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A method for the detection of shallow buried objects

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Abstract
Numerous geophysical techniques have successfully contributed to geotechnical engineering and environmental problems of the shallow subsurface. Geophysical surveys are used to: delineate geologic features, measure *in-situ* engineering properties, and detect hidden cultural features. Most technologies for the detection of shallow buried objects are electromagnetic methods which measure the contrast in ferrous content, electrical conductivity, or dielectric constant between the object and surrounding soil. Seismic technologies measure the contrast in mechanical properties of the subsurface, however, scaled down versions of conventional seismic methods are not suitable for the detection shallow buried objects. In this paper, we discuss the development of a method based on acoustic to seismic coupling for the detection of shallow buried object. Surface vibrations induced by an impinging acoustic wave from a loudspeaker is referred to as acoustic to seismic coupling. These vibrations can be remotely detected using a laser-Doppler vibrometer (LDV). If an object is present below the surface of the insonified patch, the transmitted wave is back scattered by the target towards the surface. For targets very close to the surface, the scattered field produces anomalous ground vibrational velocities that are indicative of the shape and size of the target.

Key words *acoustics – seismic – porous media – buried object*

1. Introduction

Seismic methods are the most commonly conducted surveys for oil exploration and environmental investigation. Conventional seismic techniques excite vibrations in the ground by using a mechanical source or explosion on or below the surface of the ground (fig. 1). These sources produce dilatational (P) waves, shear (S) waves, and surface waves. The characteristics of these waves, *i.e.* velocity, attenuation, and amplitude, are controlled by the mechanical or «elastic» properties of the ground. Different seismic techniques are based on measurement of a certain characteristic of a particular wave. For example, P-wave reflection methods measure the travel time of the dilatational wave reflected from subsurface interfaces between layers having different mechanical properties. Surface or Rayleigh wave techniques measure the wave velocity as a function of frequency to deduce the mechanical properties as a function of depth in the near surface. Scaled downed versions of these seismic methods have not been successfully adapted for the detection shallow buried objects.

The seismic behavior of porous materials such as sand and rock are usually described by «effective solid» models. These models assume that there is negligible relative motion between the fluid and solid component and as such the soil deforms in bulk (O'Connell and Budiansky, 1977, 1978; Spencer, 1979). On the other hand, acousticians modeling sound absorbing materials assume the porous medium to have a rigid

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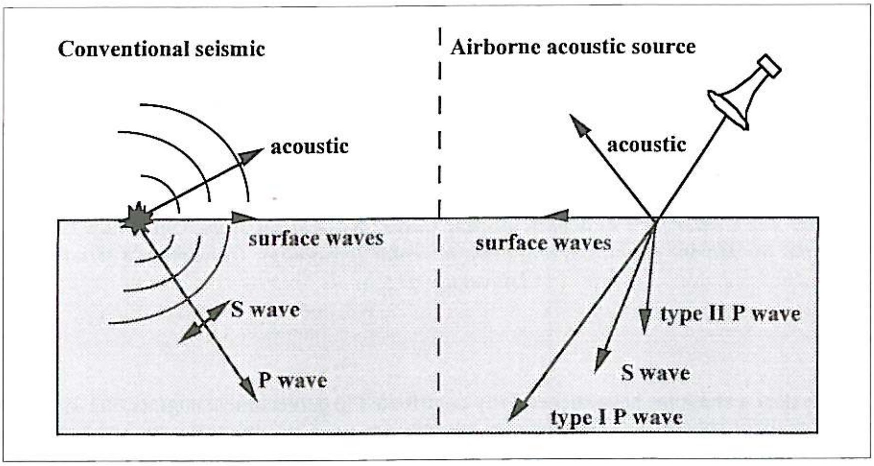

Fig. 1. Conventional seismic methods (left side) excite vibrations into the ground using contact mechanical sources which produces one dilatational wave, one shear wave, and surface waves. An airborne source excites two dilatational waves, one shear wave, and surfaces waves in the ground. The vibration of the solid component of the ground by an airborne wave is called acoustic to seismic coupling.

frame (Zwicker and Kosten, 1949; Morse, 1952; Pierce, 1989). In such models the porous material is treated as an «effective fluid» having complex material parameters. The classical theory for a rigid porous material has been used almost exclusively to interpret the reflection of airborne sound from the ground (Embleton *et al.*, 1976; Attenborough, 1985; Champoux and Stinson, 1992). The success of this model is due to the fact that the ground surface is composed of a granular framework in which its pores are filled with air. The air just above the surface induces motion of the air within the pores due to their similar inertial characteristics. The solid grains, however, having a much higher density and bulk modulus have much smaller deformations and can be neglected in the overall impedance calculation.

Several authors have observed that an airborne acoustic wave incident on a ground surface can couple energy into the ground as solid motion (Bass *et al.*, 1980; Sabatier *et al.*, 1986; Albert and Orcutt, 1989). They referred to this as acoustic to seismic coupling. Single continuum models such as an effective solid or effective fluid cannot fully account for the interaction of the solid and fluid components. Theoretical models for wave propagation which involve two coupled and interacting continua are required and are referred to here as «dual wave models». The most popular dual wave model for wave propagation through porous media was developed by Biot (1956a,b). Dual wave models are unique in that they predict the existence of two dilatational waves as well as the shear wave (fig. 1).

The use of acoustic to seismic coupling for detection of buried objects or mines is an area of ongoing research. In the early measurements (Baird, 1990) geophones were used to measure the low frequency (10-300 Hz) vertical component of the particle velocity over buried targets. These measurements were followed up with higher frequency measurements using smaller sized geophones and accelerometers. Requiring a non-contact remote measurement, recent experiments utilize a Laser Doppler Vibrometer (LDV) to measure the ground response (Arnott and Sabatier, 1990; Sabatier and Xiang, 1999; Xiang and Sabatier, 2000).

In this paper, we discuss the development and the physical bases of acoustic to seismic coupling for the detection of shallow buried objects. A brief review of the physical principles of acoustic to seismic coupling is presented in the context of the «dual wave model». Laboratory measurements are presented which support such model. Measurements with a non-contact sensor, a laser-Doppler vibrometer (LDV), for various shaped objects buried in sand are shown. If an object is present below the surface of the insonified patch, the transmitted wave is back scattered by the target towards the surface. For targets very close to the surface, the scattered field produces anomalous ground vibrational velocities that are indicative of the shape and size of the target.

2. Acoustics of porous material

The Biot (1956a,b) description of wave propagation through deformable porous materials predict the existence of two dilatational and one rotational wave. The dilatational waves are usually referred to as fast or type I *P* wave and slow or type II *P* wave. For an air-filled sand or sandstone, this theory predicts that the fast or type I *P* wave has the larger phase velocity and smaller attenuation. It deforms both the solid and fluid constituents by approximately the same amount and the deformations are approximately in-phase. Such deformation is analogous to the conventional seismic *P* wave. The slow or type II *P* wave has the lower phase velocity and larger attenuation. Both phase velocity and attenuation are strongly frequency dependent. The deformation associated with the type II *P* wave consists of primarily fluid component deformation and a very small deformation of the solid component. The deformation of the components is out of phase. This deformation is analogous to the acoustic wave in rigid-framed sound absorbing materials.

Mechanical sources placed in contact with the surface of the ground are used extensively in exploration seismology. The assumption is that they produce one dilatational wave, one shear wave (isotropic media), and surface waves. For a mechanical source in contact with a porous material it would appear that the normal component of the solid and fluid displacements of the sand at the surface should be in-phase. Such in-phase motion of material components is usually associated with the type I *P* wave at low frequencies. Based on previous research involving the interaction of airborne sound with the ground surface, it is justifiable that most but not all of the transmitted energy from an airborne source is partitioned into the type II *P* wave. Therefore, an experimental configuration consisting an airborne source, such as loudspeaker, is a good way to preferentially excite the type II *P* wave in an air-filled porous material.

Laboratory measurements on an air-filled unconsolidated packing of sand were carried out using microphones and geophones located at various depths (Hickey and Sabatier, 1997) . Two sources were employed: a loudspeaker suspended in the air above the sand, and a mechanical shaker on the surface of the sand. Figure 2a shows the arrival times *versus* depth using the suspended loudspeaker emitting a 1 kHz tone burst. The arrival times were measured using the *in-situ* vertical component geophones, *in-situ* microphones, and a probe microphone. An acoustic probe microphone consists of a graduated brass cylinder with a microphone element at one end and was developed to measure acoustic signals in soils. The reference time for these measurements was the electronic signal which is driving the source. The wave velocities are determined from the slope of the travel time curves.

For the loudspeaker source and shallow depths, less than 15 cm, the measured phase velocity determined from all sensors is about 145 m/s. This velocity is typical of the type II *P* wave at this frequency. At deeper depths the velocity determined from travel times is 240 m/s. Figure 2b shows the arrival time recorded using geophones and microphones as a function of depth where the source is a piezoelectric transducer which is in contact with the surface of the soil. The transducer is placed directly above the column of receivers to minimize shear wave energy. The graph shows only one slope indicative of the presence of only one wave as opposed to what was seen in fig. 2a. This wave is presumed to be the type I *P* wave because of the mechanical shaker source. The measured velocity is about 251 m/s which is quite close to the value measured at the greater depths using the loudspeaker source. This suggests that the

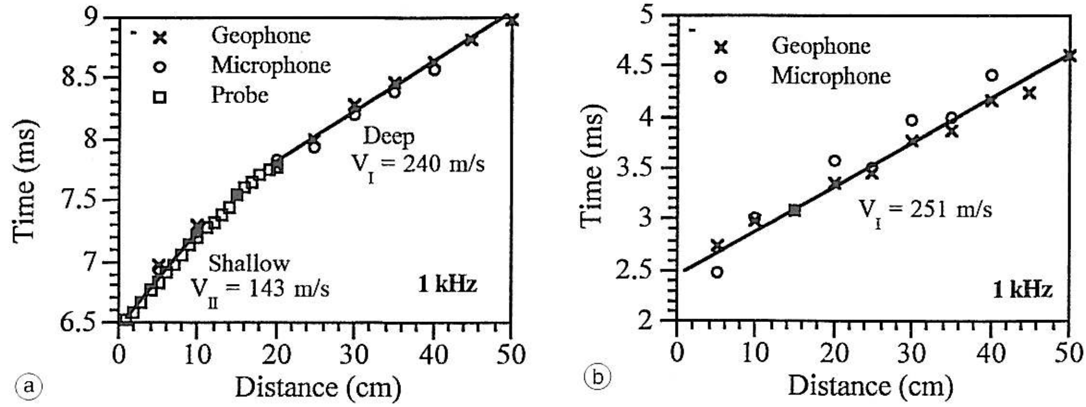

Fig. 2a,b. Travel time *versus* receiver depth measured by pulse transmission. a) A loudspeaker transmitting a 1 kHz five cycle tone burst is the source and the probe microphone, *in-situ* geophone, and *in-situ* microphone are used as receivers. Two velocities (slopes) suggest that the type II *P* wave dominates at depths less than 10 cm, and the type I *P* wave dominates at the greater depths. b) Using a mechanical shaker source transmitting a 1 kHz five cycle tone burst and, *in-situ* geophone, and *in-situ* microphone as receivers. Only one velocity (slope) suggest the presence of only one wave. Both geophones and microphones receivers yield the same results.

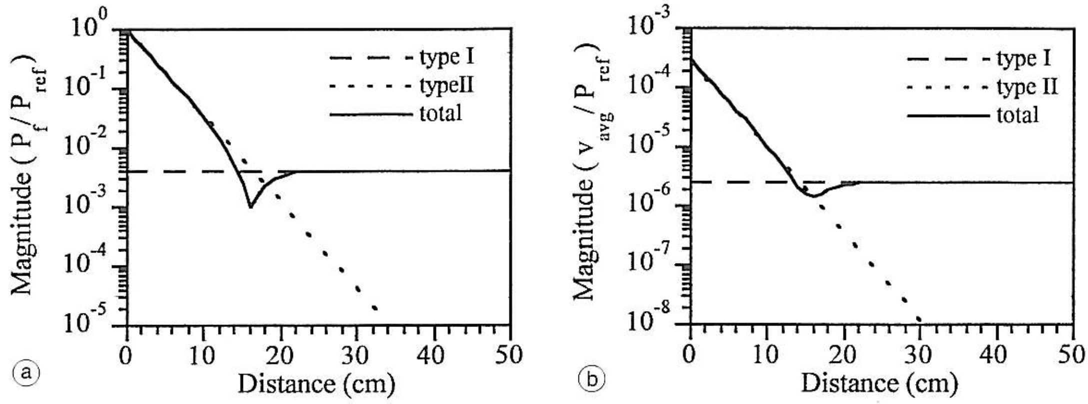

Fig. 3. Predictions of the transmitted pressure and particle velocity (acoustic to seismic coupling) in sand using the Biot poroelastic theory.

wave at the deeper depth using the loudspeaker is the type I *P* wave.

The postulated physical model for the above measurements is that the loudspeaker excites primarily type II *P* wave energy into the soil and a small amount of type I *P* wave. Since the type II *P* wave is strongly attenuated, its energy can only penetrate to a shallow depth after which the type I *P* wave dominates the signal. The two waves cannot be separated in time because the two velocities are close and the type II *P* wave is highly attenuated. The mechanical shaker however, produces predominately type I *P* wave which dominates the signal at all depths. Furthermore, it appears that both types of sensors, *i.e.* geophones and microphones, respond to both types of dilatational wave in this air-filled sand.

When an airborne acoustic wave is incident on the surface of the ground the measure solid vibration is due to a superposition of both type I and type II P waves. Figure 3 show calculations of the pore pressure and the «average velocity», as a function of depth using the Biot theory. The pore pressure should represent the response of buried microphones. The average velocity is calculated as a porosity weighted average, $v_{\text{avg}} = \varphi v_f + (1-\varphi)v_s$. At the current time it is unclear as to exactly what «velocity» a geophone or LDV measure. The velocity may actually take a different form and has to be investigate further. This preliminary modeling of the energy partitioning at the air-sand interface, shown in fig. 3, supports the above postulate that near the surface the type II P wave is dominant. At the greater depths, in this case for depths greater than about 20 cm, the type II P wave has attenuated so that the signal is now dominated by the type I P wave.

The current model of acoustic to seismic coupling assumes that the type II P wave dominates the signal near the surface but it must be remembered that although the type II P wave has the larger amplitude, its deformation is primarily fluid velocity and produces only a small solid velocity, v_s (zero in rigid frame limit). While the type I P wave may have a small amplitude, it produces a significant amount of solid velocity. A study of the importance of type I *versus* type II P wave for various soil types and depths to the objects is current underway.

Based on the model calculations and laboratory experiments conducted to date, the conceptual model for the detection of buried objects using acoustic to seismic coupling is presented in fig. 4. The surface of the ground is excited with an airborne source such as a loudspeaker. Much of this energy is reflected but due to the

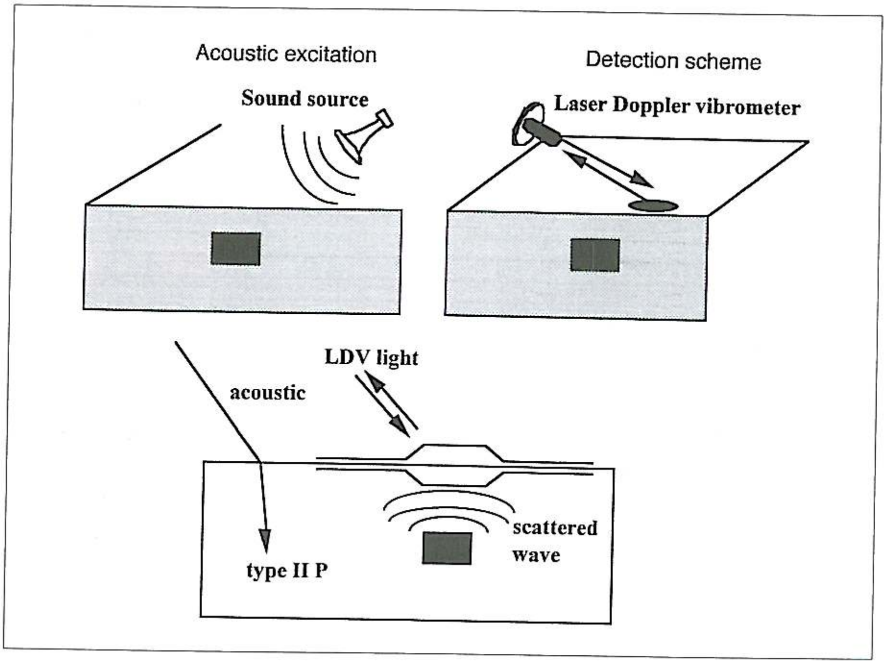

Fig. 4. Conceptual model for detection of shallow buried objects using acoustic to seismic coupling. The ground is excited using a loudspeaker, the induced surface vibrations are measured using a laser Doppler vibrometer. The surface vibrations are much larger over the target.

Fig. 5. System set-up for outdoor measurements of acoustic to seismic coupling over objects buried in sand.

porous nature of the soil, some energy is transmitted into the soil as type I and type II *P* wave. Most of the transmitted energy is partitioned to type II *P* wave amplitude. This energy is carried downward where it is scattered off of the buried object. This scattered field propagates upwards to the surface. The velocity of the surface vibrations are measured using either geophones or a scanning laser Doppler vibrometer. The superposition of the incident and scattered field are much different over the buried object than the ambient background.

3. Measurements

System set-up for outdoor measurements of acoustic to seismic coupling over objects buried in sand is shown in fig. 5. The acoustic source consists of a function generator, amplifier, and loudspeaker. The detection system consists of a single point scanning laser Doppler vibrometer (PSV 200 manufactured by Polytech PI, Inc.). The LDV system is equipped with a video camera and X-Y scanning mirrors. The scanning procedure includes controlling the mirrors in a raster scan manner over predefined grid points. At each point a laser beam is emitted from the

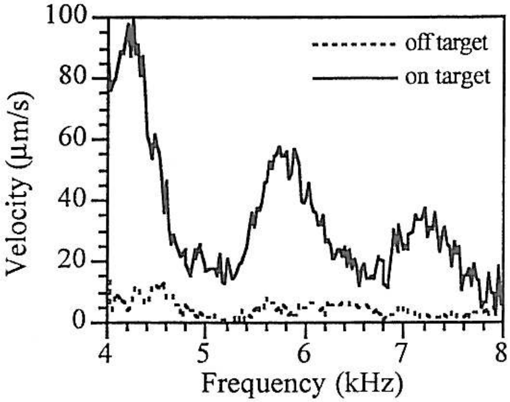

Fig. 6. Measured surface velocity using a laser Doppler velocimeter (LDV) on and off the steel disk of 10 cm diameter as a function of frequency.

LDV onto the surface of the ground where it is Doppler shifted by the vibrational velocity of the ground surface. The back scattered light is sensed by a photo detector located within the LDV head. The resulting data is a frequency-modulated (FM) signal from the photo detector which contains the information about the ground surface velocity. The video camera, laser and photo diode are enclosed in a remote head which is mounted on the front of the forklift in fig. 5.

Buried targets consisted of three steel plates in the shape of a circle, a square and an equilateral triangle. The diameter of the circle and edge of the square were each 10.2 cm, and the edge of the triangle was 9.5 cm. Each was buried at a depth of 1 cm in sand with its major surface horizontal.

A measurement can consist of broadcasting a single tone, a band of pseudo-random noise or a swept sine. For the measurements presented

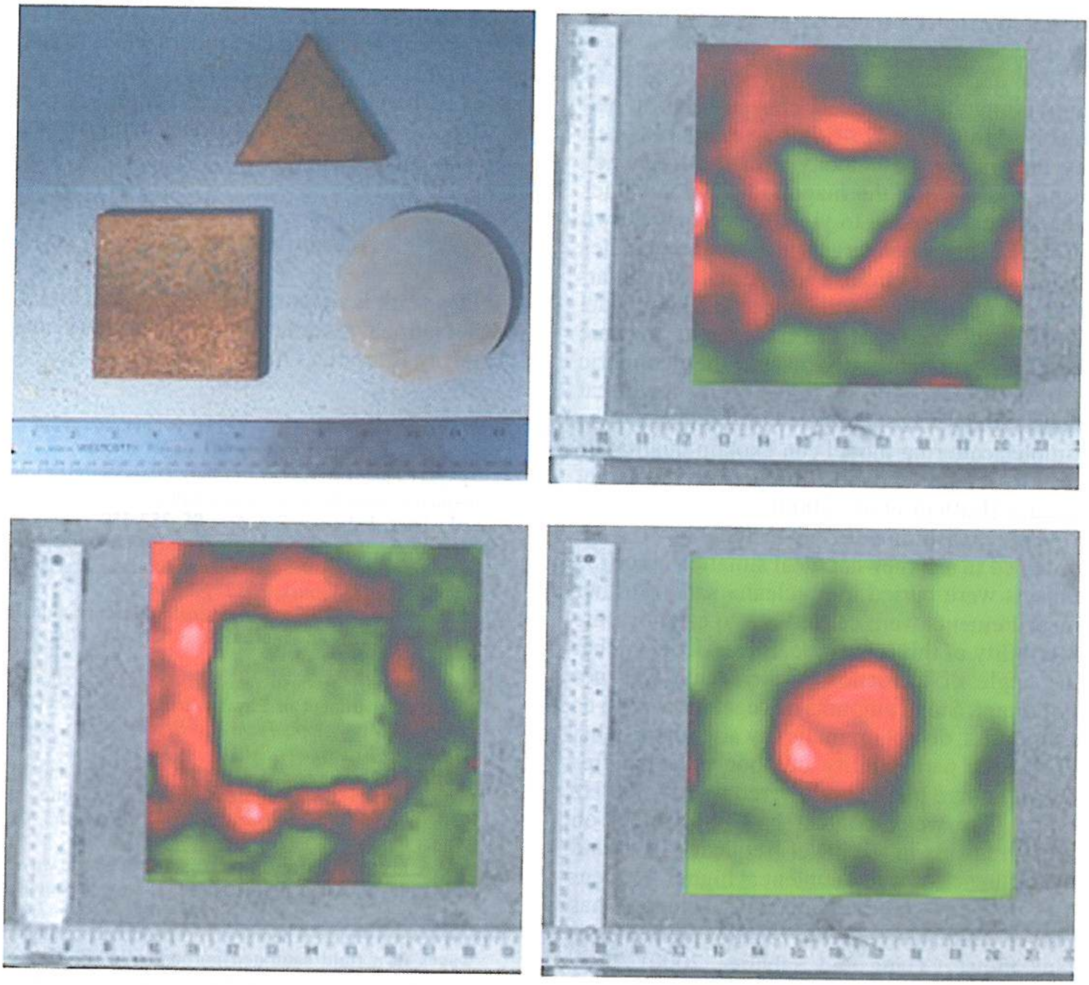

Fig. 7. Target shape characteristics: steel plates buried at 1 cm in sand. Upper left show the targets consisting of a triangle with 9.5 cm edges, a disk with a 10.2 cm diameter and a square with a 10.2 cm edge. The upper right shows an image produced over the triangular object, lower left is the square and the lower right is the disk.

here a swept sine from 100 Hz to 10 kHz was used. The complex amplitude (magnitude and phase) of the ground surface velocity at each point is measured as a function of frequency. Figure 6 shows the magnitude of the LDV measured surface velocity on and off the steel disk of 10 cm diameter. The magnitude of surface velocity is greater on target over this range of frequencies. The velocity can be almost an order of magnitude greater over the object than the measured background velocity. In the frequency range of 5.5-6.5 kHz the velocity is approximately 6 times greater than background.

For each target, a ground surface area of approximately 21 cm × 21 cm was scanned and resolved to a 32 × 32 grid. Images are obtained by integrating the velocity over the frequency band and plotting the magnitude. These values are then color coded to yield the images shown in fig. 7. The buried targets are three steel plates in the shape of a circle, a square and an equilateral triangle shown in the upper left hand side. It is easily seen that the acoustic to seismic based system can easily discern the geometric shapes of these objects. It has been shown that the standing-wave-like behavior predicted by a simple scattering model can explain qualitative features of the experimentally observed target images (Lafleur *et al.*, 2000).

The measurements presented above were obtained in a somewhat ideal situation since the objects were buried in a «clean» sand. Further measurements were carried out to establish the feasibility of this technique. It was deduced that the angle of incidence of the sound was not important. Small amounts of vegetation, such as short grass, do not dramatically alter the results. For lower permeability outdoor soils the frequency range had to be lowered to 100-300 Hz range. The water content had little effect on measurements in the lower frequency band and the influence of water content at higher frequencies have not been studied. The technique has proven quite successful in locating buried antitank mines (Xiang and Sabatier, 2000). They state that the on- and off-target velocities is effected mostly by the burial depth. Therefore, deeply buried, small targets are the most difficult to detect.

4. Conclusions

Due to the poroelastic nature of the ground, an impinging acoustic wave from a loudspeaker excites slow speed vibrational waves in the ground. This is referred to as acoustic to seismic coupling. It has been shown that a system based on acoustic to seismic coupling can easily discern the geometric shapes of object buried in sand. It is postulated that the transmitted energy is partitioned mainly into the type II P wave. This energy is carried downward where it is scattered off of the buried object. This scattered field propagates upwards to the surface which enables the buried object to be detected. Further study of the importance of type I *versus* type II P wave for various soil types and depths to the objects is required.

Acknowledgements

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