ARO 24600.1-EG

(7)

BURIED OBJECT DETECTION

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Institute for Technology Development
Turning ideas into innovations

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Final Report

19 January 1987

Army Research Office

Contract No. DAAL03-87-K-0052

National Center for Physical Acoustics
P. O. Box 847
University, MS 38677

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SECURITY CLASSIFICATION OF THIS PAGE

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 24600.1-EG
6a. NAME OF PERFORMING ORGANIZATION Institute for Technology Development 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office
6c. ADDRESS (City, State, and ZIP Code) 700 North State Street; Suite 500 Jackson, MS 39202	7b. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U. S. Army Research Office 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAL03-87-K-0052
8c. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Buried Object Detection

12. PERSONAL AUTHOR(S)
James M. Sabatier and Kenneth E. Gilbert

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 4/15/87 TO 4/14/88	January 22, 1988	18

16. SUPPLEMENTARY NOTATION
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Acoustic, Seismic, Acoustic seismic coupling, porefluid, pulse echo, propagation, soils, sound speed, attenuation, buried objects, detection

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

When an airborne sound wave strikes the surface of the ground it reflects but also transmits as a pore-fluid wave and seismic body waves. The pore-fluid wave travels in the pores and through viscous drag as the pore walls transfer energy to the frame or soil matrix. As a consequence, this wave is highly attenuated and travels with a slow phase speed (100 dB/m, 10 m/s at 100 Hz) and is the source of seismic waves in the soil. Because the ground is weathered or layered (depths of tens of centimeters to meters) interferences between down and up going wave setup the steady-state interference minima and maxima that one observes in the seismic transfer function.

An acoustic scheme for buried object detection is thought to involve a sound source above the ground and a microphone as a receiver. In the simplest scenario, an airborne acoustic pulse would be transmitted, strike the ground surface, propagate through the pores and reflect off the surface of a non-porous object. The microphone would then be used to detect the pore-fluid echo. These ideas were first considered in a sound tube with spherical beads

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

used as the porous medium. Experimental measurements of the pore-fluid propagation constants were compared to rigid framed model calculations for model verification. These experimental and theoretical results were then used to make predictions of the sound levels required to detect objects buried a few centimeters in outdoor soils. In addition, we chose a detection criteria which required that the pore-fluid echo be at least ½ cycle behind the pulse reflected from the ground surface. This criteria is quite arbitrary and conservative, but it allows for source specifications and from an experimental point of view appears as a realistic criteria for detection.

The models allowed for prediction of reflection losses, propagation losses, phase velocities and source levels based on burial depths of a few centimeters. Using these calculations various off-the-shelf acoustic sources were considered and it was realized that none were available to use existing sound sources to demonstrate that non-porous objects could be detected a few centimeters below the surface of institutional or grass soils. Research to develop a sound source which meets the original design criteria is on-going.

With modifications to off-the-shelf drivers, we were able to demonstrate that objects buried a few centimeters below the surface of a typical outdoor soil could be detected.

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BURIED OBJECT DETECTION

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The experimental work described in this report was perfomred by Dr. James M. Sabatier. The effort was administered and reviewed by Dr. Kenneth E. Gilbert. Questions concerning the technical content of the report should be addressed to Dr. Sabatier. Administrative questions should be directed to Dr. Gilbert.

BURIED OBJECT DETECTION

1.0 INTRODUCTION

Research at the University of Mississippi (UM) and the Institute for Technology Development (ITD) in the area of acoustic-to-seismic (A/S) coupling has been on going for several years.[1] The initial A/S coupling work was carried out between UM and the United States Army Waterways Experiment Station (WES).[2,3] More recently, through the support of the Army Research Office, models have been developed [4,5,6,7] which have been used to explain this interaction of sound with the ground. WES has continued to support a research effort in A/S coupling at UM and for over the past years we have come to understand the interaction of sound with the ground.

When an airborne sound wave strikes the surface of the ground it reflects but also transmits as a pore-fluid wave and seismic body waves. The pore-fluid wave travels in the pores and through viscous drag as the pore walls transfer energy to the frame or soil matrix. As a consequence, this wave is highly attenuated and travels with a slow phase spaced (100 dB/m, 10m/s at 100Hz) and is the source of seismic waves in the soil. Because the ground is weathered or layered (depths of tens of centimeters to meters) interferences between down and up going waves setup the steady-state interference minima and maxima that one observes in the seismic transfer function.[6,7]

The research effort in buried object detection came about because of continued association with WES. Models which had been developed to understand and make predictions concerning A/S coupling were also used to make predictions concerning the detection of buried objects. As a consequence, we developed a three-phase effort related to buried object detection: surface seismic measurements using geophones, remote seismic measurements using a laser velocimeter and pore-fluid echoes. The latter of these three is the subject of this report. On going work in the other two areas has progressed rapidly and the success has led to a security review of the program.

An acoustic scheme for buried object detection is thought to involve a sound source above the ground and a microphone as a receiver. In the simplest scenario, an airborne acoustic pulse would be transmitted, strike the ground surface, propagate through the pores and reflect off the surface of a non-porous object. The microphone would then be used to detect the pore-fluid echo. These ideas were first considered in a sound tube with spherical beads used as the porous medium. Experimental measurements of the pore-fluid propagation constants were compared to rigid framed model calculations for model verification. These experimental and theoretical results were then used to make predictions of the sound levels required to detect objects buried a few centimeters in outdoor soils. In addition, we chose a detection criteria which required that the pore-fluid echo be at least 1/2 cycle behind the pulse reflected from the ground surface. This criteria is quite arbitrary and conservative, but it allows for source specifications and from an experimental point of view appears as a realistic criteria for detection.

The models allowed for prediction of reflection losses, propagation losses, phase velocities and source levels based on burial depths of a few centimeters. Using these calculations various off-the-shelf acoustic sources were considered and it was realized that none were available which met the design criteria without some relaxation. In this research effort, it was possible to use existing sound sources to demonstrate that non-porous objects could be detected a few centimeters below the surface of institutional or grass soils. Research to develop a sound source which meets the original design criteria is on-going.

2.0 PREVIOUS EXPERIMENTAL MEASUREMENTS OF THE PORE-FLUID WAVE

Measurements of the A/S coupling phenomena led us to use microphones which were designed to be buried below the surface of the ground. Using these microphones, it is possible to measure the pore-fluid wave propagation constants in outdoor soils. These measurements were critical to the understanding of how sound interacts within the ground and have explained the commonly assumed local reaction property of the ground.[5]

A question we were led to ask ourselves was, "Is it possible to observe a pore-fluid wave echo from the soil, and could it be used as an acoustic probe in soils"? It was decided to conduct scale model experiments in which the various physical properties of the porous media could be controlled in an attempt to make predictions of the feasibility of the pore-fluid probe idea.

In this section, the experimental apparatus and measured propagation constants in low resistivity stacks of porous glass beads are presented.

2.1 Experimental Apparatus

The experimental apparatus consisted of a large aluminum sound tube, solid dielectric transducer, pulse-echo circuit and the transmitting and receiving electronics. Acoustic measurements in sound tubes with transducers of this type have been conducted in this lab for many years.[8] The tube used in these measurements was 7m x 0.25m in diameter and air-filled unconsolidated stacks of glass beads were used as the porous media in the tube which was positioned vertically. Figure 1 shows the sound tube, transducer, and how glass beads samples could be loaded into the tube for analysis.

At the upper end of the tube a 0.25m diameter solid dielectric transducer was positioned. This type dielectric transducer has also been used for many years[8] and the main advantage in this work is it is a good plane wave source in the sound tube even at frequencies above cutoff in the tube. A fast analog switch (2MHz) was used to switch from the transit to receive mode. In addition, it is possible to design these transducers with high frequency response (1MHz) and modifications can be made to the back plates to increase the output

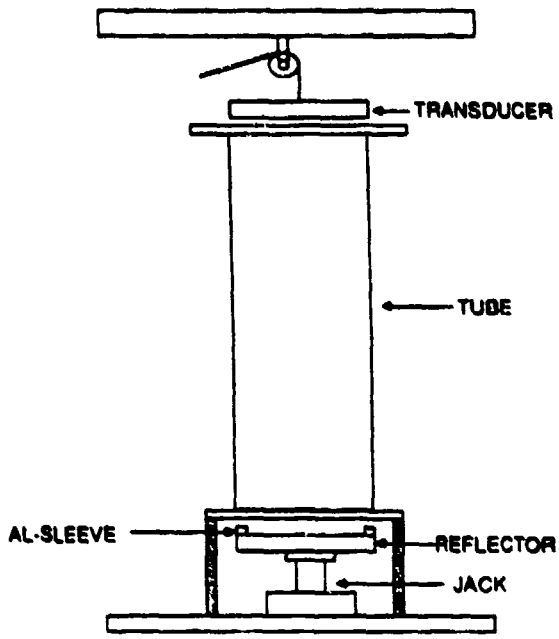


Figure 1. Sound tube configuration used in experimental work.

(at the expense of frequency response). This makes this transducer type suitable for the short tone burst used.

Typically, a two to four cycle tone burst with a peak voltage of 100 volts (rms) is delivered to the transducer. The acoustic return from the bottom of the tube (a few millivolts) is amplified and then displayed using a digital oscilloscope. Data can be sent to a minicomputer for storage and analysis via RS-232 interface between the computer and digital scope.

2.2 Pore-fluid Wave Propagation Constants

Initially, physical properties influencing propagation in stacks of spherical beads were determined. The beads used have bead diameters which range from 10mm to 1mm. Manufacturers of the beads indicate that these are less than 15% irregularly shaped particles and the sizes are as specified to within $\pm$ 0.2mm. The beads were also smoothed and polished.

Measurements of the flow resistivity of the beads were made with a Leonards apparatus and the results are indicated in Table 1. In addition, the porosity was determined by

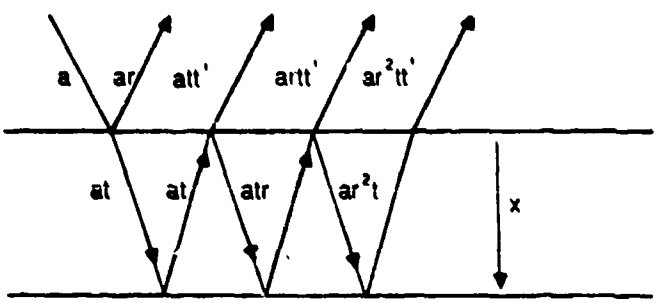
Spherical Glass Beads and Lead Shot

Size(mm)	Flow resistivity(rayls/cm)	Porosity
1.0	19.6 ± 2.0	.39
2.0	6.2 ± 0.70	.39
3.0	3.30 ± 0.34	.39
5.0	1.10 ± 0.12	.39
9.4 (lead)	(0.32) Calculated	.38

Table 1

measuring the volume of water necessary to fill the voids in a 100 cm^3 sample of beads. Measured values of the porosities of different beads sizes are shown in Table 1.

When an acoustic pulse is incident at the surface of the beads, it reflects from the surface but also bounces back and forth within the hard backed layer of beads producing an echo for each round trip it makes within the layer. Figure 2 schematically shows the phenomena.



Ray diagram of reflections from the surfaces of hardbacked layer of beads.

Figure 2

In Figure 2 the amplitude of the incident wave is a, the surface reflection coefficient is r, air-to-beads the transmission coefficient is t, the bead-to-air transmission coefficient is t' and the layer thickness is x. The first return has a magnitude

$$P_0 = ar. \tag{1}$$

The second return can be expressed as

$$P_1 = att'e^{-2\alpha x/20}, \tag{2}$$

Where α is the attenuation coefficient in dB per unit length. The logarithmic ratio of equations 1 and 2 is

$$\log\left(\frac{P_1}{P_0}\right) = \log\left(\frac{tt'}{r}\right) - 2\alpha x/20.$$

When the amplitudes of the first two echoes are plotted on a semilog scale as a function of layer thickness, the slope of the straight line is the attenuation coefficient in dB per unit length.

The pore-fluid wave phase speed was determined by measuring the time between the surface return and the first round trip return from within the stack of beads. Measured values from phase speed and attenuation coefficient are shown in Figures 3 and 4.

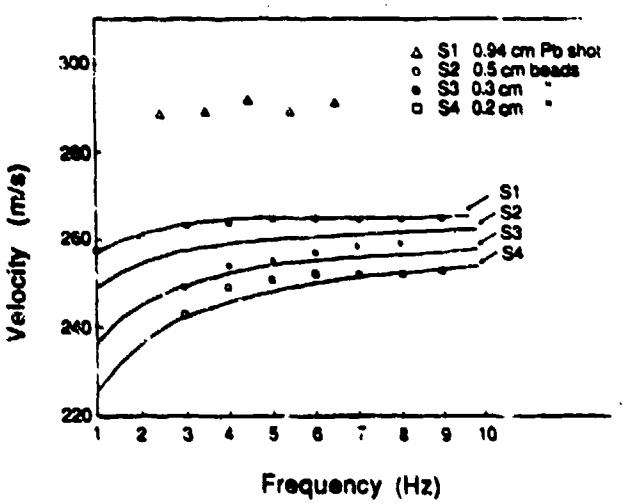


Figure 3

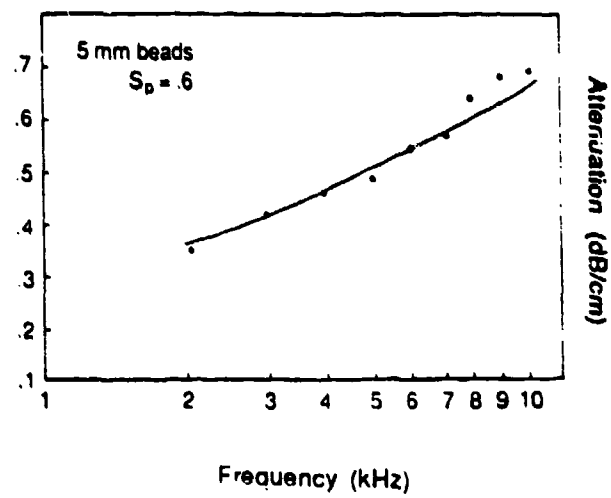


Figure 4

In the same figures are shown the theoretical values of the phase speed and attenuation constant. The calculations were made using the porous rigid frame model[9] using the measured values of flow resistivity and porosity. The grain shape factor and pore shape factor ratio were typically 0.5 and 0.8, respectively. It can be observed that as the flow resistivity increased there is a trend for the experimental and theoretical calculation to agree.

3.0 EXTENSION TO OUTDOOR SOILS

The work described thus far indicates that it is possible to observe the pore fluid pulse in stacks of low resistivity glass beads. In order to observe this pulse in a realistic soil with a flow resistivity of 100-300cgs rayls/cm, the losses upon reflection at the ground surface and the pore-fluid attenuation must be considered. Realistic output levels of acoustic transducers, the penetration depth required and the soil reflection coefficient will determine the optimum frequency for the outdoor measurement.

A useful property of the rigid frame model is that it can be used to make predictions of both the reflection and propagation losses in soils. For frequencies above 2kHz, calculations indicate that the reflection losses when the pore-fluid transmits across the air-soil boundary twice will be less than 6 dB. Model calculations for this attenuation in a soil with a porosity of 0.269, and shape factor ratio of 0.28 and a flow resistivity of 300 rayls/cm are shown in Table 2.

Signal Loss

300 rayls/cm, S_p = 0.28, Ω = 0.269, n' = 0.5		
min. frequency (Hz)	attenuation (dB/cm)	reflection losses (dB)
100	.7	16.0
200	1.0	13.9
500	1.5	9.0
1 k	1.8	7.0
2 k	2.2	6.1
5 k	3.0	5.8
10 k	4.0	5.6
20 k	5.3	5.5
50 k	8.1	5.4
100 k	11.3	5.4

Table 2

There has been much experimental and theoretical work done related to pore-fluid properties in outdoor soils. The inputs used in the calculations shown in Table 2 are quite typical for soils and sands.

3.1 The Acoustic Source

Acoustic sources which meet the output levels indicated in Table 2 are available; however, there are other criteria to consider. The acoustic source must "turn off" such that the echo from the buried object can be observed behind the ground surface reflection. Since one or two cycles of a tone burst are used, the band width of the transducer must be sufficiently high to insure the high frequency Fourier components required to "turn off" the transducer are present. Because of the signal losses resulting from the ground properties and the expected time delay for the pore-fluid echo for a 10 kHz tone burst, a source with an output that is down 40 dB one cycle after turn-off time is desirable in order to observe the pore-fluid echo from a few centimeters below the soil surface.

Several off the shell acoustic sources were considered; a 20kHz comparison driver and horn, a 40 kHz leaf tweeter and a 30 kHz dome tweeter. In these transducers the turn off time is controlled by the upper frequency response. Consequently, the output wave form from these transducers was somewhat dissatisfactory. In addition to these three transducers the solid dielectric transducer was considered as a source. No single device of this type is capable of producing the required sound pressure levels.

Recent work at this lab,[10] has shown that the frequency response of dielectric transducers can be precisely controlled. The frequency response of the solid dielectric transducer can be altered by changing the thickness of mylar, area of the backplate, tension on the diaphragm, and the roughness of the backing plate. The roughness of the backplate can be controlled by taking a smooth backplate which is only microscopically rough and applying an abrasive material, such as sandpaper or sand from sandblasting, to the surface. The result of this roughening is the replacement of most of the random microscopic cavities of roughly the same dimensions which have roughly the same resonant frequency. This results in a very narrow range of resonant frequencies with an increased sensitivity. The replacement of the majority of the smaller cavities with the larger cavities also results in the loss of high frequency response of transducer.

This same effect can be achieved by placing concentric grooves in the backplate which divides the backplate into two regions. The first region is the groove where the diaphragm is stretched over a cylindrical ringed cavity of trapped air. This region is similar to a standard capacitor microphone. The second region is the rail where the diaphragm is stretched over a cylindrical ringed backplate with air trapped in microscopic cavities. This is similar to a typical solid dielectric transducer.The total response of a transducer of this type is assumed to be the sum of the two regions. An array of dielectric transducers can be used to increase the output signal level. In current work, several such transducers are being used to achieve this goal and determine if the required pulse length can still be maintained.

Of the other three sources neither are capable of meeting the design criteria without further signal processing and design modifications. It was possible to make modifications to the 20 kHz compression driver that allowed it to be used in the outdoor experimental apparatus. The signal level was 40dB down 2 cycles after turn off as opposed to the design criteria of one cycle. Figure 5 is a diagram of the experimental apparatus with the acoustic

source. The horn driver was flush mounted to a 1m diameter piece of plexiglass. In addition the back of the driver was removed. Each of these steps had the effect of decreasing the effective period of the output pulse received by a 70kHz, 1/4 inch B and K microphone mounted between the driver and the ground. The modifications served to supress the arrival of the horn's back wave and waves diffracted from the baffles outer rim so that the pore-fluid wave could be observed.

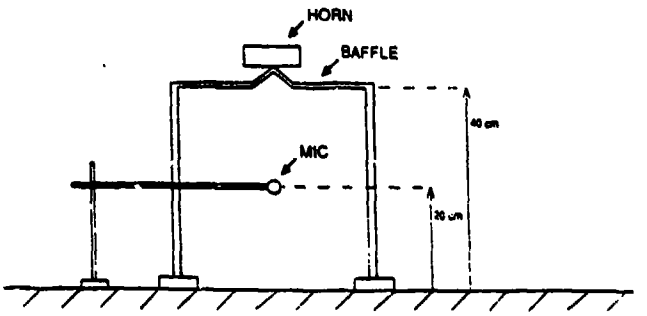


Figure 5. Experimental Apparatus

3.2 Echoes From Outdoor Soils.

The apparatus shown in Figure 5 was set up over a 80-100 square foot area of well spaded soil which had a measured flow resistivity of 40 c.g.s. rayls/cm and moisture content of 20%. When the horn driver was pulsed for one cycle at 10 kHz, the first pulse received by the output was similar to that shown in Figure 6. The time traces of the microphone output were shifted so that the pulse leaving the horn or the incident pulse was at the far left side of the oscilloscope trace. A much higher band width source would improve the incident pulse shape as indicated in a previous section of this report.

Figures 6, 7, and 8 show the results of an experiment conducted over the spaded soil area. In Figure 6 the arrow indicates the time at which the echo from the soil surface is expected at the microphone. When a piece of plywood was placed directly over the soil, the amplitude of this echo was approximately the same size and had the same shape as the incident pulse. Figures 7 and 8 show the echo from the ground when a 33 cm diameter hollow metal cylinder, 10 cm in length was buried 1 cm and 5 cm below the soil surface, respectively. Two observations can be made. The amplitude of the echo is increased when the object is present, and the pulse shape and length are changed for each of the burial depths. It can be noted that the ground echoes are arriving earlier in time and this is because the top surface of the buried object was placed flush with the soil surface and then soil added to achieve the desired burial depth. When the non-porous hard object is buried below the surface, the ground surface impedance is increased and consequently the reflection coefficient

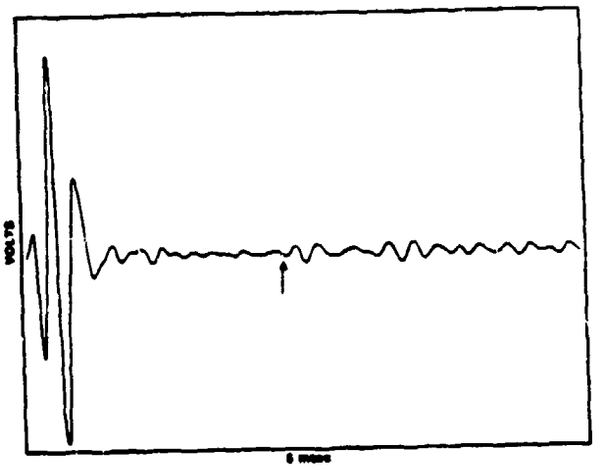


Figure 6

Echoes received from a large area of 40 rayl/cm soil.

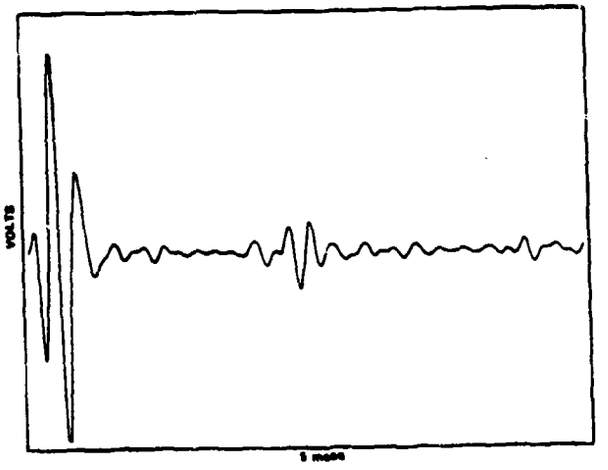


Figure 7

Echoes received from 40 rayl/cm soil when metal object was buried 1 cm below surface.

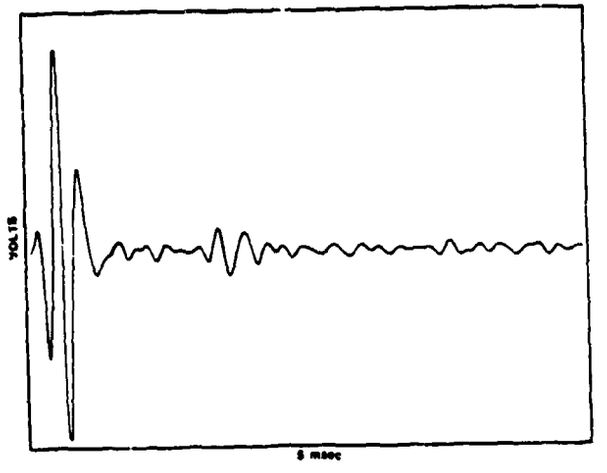


Figure 8

Echoes received from 40 rayl/cm soil when metal object was buried 5 cm below surface.

is increased resulting in a larger return. For this rather loose low flow resistivity soil, the amplitude change is sufficient for location of the buried object. There is not a separation between the surface and pore fluid echo but rather a smearing together. This results from the lack of homogeneity of the soil, the dispersive characteristic of the pore-fluid wave and the poor quality of the incident pulse.

In Figures 9, 10, and 11, the results of a somewhat different measurement are shown. The experimental apparatus was set up over an area of undisturbed grass or institutional soil as opposed to the large area of loose soil. The echo from the grass surface is shown in Figure 9. An additional echo (to those already described) at the far right of the time trace results from the reflection of the ground return at the horn baffle. In the previous site, the flow resistivity was 40 rayl/cm as opposed to 300 rayl/cm for this second site.

Next a 33 cm diameter, 15 cm deep cylindrical hole was dug and back-filled with the 40 rayls/cm loose soil. The resulting echo from this empty hole configuration is shown in Figure 10. This echo is observed to be smaller in amplitude than for undisturbed soil and 6-7 cycles long. Also note that the amplitude of the reflected pulse is larger than in previous measurement. This results because the reflected pulse reflects from an area larger than the 33cm diameter disturbed area. Good separation between the echo from the top of the soil-grass surface and the echo from the bottom of the 15cm deep hole is not achieved and consequently these echoes result in an extended pulse. Finally, the metal cylinder was placed in the hole with 3 cm of soil covering it. The echo observed is indicative of a less deep hole (see Figure 11). This echo does not "ring" for 6-7 cycles but rather 3 or 4. The superposition of the two echoes occurs in a shorter time period because the hole depth is less due to the presence of the hard object at 3 cm. The amplitude of the echoes in Figures 9, 10, and 11 are also different. The largest is for the undisturbed soil, and the smallest for the hole without the object. Disturbing the soil results in a decreased surface impedance (the flow resistivity goes from 300 rayls/cm to 40 rayls/cm) so that increased penetration (larger amplitude behind the incident pulse) is observed in Figures 10 and 11. In Figure 11 the propagation distance to the bottom of the hole is decreased because of the presence of the object and consequently the echo closely follows (in time) the incident pulse. Instead of the pulse traveling 30 cm in the soil, it propagated through only 10 cm of soil. In addition to that, the pore-fluid pulse is reflected from a non-porous hard surface which in this case results in reduced attenuation. Here, as in the previous measurement, the amplitudes of the ground returns are explained in terms of the effective surface impedance of the boundary. Also as before, the separation in surface and pore-fluid echo is not achieved.

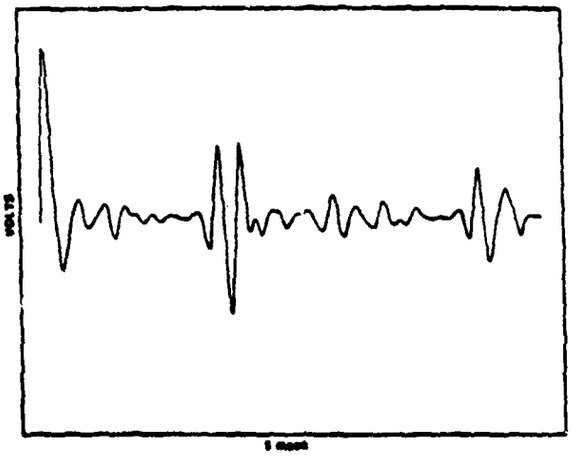


Figure 9

Echoes received from undisturbed 300 rayl/cm soil.

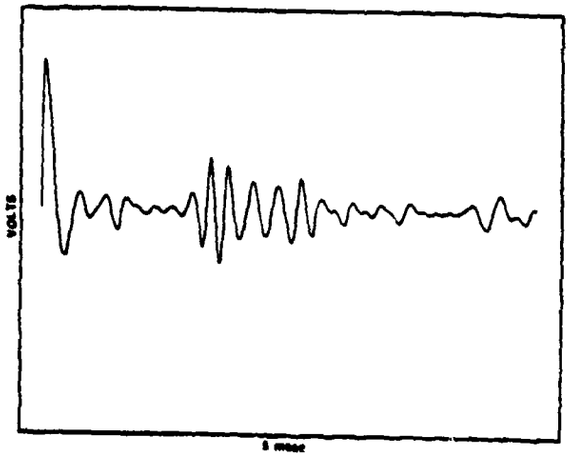


Figure 10

Echoes received from a hole formed in the soil.

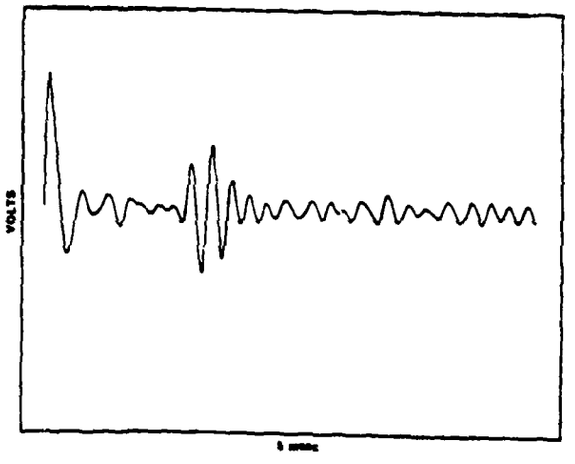


Figure 11

Echoes received when metal object was buried in the soil.

4.0 CONCLUSION AND RECOMMENDATION

In homogenous samples of glass beads it is possible to make measurements of pore-fluid echoes. These measurements yield values of the propagation constants that are explained in terms of the viscous effects at the pore walls and the rigid frame model calculations. The measurements were made in samples with flow resistivities much lower than for soils but model predictions indicate similar measurements can be made on outdoor soils. Indeed, continuous wave measurements of the pore fluid propagation constants in sandy soils have been done and model agreement was reasonable.[5]

Our initial calculations indicated that we would be able to observe the pore-fluid echo or separate the pore-fluid echo from the ground surface return. Because the source could not meet the design criteria, this observation was not made. But, we quickly learned that the amplitudes of the combined returns were significantly different to allow for buried object detection.

The results of the outdoor pulsed measurements to detect buried objects can be summarized as

1. The acoustic source used in the measurements did not allow for separation of the pore fluid echo from the surface echo for burial depths of 1–5 cm in the soils considered (and there are no better commercially available sources).

2. The dispersive characteristics of the pore fluid and the lack of homogeneity of the soil tend to smear the pore fluid echo and the surface return.

3. Even through the echo from the object cannot be cleanly separated from the surface return, the combined amplitude of the surface and pore fluid return's can nevertheless indicate the presence of objects buried 1-5cm below the soil.

The work done with the acoustic technique of buried object detection is promising and should continue. At this time we would recommend that work continue in two areas. First, the development of the acoustic source described in the designed criteria. Secondly, the work thus far has been driven by the detection in time domain of the pore fluid echo; a frequency analysis of the surface and pore fluid returns would allow for the interference phenomena associated with boundaries to be used in a detection scheme.

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