration procedures based upon the speed of the electromagnetic signal through the material being surveyed, the time scale can be interpreted in terms of depth.

Limitations of the electromagnetic method include the following:

- (a) The electrical conductivity of the soil and other subsurface materials has a large effect on the depth of penetration
- (b) Reinforcing steel in concrete pavements distorts the reflected signal
- (c) Salt water severely attenuates the propagated signal
- (d) Asphaltic concrete attenuates the propagated signal
- (e) Highly plastic clays attenuate the propagated signal
- (f) A considerable amount of training and effort is required to interpret the data

Video radar effectiveness for subsurface surveying depends on the type, thickness, moisture content, and density of the material through which the survey is being conducted [8]. For small changes in moisture content or density, large changes occur in dielectric constant and conductivity. The dielectric constant affects the velocity at which the video pulse travels through the material. The conductivity affects the amount of energy that is attenuated during propagation and the shape of the returned pulse through the material. Figure 8 shows the effect of water content on conductivity for two types of material. Figure 9 shows the effect of water content on the relative dielectric constant for three particular soils.

The depth of penetration of the signal is dependent on the strength and frequency of the signal. Low frequency signals propagate to deeper depths than high frequency signals. However, higher frequency signals provide greater resolution (that is, provides the capability to discriminate better between closely spaced interfaces and targets).

A particular electromagnetic system for carrying out subsurface surveying is outlined in Reference 8. This system has been shown to be effective in locating underground utility lines and has been of some value in the evaluation of airfield pavements. This equipment was also used at the Philadelphia Naval Shipyard in an attempt to locate possible voids behind quay walls [9]. An example of output data obtained at this site is shown in Figure 10. Unfortunately the site conditions were far from ideal, having buried conduits, brackish water, steel utility poles, etc. Perhaps for this reason the demonstration did not verify the capability of the equipment to define voids.

The following conclusions were made from tests with a video radar subsurface surveying system for rapid evaluation of airfield pavements [8]:

1. Subsurface anomalies could be detected by observing the variations in the graphic display. Layer changes representing anomalies of less than 1 foot (0.3 m) in 20 feet (6.1 m) of scan could be detected by observing where the bands break up. It was noted that, when these bands broke up, a filled-in trench, a pipe, a rock, or some other unknown object occurred beneath the surface.

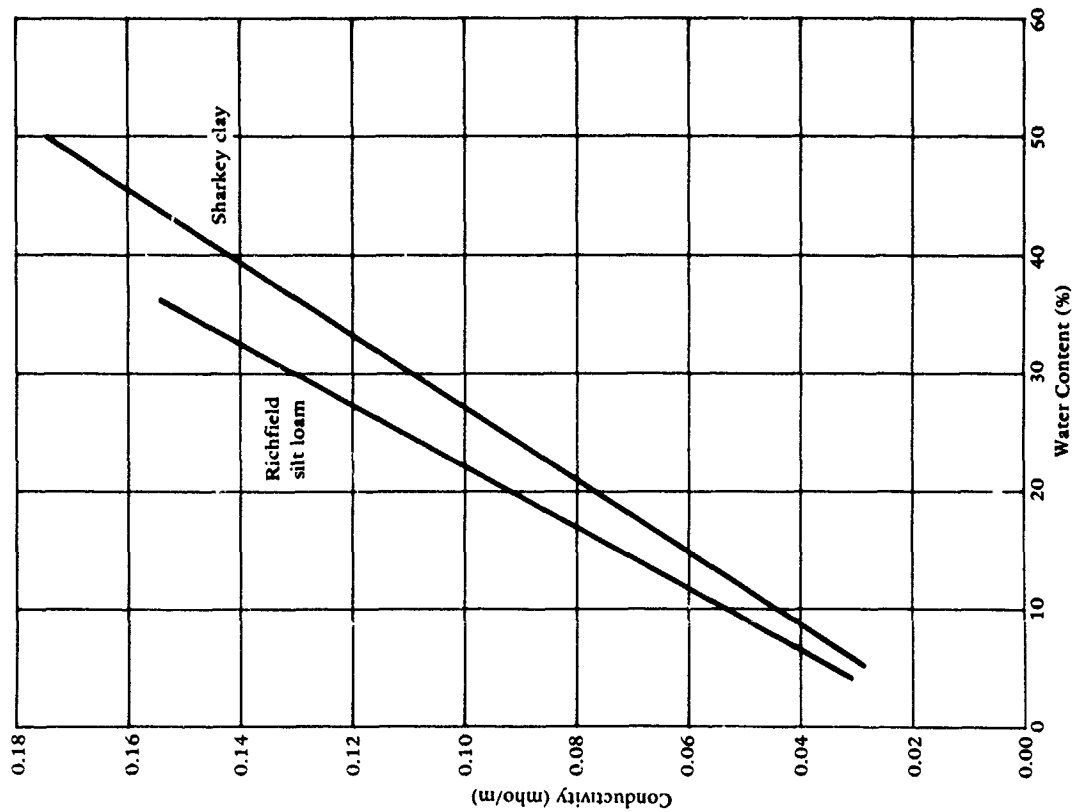


Figure 8. The effect of water content on the conductivity of two specific soils (after Reference 8).

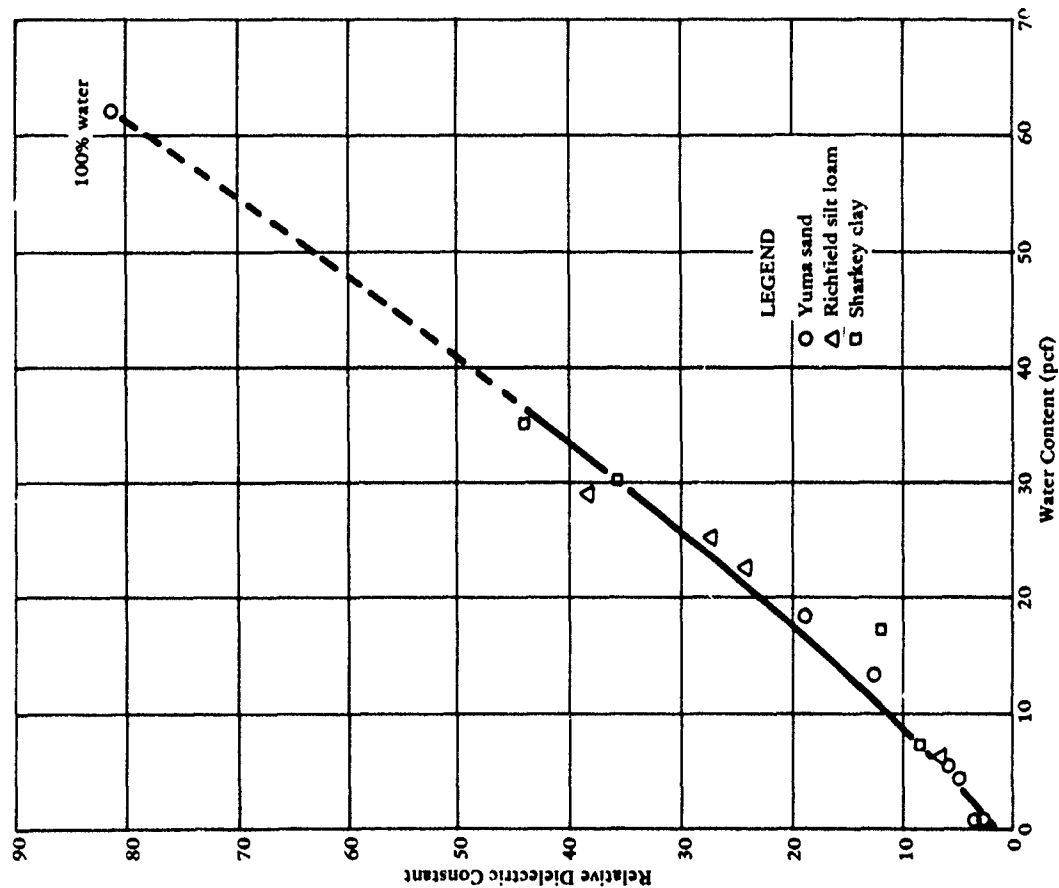


Figure 9. Relative dielectric constant versus water content P-Band 297 MHz (from Reference 8).

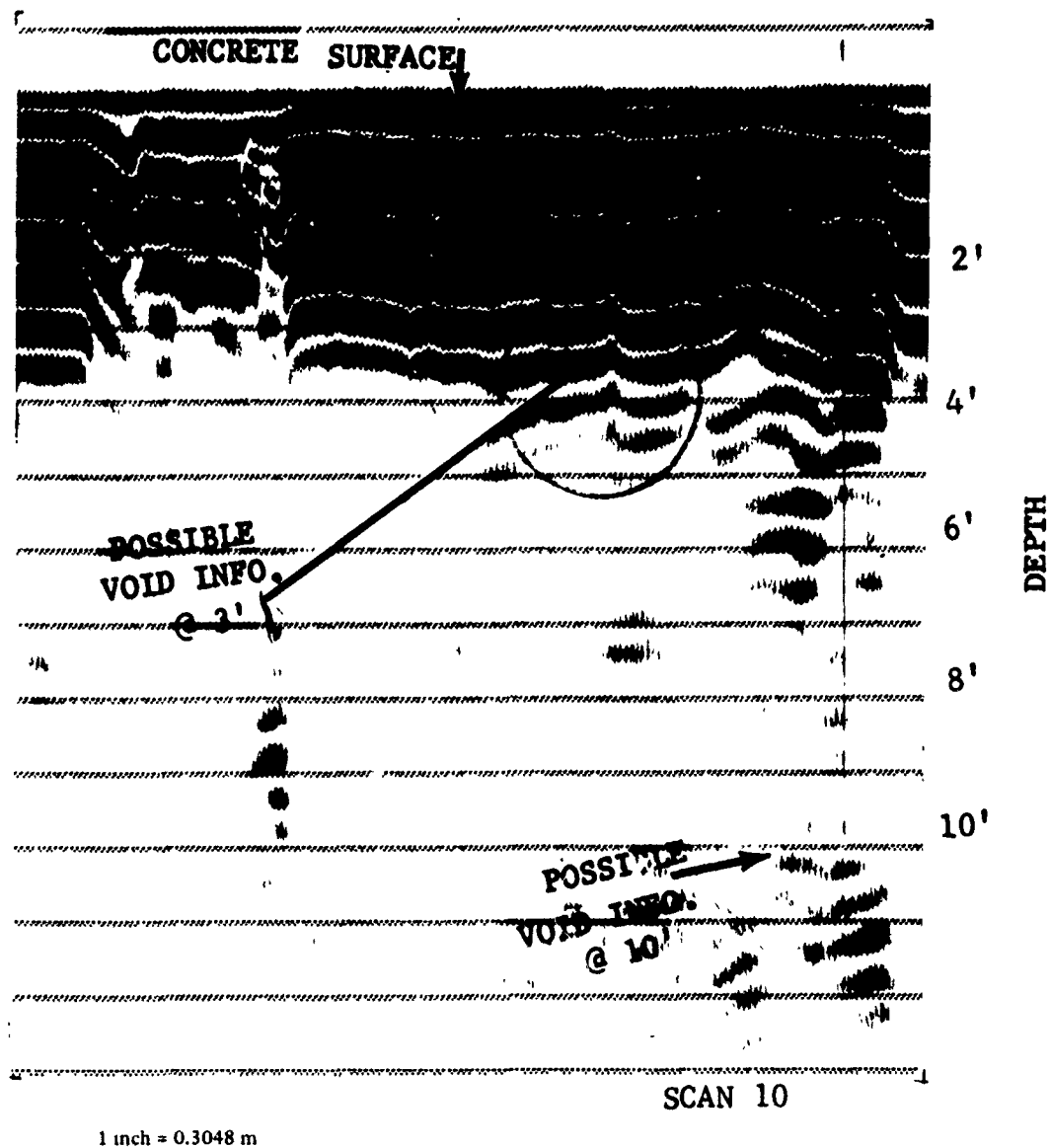


Figure 10. Example of record obtained by electromagnetic profiling at Philidelphia NSY (from Reference 9).

2. Presently, test pits are required to calibrate the radar system with the local soil layers. It is anticipated that with further development of the system using a narrower pulse, computer data analysis, and multilayer theory, the test pits can be eliminated.

3. More advanced development of the system is required before the structure of the upper 2 feet (0.7 m) of a pavement system can be differentiated.

An application of sinusoidal electromagnetic waves to the detection of subsurface voids is presented in Reference 10. Experiments were performed with a vehicular-mounted system operating at 13.4 GHz, 37 GHz, and 94 GHz in an area containing karst features in El Dorado County, California. These experiments showed that subsurface voids beneath several tens of feet (a few tens of meters) of soil cover are recorded as radiometric "cold" anomalies. It was concluded that microwave radiometry does not uniquely identify subsurface voids because of such factors as changes in surface roughness and changes in soil moisture content. However, with information from other geological and geophysical methods, it would be possible to identify these voids.

Earth Resistivity Measurements

Resistivity of a material such as soil is defined as the resistance (ohms) between opposite faces of a unit cube of that material [11]. The units of resistivity are ohms multiplied by length. The measurement of resistivity of a material is illustrated in simplified form in Figure 11. The material is considered to be a semi-infinite solid of uniform resistivity. Four electrodes are inserted into this material at locations A, B, C, and D. The outer electrodes A and B, which are connected to the battery, deliver an electrical current to the solid material. The potential gradient between any two points in the material is measured by a voltmeter attached to the inner electrodes C and D. The resistivity of the material is computed by a simple equation relating the measured quantities of voltage, current, and electrode separation distances.

Figures 12 and 13 illustrate, respectively, the profile and plan view of the current flow paths and equipotential lines in a semi-infinite solid of uniform resistivity, as discussed above. Any deviation in resistivity from the ideally uniform situation will cause changes in the pattern of current flow and, therefore, result in changes in the equipotential lines. Voids located in the material will cause such changes. In application of this method for detecting subsurface voids, the soil is assumed to be idealized as above. Any deviation of the current and equipotential lines is an indication that voids may be present. Air-filled voids will appear as high resistivity anomalies. It is not certain whether water and mud-filled voids appear as high or low resistivity anomalies [12].

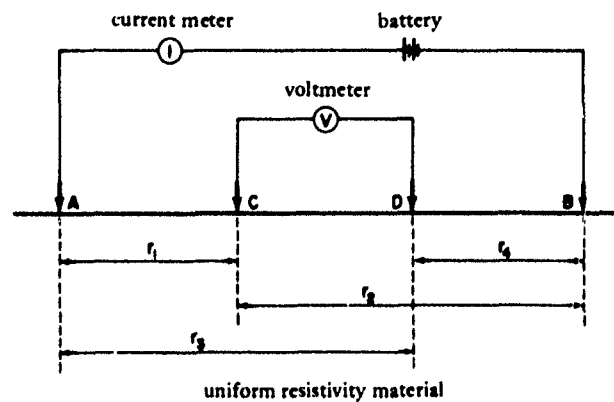


Figure 11. Schematic diagram of a resistivity instrument (©Courtesy of Soiltest, Inc., Evanston, Ill. [11]).

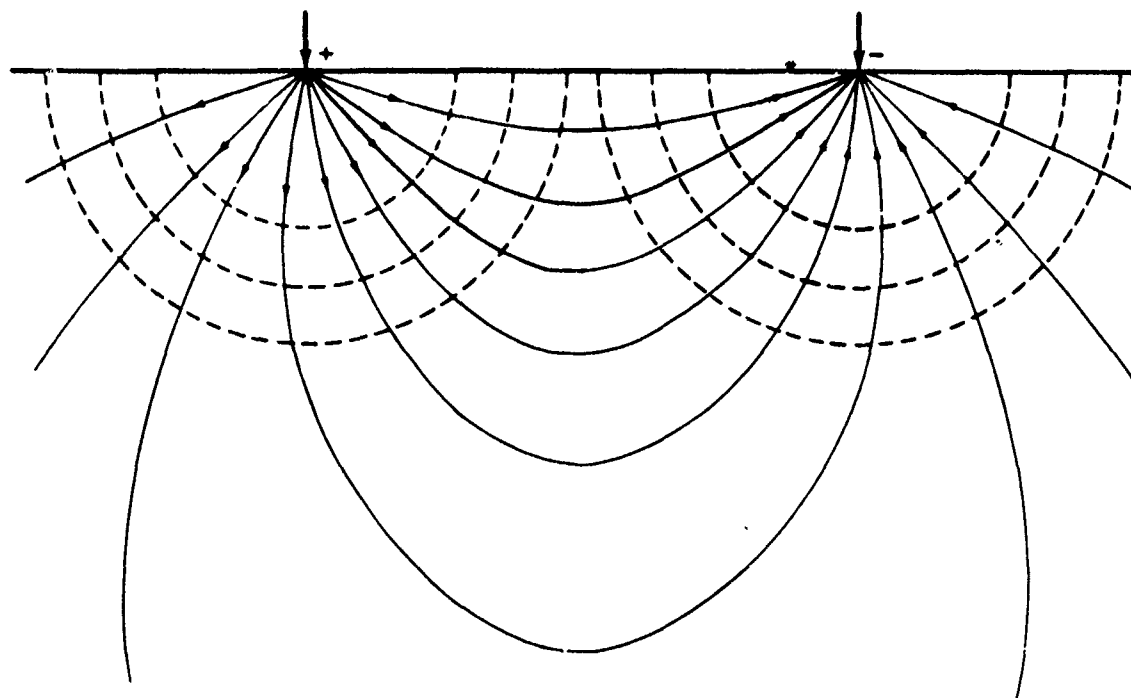


Figure 12. Vertical cross section of an idealized material showing electric field lines (solid lines) and equipotential surfaces (dashed lines) (©Courtesy of Soiltest, Inc., Evanston, Ill. [11]).

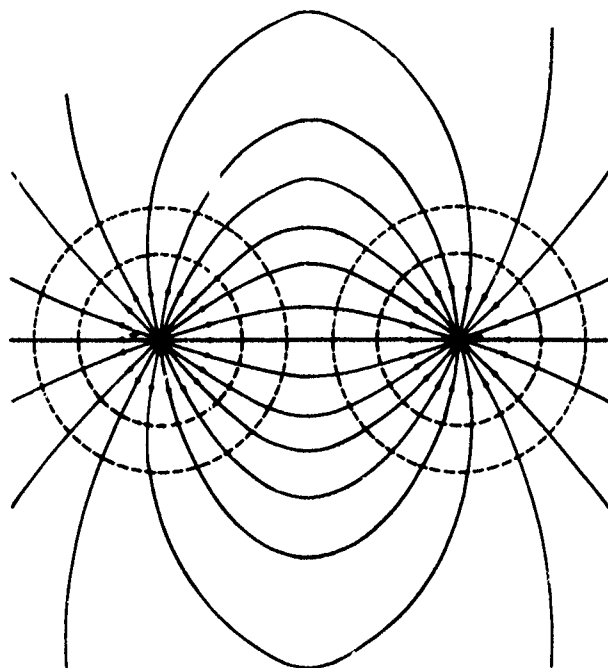


Figure 13. Plan view of an idealized material showing electric field lines (solid lines) and equipotential lines (dashed lines) (©Courtesy of Soiltest, Inc., Evanston, Ill. [11]).

By varying the relative positions of the electrodes, it is possible to perform a horizontal or vertical profile survey of the subsurface material. Some of the common methods used in resistivity surveys include the horizontal Wenner, vertical Schlumberger, and the modified Bristow. According to Bates [12], the modified Bristow method is the most successful for detecting air-filled subsurface cavities. In field tests with this method, air-filled cavities 8 feet (2.4 m) in diameter at depths greater than 100 feet (30 m) were successfully located. This method uses four electrodes, but the current electrode is located at what is effectively infinity (a distance of five to ten times the depth to be surveyed away from the second current electrode). The potential electrodes are kept a constant distance apart while measurements are made along the traverse route on each side of the second current electrode. When the desired survey depth has been completed, the second current electrode is moved a specified distance along the traverse route, and the potential measurements are repeated. The distance the second electrode is moved is such that overlapping data sets are obtained along the traverse route.

The field data are converted to resistivity values using the assumption that the equipotential bowls around the second current electrode are in the form of hemispheres. Although in-situ conditions are generally not homogeneous and anomalies such as the cavities themselves

create heterogeneous conditions, repeated field tests have demonstrated the utility of this assumption. The resistivity values determined based on this assumption and the measured field data are then plotted with respect to distance from the current electrode. Any readings that are considerably higher or lower than a smooth line through the plotted points are identified as anomalies. These anomalies are then plotted on a bar chart similar to the one shown in Figure 14 at the respective location from the electrode during measurements. When all bar charts have been plotted, a graphical technique is used to interpret the data.

Circles of radii equivalent to the distances from the electrode location to either side of each anomaly are then drawn with the center of the circles located at the ground surface in a profile view. The intersection location of all the circles defining a given anomaly is considered to be the location of the anomaly. The size of the anomaly is also identified by the area enclosed by the intersecting circles. Figure 14b shows the solution of a problem by this graphical procedure.

Although the resistivity method has successfully located cavities in field tests, it has not always been successful. Some known air-filled cavities were not detected in the tests in Reference 12. It is also not known how effective this method would be for detecting cavities filled with water or mud.

An application of the earth resistivity method to determine the thicknesses of concrete pavements and the thicknesses of the associated underlying base courses is presented in Reference 13. Both steel-reinforced and unreinforced concrete pavements were examined. Figure 15 summarizes data obtained for a reinforced concrete roadway slab 10 inches (25 cm) thick. The dashed lines represent resistivity versus electrode spacing. The solid straight lines represent the cumulative values of each point on the dashed line with progressive distance away from the central electrode. Note that in addition to an accurate determination of the slab thickness (as compared to the core thickness plotted along the bottom of the figure), the location of the reinforcing steel is also indicated. The thickness of the slab, the location of the reinforcing steel, and other discontinuities in the pavement system occur at the depths where discontinuities occur in the straight line cumulative plot.

Since the earth resistivity method has been successfully used to determine the thicknesses of pavements and underlying base courses, it is possible that this method is applicable to detecting voids beneath the pavement and in the underlying material. Such voids would most likely be identified as high resistivity anomalies (if air-filled) and would show up in a cumulative plot of the resistivity values similar to Figure 15.

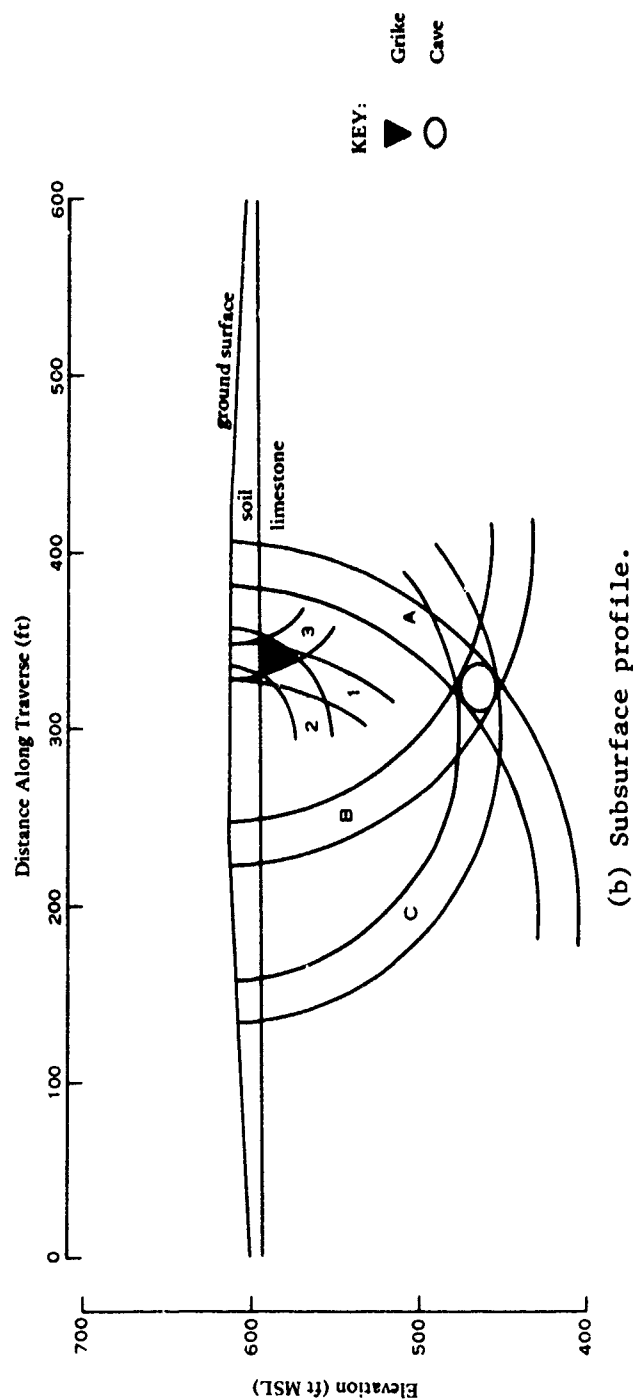
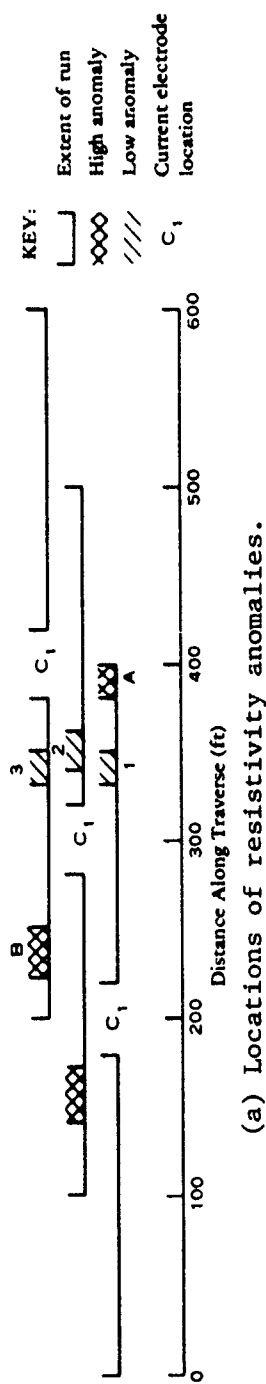


Figure 14. Simplified example of graphical solution for anomaly location (from Reference 12).

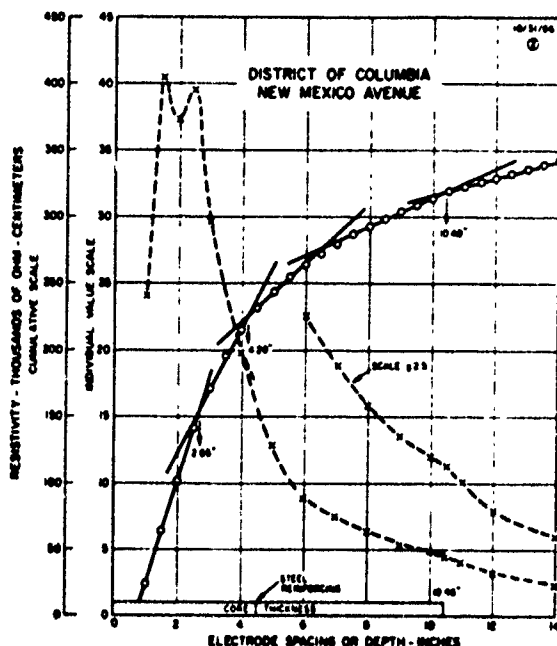


Figure 15. Earth resistivity test over 10-inch-thick (25 cm) reinforced concrete roadway slab (from Reference 13).

Factors affecting resistivity measurements include the following:

- (1) Increasing moisture content decreases resistivity
- (2) Increasing salinity decreases resistivity
- (3) Increasing soil temperature decreases resistivity
- (4) Any material variations, particularly those involving conducting structures, such as fences, railroad tracks and pipes, will cause alterations to the theoretical current flow pattern

Seismic Surveys

The two basic approaches for performing subsurface seismic surveys are seismic reflection profiling and seismic refraction profiling. Both of these methods monitor the time of travel of an induced compressional body wave (P-wave) through the soil medium. Typical wave paths are illustrated in Figure 16 [14]. P-waves are the fastest traveling of the displacement waves and, thus, are the most easily recognized. Subsurface features, such as structural layers and voids, can be detected as anomalies in the records.

The compressional waves can be induced by various sources. These include: conventional explosives, falling weights, sledge hammer-plate impact, mechanical- or gas-operated impactors, vibrators, and electro-mechanical transducers. Because cost, cumbersomeness, and introduction of extraneous signals are minimal with the sledge hammer-plate source, this is the most popular of the above methods.

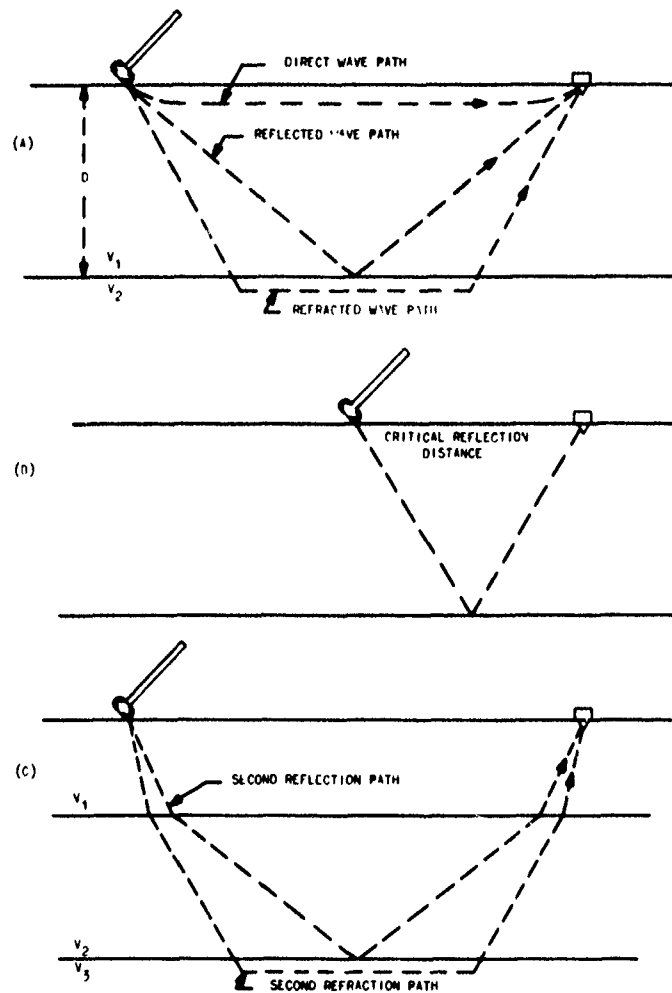


Figure 16. Idealized vertical cross sections through the subsurface to illustrate direct, refracted, and reflected wave paths (©Used by permission. BISON INSTRUMENTS, INC., Dr. Harold M. Mooney [14]).

Geophones are used to monitor the seismic signals travelling through the soil. The geophones are generally placed in a shallow hole such that good coupling is attained with the ground. In areas with rock outcrops, the geophones can be placed directly on the outcrop.

Factors influencing the effectiveness of the seismic approach include (a) vibrations in the ground generated by the wind blowing through trees and other vegetation, (b) noise from nearby traffic and operating machinery, (c) inadequate coupling of the geophone with the ground, and (d) inappropriate assumptions of travel path.

A study performed to determine the feasibility of detecting subterranean tunnels by means of sonic sounding is presented in Reference 15. Detection experiments were performed near known voids including a 2-foot (0.6-m) diameter, 6-foot (1.8-m) deep hole and a 4-foot (1.2-m) high tunnel, 6 feet (1.8 m) by 9 feet (2.7 m) in plan, at a depth of 18 feet (5.5 m). The objectives of this study included the determination of (a) wave velocity in the soil and functional relationships of this velocity with depth, soil moisture, soil composition, frequency, and direction of travel; (b) sonic wave attenuation per unit distance and its dependence upon factors such as those mentioned above; and (c) reflectivity or backscatter properties of tunnels and cavities. Piezoelectric transducers were used both to transmit and receive signals. The waveform chosen was a gated sine wave that confined the transmitted sonic energy to a narrow band of frequencies. The frequency band was adjustable. Bandpass filters were incorporated in the receiving system to reject unwanted noise, i.e., signals with frequency contents outside the transmitting range. The received signals were displayed on a cathode ray oscilloscope.

The following were noted:

(a) The best frequency range for detection of subterranean voids is between 100 and 600 Hertz - below 100 Hertz adequate target resolution is not provided; above 600 Hertz, unacceptable attenuation of the signal results.

(b) The velocity of sound in unsaturated soil is moderately influenced by moisture content; however, moisture does not affect velocity until the degree of saturation is 50% or more.

(c) Sound velocities measured for soils near Falls Church and at Ft. Belvoir, Virginia, were, respectively, about 1,000 ft/sec (300 m/sec) and 1,150 ft/sec (350 m/sec).

(d) The attenuation of longitudinal pressure waves was found to be less than 1 db/ft (3 db/m) at 200 Hertz and increased rapidly to 12 db/ft (36 db/m) at 1,700 Hertz.

(e) The piezoceramic transducers performed effectively, were compact and rugged, and coupled easily to the earth simply by burying them.

(f) Detection experiments near known voids demonstrated the ability to detect reflections that "appeared" to come from the air voids.

The reflection of seismic energy from a subsurface horizon is a function of the amplitude reflection coefficient [16]. This coefficient (for normally incident waves traversing from medium 1 to medium 2) is expressed as:

$$\frac{A_r}{A_i} = R = \frac{V_2 \rho_2 - V_1 \rho_1}{V_2 \rho_2 + V_1 \rho_1} \quad (1)$$

where A_r = amplitude of reflected signal

A_i = amplitude of incident signal

R = reflection coefficient

V_1 = seismic velocity in medium 1

V_2 = seismic velocity in medium 2

ρ_1 = density of medium 1

ρ_2 = density of medium 2

The product of V and ρ is termed the seismic impedance. As the contrast between the seismic impedances of the two media increases, the reflection coefficient also increases. From Equation 1, it can be seen that the amplitude of the reflected wave from the top of the cavity will generally be of greater (absolute) magnitude than that from a horizon between two solid media. Similarly, reflected waves from horizons below a cavity impinging on the underside of the cavity will be reflected downward as in Figure 17 and, thereby, produce a seismic amplitude shadow. Thus, by monitoring these seismic shadows and other seismic reflection amplitude anomalies, it is possible to detect subsurface voids. Such a procedure has been successful in detecting solution-mined salt cavities [16].

Other types of nondestructive testing might be considered within the seismic family, even though they deal with the propagation of other than longitudinal compression waves. These approaches utilize other body waves, such as shear waves [17], or surface waves, such as Rayleigh waves [18]. To date, these techniques have been directed toward determination of material interfaces. These types of displacement waves might be adapted to the problem of void definition. However, they will not be considered further herein.

Load-Deflection Methods

Load-deflection methods, which are used primarily in pavement evaluation include both static and dynamic tests. The static method most commonly used is the plate-bearing test. In this method, plates of various sizes are loaded quasistatically, and the resulting deflections are measured. Plots of load-versus-deflection are made. By assessing the characteristics of the plotted data, it is possible to make an evaluation of the quality of the pavement system and determine if any defects are present.

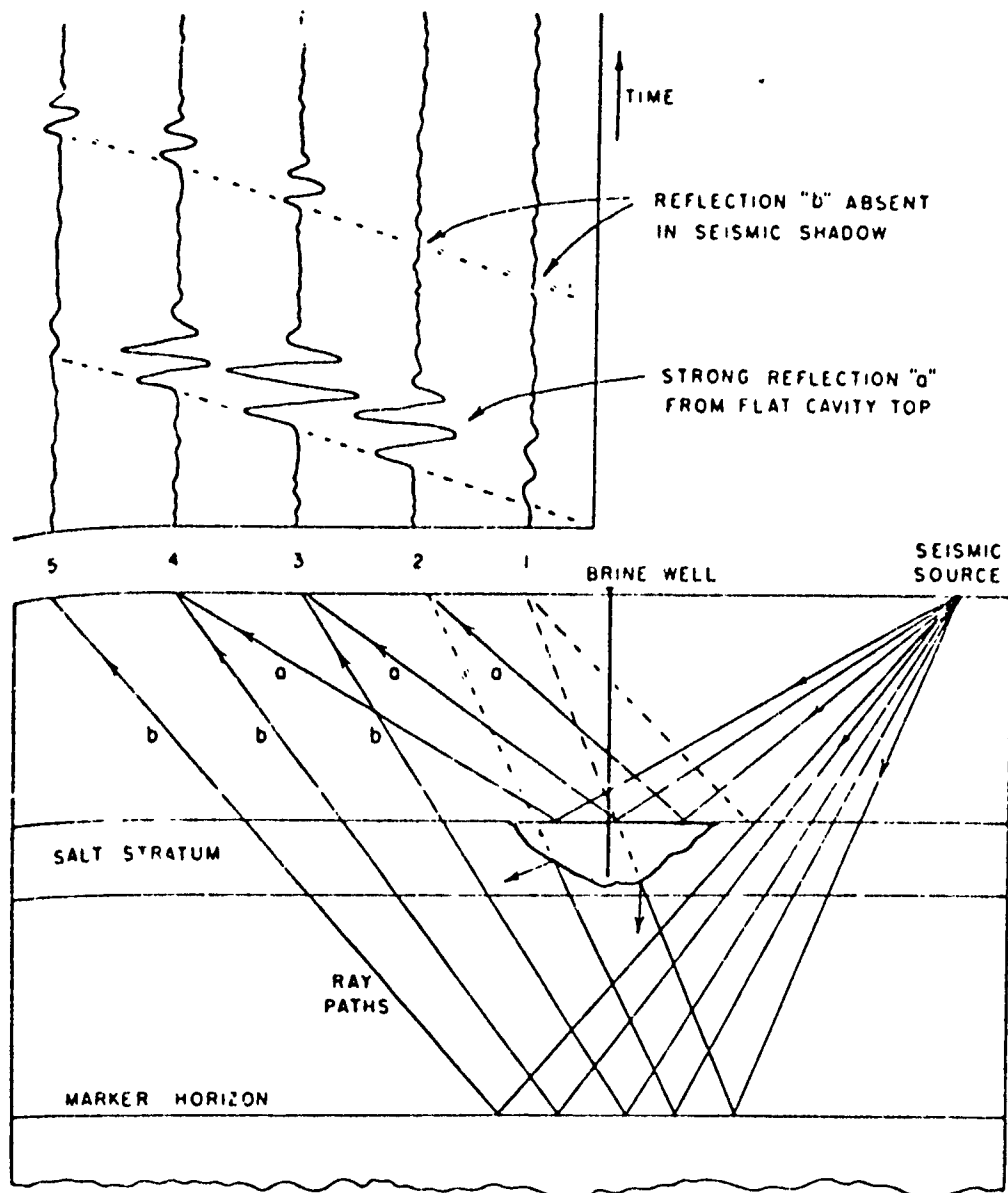


Figure 17. Idealized seismogram and solution cavity showing expected results (©Used by permission. Society of Exploration Geophysicists, J. C. Cook [16]).

An example of the dynamic test method is described in References 19 and 20. The equipment described therein evaluates a pavement system by monitoring the dynamic surface deflections of the pavement system under steady-state vibratory loadings. This particular equipment is capable of exerting a static load of 16 kips (71 kN) and of applying vibratory loadings with a frequency of 15 Hertz over an amplitude range of 0 to 15 kips (67 kN). The test loadings are applied to the pavement through an 18-inch (457-mm) diameter steel plate. Load cells and velocity transducers are used to monitor the test. Deflection is obtained by integrating the velocity record. The complete testing system is mounted in a readily transportable tractor-trailer unit. A test at each location can be performed by this unit in 2 to 4 minutes. Plots of dynamic load versus deflection basin are obtained by this method. Equipment capable of exerting various levels of applied load over different ranges of frequency has been developed by others.

A nondestructive dynamic testing method used in an investigation of the airfield runway on San Nicolas Island (NOLF San Nicolas), is described in Reference 21. The major objective of this investigation was to determine if subsurface cavities due to underground piping existed beneath the runway at depths shallow enough to impair the load-bearing capacity of the structure. Dynamic deflections and the slopes of the basins created by the loading plate were measured. These data were then separately plotted and contoured to prepare isodeflection and deflection basin slope maps. Areas on these maps in which large deflections and slopes occurred could be interpreted as containing possible defects either in the pavement system itself or in the underlying soil.

Thus, the load-deflection method can be used to define areas of possible subsurface voids through assessment of the load-deflection behavior of the pavement system. The confirmation of such voids still requires some form of direct augering or coring. Thus, load-deflection methods can be relatively rapid, but they are unable to differentiate between the effects of possible voids and other defects in the pavement system.

Nuclear Detection

Detection of underground voids by nuclear techniques is not routinely done except, possibly, in borehole logging. Detection of density anomalies is very limited because of the relatively shallow penetration of nuclear radiation. Void detection would, in general, have to use a surface sensor, and success would depend primarily on its ability to discriminate intensity variations in the backscattered radiation. Nuclear backscatter would be the result, mainly, of interaction with silicon atoms. Because of accuracy and sensitivity limitations on practical nuclear detectors, void detection is not feasible if the round-trip attenuation exceeds 30 dB, i.e., where the ratio of received to incident radiation is less than 0.1% [4]. For practical radiation sources located at the surface, the effectiveness of nuclear techniques is limited to depths of about 18 inches (457 mm).

An artificial source of radiation is required because of the absence of natural radioactivity at levels large enough to make void detection possible. The basic procedure is to differentiate between two signals that differ in number of counts*. Utilization of natural soil radioactivity would mean differentiation between zero counts (void) and a very small number of counts (no void). Practical nuclear methods cannot sense such small differences without making the measurement time unreasonably long or the signal processing equipment unreasonably expensive.

For voids at depths down to about 18 inches (457 mm), x-rays or gamma rays could be used. In systems that both generate and detect photons, the backscattered radiation would be the result of Rayleigh, Compton, or fluorescence scattering [4, 22]. Of these three types of scattering, Compton scattering would be the only one having a large enough count number to be of practical use [22]. Although, in principle, voids could be detected by photoneutron backscatter, the energy of the source gamma rays would have to be in the neighborhood of 10 Mev (10^7 electron-volts). The machinery required to produce such energies is too large and heavy for convenient use in the field.

Incident neutrons could also be used to detect underground voids, but the depth limitation is even more severe than with incident photons. 14-Mev neutrons will produce backscattered gamma rays (1.78 Mev) in silicon. However, for voids deeper than about 6 inches (150 mm), the high activation of silicon near the surface will mask the return radiation from the silicon at greater depths [23]. If the top of the void is covered by 3 inches (75 mm) or less of earth, it can be detected by 14-Mev neutrons provided that the source strength is around 10^{10} neutrons/second. Unfortunately, a portable, relatively safe source of 14-Mev neutrons having the required strength is not within the state of the art.

The size of underground voids detectable by incident photons or neutrons is a function of the total irradiated volume of earth and the number of received counts. Under the assumption that the signal should be at least twice the measurement uncertainty, it can be shown that the volume of the void is given by

$$V_o = 2 \sqrt{2} \frac{V_T}{\sqrt{M}}$$

where the signal is equal to the quantity, $M-N$; M is the counts from the total irradiated volume, V_T ; N is the counts from the same volume containing a void of volume, V_o . The measurement uncertainty is assumed to be $\sqrt{M+N}$.

The following example illustrates the application of the above equation:

$$V_T = 1 \text{ ft}^3 (0.028 \text{ m}^3)$$

$$M = 10^4 \text{ counts, produced by 1.78 gamma rays from silicon irradiated by 14-Mev neutrons with a counting time of 1 minute}$$

* In nuclear detection the observed quantity is counts; the optical analogy is intensity (watts/cm²).

$$V_o = 48.9 \text{ in.}^3 \text{ (801 cm}^3\text{)}$$

This represents an idealized situation, and, as stated above, would require a neutron source not easily adapted to field use.

In conclusion, it can be stated that nuclear detection of underground voids is not feasible for depths beyond 1.5 feet (0.5 m). Even at shallower depths nuclear techniques still require hard-to-handle, possibly hazardous equipment. Detection probability will be marginal and depth resolution low, probably not better than one foot (0.3 m). Also, scanning speeds will be low (e.g., as predicted in Reference 23, about 7 ft/hr (0.6 mm/sec) along a 12-foot (3.6-m) wide path).

Acoustic Holography

Acoustic holography is a recently developed technology, the major applications of which, at the present time, are in the fields of medical diagnosis and nondestructive testing of materials. The basic function of acoustic holography is to permit looking inside an optically opaque material and to generate a three-dimensional image for televising, photographing, or direct viewing. The three-D imaging capability of acoustic holography represents one of the main practical differences between this technique and x-ray techniques, which produce a two-dimensional shadow of the object under scrutiny. Another important distinction is the fact that, in acoustic holography, the transmitter and receiver can be on the same side of the target.

Acoustic holography works the same as optical holography in that the diffracted acoustic wave from an acoustically irradiated target is superimposed on a coherent reference wave, and the result is recorded in the hologram domain. The hologram may be a surface or a volume. The most common type of hologram is a plane surface; the interacting reference and diffracted waves produce intensity variations over this surface, which can be recorded as density changes in a photographic film. Irradiation of this type of hologram with coherent light (as from a laser) creates a distorted image of the target in the optical system of camera or eye. The unique feature of a hologram is that it preserves phase as well as amplitude information contained in the resultant wave produced by the target and reference wave. For large underground formations, the hologram plane could be at ground level and could consist of an array of hydrophones; phase and amplitude information would be recorded digitally on tape.

The holographic detection of voids in metallic materials is done routinely as part of quality-control testing. The acoustic frequencies are in the order of a few megahertz, and the voids have dimensions on the order of millimeters and are located at depths not greater than about 0.3 meter [24, 25]. As yet, an acoustic holography system is not available for the routine detection of underground voids having dimensions of the order of centimeters or meters. It might be possible to detect millimeter-size, underground voids using the same equipment for detecting voids in metals, but the information would probably have engineering

value only in rare cases, e.g., pavement examination. Furthermore, metal-flaw detectors might not be able to distinguish between holes in the ground and small pieces of rock. Finally, metal-flaw equipment might detect nothing at all, since they are designed to sense acoustic impedance changes resulting from a metal/air interface and not those caused by a soil/air interface, which, in general, would be smaller.

Holographic detection of relatively large voids under the ground, i.e., a few cubic inches (several cubic centimeters) up to thousands of cubic feet (hundreds to thousands of cubic meters), would be a matter of having the correct wave length, signal strength, aperture size, and signal-processing system. Concepts for the application of acoustic holography to underground density anomalies are described in References 26, 27, and 28. These papers, however, address the problems of examining fairly large formations such as oil reservoirs and ore bodies.

An acoustic holography system for detecting and making measurements on subsurface voids of the order of one cubic foot (0.028 m^3) at depths up to a few feet (approximately 2 to 3 m) could utilize a single, small-diameter source of acoustic waves, having a frequency between 100 kHz and 1 MHz. The source would be at ground level and coupled acoustically to the soil by means of a suitable liquid (e.g., water) contained in a shallow, open-bottom tank pressed against the ground. The receiving aperture could also be at ground level and consist of either a static, plane array of acoustic sensors or a single sensor attached to a mechanical surface-scanning system. The receiving aperture need not be larger than about 10 square feet (0.9 m^2). It could be coupled to the ground in the same way as the source. The reference wave could be fed to the receiver system by surface waves traveling directly from the source; also, an internal reference could be used, i.e., superposition of a coherent signal onto the received signals by electronics alone.

Real-time visualization of an underground void would require fairly complex electronics and optics. Two problems in acoustic holography are: (1) measurement of the depth of the target, and (2) elimination of the large depth distortion that occurs when a visual image is constructed by irradiation of the acoustic hologram with visible light. Various methods [24, 25] have yielded solutions to these problems; but, in general, these methods are complicated and expensive.

To summarize, an acoustic holography system could be built for detecting, measuring, and visualizing underground voids of the size and depth range of interest to the construction engineer. The system would be expensive, and, for depth and size determination, would consume relatively long time periods, possibly an hour for every 100 square feet (9 m^2) of ground surface. The main advantages would be good resolution, probably an inch (2.5 cm) or so laterally and a few inches (several cm) vertically, and relatively short time periods (minutes) to confirm the existence of the void.

DISCUSSION

Of the void-detection methods discussed in this report no single method appears to be superior in all respects. The choice of method must depend upon the type of soil, the type and geometry of the ground surface, available information (e.g., data from previously drilled boreholes), the requirements of the structure, and the logistics of performing the survey.

Type of soil is a major factor controlling choice of void detection method. Because of this a certain amount of preliminary soil information is desirable, either from indirect techniques or from soil boring, etc. For example, the detection and measurement of voids in rock or extremely dry soil can be more efficiently accomplished with seismic or radar methods than with resistivity methods. Alternatively, if the soil is wet, resistivity methods would probably be the most effective, provided the soil was not covered by pavement, thereby making the insertion of ground rods (contact with the ground) difficult.

The geometry of the ground surface can affect the logistics of the survey. For example, the slope or topography may be such as to prevent transport of equipment from one measurement point to another. Pronounced surface outcroppings will probably eliminate the gravity method as a possible choice if it has not already been eliminated by other considerations.

If boreholes already exist, the detection of voids may be facilitated by use of direct as well as reflected signals. If the reflected signals - acoustic, radar, or nuclear - indicate the possibility of a subsurface void, and if there is an existing borehole in the vicinity, the void location may be verified by lowering the signal source into the hole and positioning the surface detector in line with the source and the void. The borehole could, similarly, be used to confirm the existence of the void by the resistivity method. Interception of the void by a straight line current path, between surface electrode and a subsurface electrode, would produce a considerably larger effect than with both electrodes at the surface.

The earth resistivity method requires relatively unsophisticated equipment and, at the same time, is sensitive to voids in the size range of concern to this study. Basically, all that is needed is a source of well-regulated direct current, a highly sensitive DC voltmeter, and a set of pointed metallic rods - all of which are readily available from commercial suppliers. The objection to this method is the considerable time that may be required to conduct the survey and to process the data. One factor that consumes survey time is the requirement of a good electrical connection to the earth.

In looking for voids underneath pavement it would probably be necessary to drill through the pavement at every point where a ground rod is needed. Data processing time would be long, because the resistivity method, like the gravity method and magnetic method, is dependent on a field effect, i.e., a change in a certain type of physical field, in this case, a potential field, that occupies a relatively large volume

(compared to the void). Radar and acoustic methods, on the other hand, depend on a change at a single point or relatively small region in space. The radar and acoustic methods utilize directed energy, and, in principle, the reflecting point or small region can be localized by triangulation. Field effects, in general, require a mapping (measurement at many positions), to localize the cause of the change in observed quantity.

A quantitative relationship for the observed change in earth resistivity resulting from an underground void may be derived from the following theoretical expression for resistance between ground rods as a function of void radius and depth:

$$R_1/R_0 = 1 + (r_0/r)^3$$

where R_1 is the resistance with the void present, R_0 is the resistance with the void absent and r_0 and r are the void radius and depth, respectively. The above equation assumes a spherical void and uniform current flow at large distances from the void. Thus, for a radius-to-depth ratio of less than about 0.2, the observed change in resistance would be less than 1%.

An expression similar to the above equation gives the observed change in magnetic field resulting from the presence of a spherical void:

$$H_1/H_0 = 1 - \left[\frac{\mu-1}{\mu+1} \right] (r_0/r)^3$$

where H_1 and H_0 are the observed magnetic fields with and without the void, respectively and μ is the ratio of the magnetic permeability of the soil to that of air. This relationship shows that the magnetic field effect is about 75% of the earth-resistivity effect, provided that the magnetic permeability of the soil is at least ten times that of the air. Only in very exceptional cases, however, does the soil have a magnetic permeability this large; hence, the magnetic method would rarely prove satisfactory.

To compare the resistivity and magnetic methods to the gravity method, the following expression, having the same form as that of the previous two equations, can be used:

$$F_1/F_0 = 1 - (4\pi G \rho_2/3g)(r_0/r)^3(r)$$

where F_1 and F_0 are the gravity forces with and without the void, respectively g is the acceleration of gravity (cm/sec^2), and the other parameters are in cgs_3 units and have previously been defined. Thus, for soil of 2.7 gm/cm^3 density, the factor $4\pi G \rho_2/3g$ equals 7.7×10^{-10} . The above equation clearly shows that the gravity-field effect is several orders of magnitude smaller than the resistivity effect for void sizes and depths in the range* of interest to this study.

* Because of r^2 in the denominator, instead of r^3 , as in the previous equations, the second term in the above equation could be made much larger by making r_0 and r unrealistically large. However, this would require considering void sizes and depths well outside the range of practical problems.

Realistic comparison of two measurement techniques requires not only equations giving the dependence of the observed quantity on the measured parameters, but also knowledge of noise levels and bandwidths accompanying the measurements. The functional relationship between the earth resistance ratio, R_1/R_0 , and the void radius-to-depth ratio, r_0/r , is of purely academic interest if the measurement technique does not provide adequate cancellation of background noise on performing the calculation of R_1 divided by R_0 . Fortunately, state-of-the-art electronic filtering techniques will usually provide the required suppression of noise effects. Thus, reliable measurement of R_1/R_0 may be obtained even though the amplitude of the data current between ground rods is equal to or even slightly less than the amplitude of the noise current.

In applying the earth resistivity method to the detection of underground voids, a practical upper limit on voltage is about 100 volts, and a practical lower limit on current is about 10^{-13} ampere. Therefore, the upper limit on R_1 is about 10^5 ohms. For a practical ground-rod radius of 3 cm, the upper limit on earth resistivity* would be 10^6 ohm-cm, which is the resistivity of dry sand. Actually, a ground resistivity of 10^6 ohm-cm would strain the noise suppression capability of the measurement system for void radius-to-depth ratios less than 0.1 so that a more realistic upper limit on soil resistivity would be 10^5 ohm-cm, which is the resistivity of shales, sandstones, and clays. For soils having a resistivity greater than 10^5 ohm-cm or where resistivity anomalies not caused by voids are suspected, the earth resistivity method should not be used.

Void-detection methods that utilize either radar or acoustic signals measure the travel time of the signal to the void and back. Radar techniques that measure phase are not sufficiently developed for consideration as methods of detecting voids. Acoustic techniques that utilize phase information from the target are classified as holographic techniques, which, at the present time, are used only in the detection of millimeter-size voids in metals. Acoustic methods of underground void detection are called seismic methods, and the phase of the signals is utilized only insofar as is required to form the beam of radiated energy.

Soil-penetrating radar can detect and measure void depth simultaneously only if a single void is present, surface-to-source impedance is relatively low or its effect can be time-gated out, and the soil is sufficiently homogeneous to prevent too much background clutter. This ideal situation rarely occurs, and it will probably be necessary in most cases to supplement the radar method with a seismic method. The main advantage of radar and seismic methods is that they don't require the stringent physical connection to the earth required by the earth-resistivity methods (although acoustic holography methods would). This advantage is somewhat negated in the requirement for complex electronic circuitry and special energy sources.

Obtaining a quantitative relationship between received signal and void parameters is not as easy for radar and acoustic methods as it is for the field-effect methods based upon resistivity, magnetism, and gravity. The void detection process involves a reflection of energy at

* $R_0 = (k_0/\pi) \{ (1/a) - (1/L) \}$, where k_0 is resistivity (ohm-cm), a is ground rod radius (cm), and L is the distance between rods (cm).

a soil/air interface; this reflection, in turn, is a function of bulk soil characteristics, microtopography of the void wall, and the frequency and angle of incidence of the radar or acoustic wave. The level of the received signal is further dependent on the bulk absorption and scattering of energy occurring between the underground void and the ground surface.

A general expression for reflectance is given by:

$$R = (n_1 - n_0)/(n_1 + n_0)$$

where, for radar, n_1 and n_0 are electromagnetic indices of refraction for soil and air, respectively; and, for acoustics, they are the products of density and sound velocity for soil and air, respectively.

Acoustic reflectance at a soil/air interface is near unity; hence, reflected energy would be about 100% of incident energy. The problem is that the interface is usually not specular, so that the reflected energy is spread out over a hemisphere, and only a fraction is received by the measurement system. Radar reflectance is generally lower than acoustic reflectance. For example, at radar frequencies above 1 MHz, planewave reflectance varies from about 0.2 at 0-degree incidence to 0.6 at 75-degree incidence.

Acoustic absorption coefficients for soil are given in the literature as empirical functions of the frequency. Typical absorption coefficients are $(1.2 \times 10^{-4}) f$ dB/ft (dB/0.3 m) for shale, and $1.2 + (0.002) f$ dB/ft (dB/0.3 m) for clay, where f is frequency, (Hz). Thus, at 10 kHz and a round trip of 25 feet in shale, the loss is 30 dB, i.e., a received signal of 0.1% relative to the source signal, provided reflectance is 1.0 and the void/air interface is specular.

Radar absorption is proportional to the penetration depth, δ , which, in turn, is expressed by relatively simple equations derived from theory:

$$\delta = (1/\pi f \mu \sigma)^{1/2} \text{ meters, if } \sigma^2/4\pi^2 f^2 \epsilon^2 \gg 1$$

and

$$\delta = (2/\sigma)(\epsilon/\mu)^{1/2} \text{ meters, if } \sigma^2/4\pi^2 f^2 \epsilon^2 \ll 1$$

where f is frequency (Hz), σ is soil conductivity (mho/m), μ is magnetic permeability (H/m), and ϵ is dielectric constant, (F/m). For example, if σ is 10^{-3} mho/m (shale), and f is 100 MHz, then the second of the above formulas applies, and δ is a little over 5 meters or about 17 feet. This means that, at a depth of about 17 feet, the radar wave amplitude will be about $1/\epsilon$ (0.37) of the source amplitude.

The problem with both acoustic and radar waves, as can be seen from the above equations, is that a low absorption must be accompanied by a poor resolution. This is because the only way to decrease absorption (or increase the penetration) is to lower the frequency, and, unfortunately, resolution varies inversely as the frequency. For example, in the case of a 100-MHz radar wave, the wavelength in shale would be close to 10 feet

(3 m), and, hence, depth resolution would be about 3 feet (1 m) (around a quarter of the wavelength). Void detection would probably be possible at three times the penetration of the depths of the preceding example, or about 50 feet (15 m).

Again, as with the field methods of void detection, realistic comparison of radar and acoustic methods requires knowledge of noise levels. A useful relationship involving the signal-to-noise ratio is the equation for travel-time uncertainty:

$$\sigma_t = \frac{1}{\Delta f \sqrt{2E/N}} \text{ seconds}$$

where σ_t is the random error in travel-time measurement, Δf is the frequency bandwidth (Hz) of the receiver, and E/N is the signal-to-noise ratio. This equation is used in system design, and it yields the range error, $\sigma_t V$, where V is the wave velocity. The range error must be combined with the range resolution before overall system accuracy can be predicted. The important tradeoff in the above equation is contained in the dependence of noise level, N , on Δf . Thus, efforts to decrease σ_t by increasing Δf can only go so far because more noise is admitted to the receiver as Δf increases. In an acoustic system where a typical value of Δf is 10^3 Hertz the value of E/N must be around 50 to get σ_t equal to 10^{-4} second, which yields a range error of about 1 foot (0.3 m) in most soils.

CONCLUSIONS

1. There is clearly no one nondestructive method capable of accurately locating and defining voids in all situations of interest.
2. Magnetic intensity measurements are not adequate for defining voids except in those exceedingly rare situations where the magnetic permeability of the soil is about ten times that of air.
3. Gravity methods are not considered appropriate for locating voids within the range of interest for this study. This conclusion is based upon problems associated with electronic filtering, mechanical stabilization, delicacy of required measuring devices, and need for complicated data processing.
4. Nuclear detection methods are not feasible for investigating voids located more than a foot (0.3 m) below the surface due to the requirement for hazardous, difficult-to-handle equipment.
5. Load-deflection methods can be used to investigate the load-carrying competence of specific sites, but they give no specific data on void size or location. The static load method is generally very slow and can be excessively expensive. The dynamic load-deflection method requires relatively complex instrumentation, but it can provide a valuable supplementary technique when used along with another method or methods.

6. Acoustic holography, at the present time, does not have commercially available equipment for underground void detection of the size of concern to this study. However, this method shows promise of being developed to the point where it would be better than any other non-destructive method available. A major restraint may be that liquid coupling will be essential between ground surface and the transducers. The principal attractions of this method will be: good resolution in real time, three-dimensional viewing, real-time visualization of the void, and accurate depth determination. The first two advantages could be obtained with current state-of-the-art components. The third advantage, accurate depth determination, will require further development of integrated-optics computers to permit near-real-time depth determination.

7. The most promising approach to void detection and definition at the present time appears to be one or a combination of the three methods: (a) earth resistivity, (b) seismic methods, and (c) subsurface radar or electromagnetic waves. These three methods offer varying degrees of void definition, depending upon the specific circumstances. Unfortunately, it is not clear in advance the degree of success that can be obtained at a particular site with each of these three methods. They all require essentially different types of specialized equipment and instrumentation; nevertheless, they can be relatively rapid and are economically justifiable for use in those situations for which they are best suited.

RECOMMENDATIONS

A detailed analysis of void detection methods based upon earth-resistivity, seismic methods, and subsurface radar should be conducted. This study would provide:

1. The degree of accuracy and the reliability to be offered by each of the three detection methods for any designated site
2. A cost analysis for each of the various techniques at a specific site
3. A cost effectiveness study to determine the merits of obtaining void investigations by contract or by developing Navy in-house capabilities.

If it should be decided that the present state-of-the-art of non-destructive void detection does not satisfy current Navy requirements, the following studies could be initiated:

1. An experimental investigation at CEL for developing methods of rapidly inserting and establishing good electrical contact of ground rods for use in the detection of voids by means of the earth resistivity method.

2. An acoustic holography system designed and built under contract for the detection and visual display of underground voids in the size range of a few cubic inches (several cubic centimeters) up to several cubic feet (few cubic meters) at depths up to 50 feet. The hologram unit should be about 10 by 10 feet (3 m x 3 m) and consist of a shallow tank, with no bottom, capable of being raised and lowered and rapidly filled with water for coupling acoustic transducers to the ground surface.

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