

Acoustic Interrogation of Soil and Possible Remote Detection of Shallow Buried Inclusions

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Abstract—Here we address the problem of remotely interrogating the shallow subsurface of soil using low power mechanical energy transmission and sensing the subsequent backscattering from the soil bed to find small buried objects at very shallow depths (~ 15 cm or less). The effort is geared towards the development of better technologies for the remote detection and imaging of buried land mines, improvised explosive devices (IEDs) and other undesirable objects. We present our studies against the backdrop of what is known in this field today. Our ongoing work is briefly summarized with an outline of the underlying physics of acoustic backscattering from shallow buried objects and of how such backscattering can be inexpensively and remotely detected and interpreted for possible use in automated mine clearance operations.

I. INTRODUCTION

Soil is a highly complex and nonlinear medium comprised of elastic grains with typical size distribution spanning between ~0.002 mm for clay to ~ 2mm for coarse sand, varying shapes and typically with variable proportions of interstitial water [1]. Not surprisingly, interrogating soil for possible detection and imaging of shallow, non-metallic, buried objects is a major challenge [2]. Negotiating this challenge is central to the successful detection and imaging of small, regular shaped buried objects such as land mines or IEDs. There is no single mode by which such detection is achievable for any given soil type and there are many independent ways – such as electromagnetic, chemical, nuclear and acoustic [3]. It is widely believed that a highly developed suite of technologies placed on a mine reconnaissance vehicle might be the best way to deal with the problem of detection of such shallow, buried objects [4]. But for now, such a suite is not quite there and even if they are, they are not designed to be affordable to small non-

governmental organizations in economically deprived and remote mine infested areas of Cambodia, Afghanistan, Iraq, Sudan, The Falkland Islands and some 100 other countries. In almost every case, paralyzing mine infestation in what used to be civilian inhabited arable land, has had a devastating effect on people's lives and hence on the economies.

Here we focus on one of the less understood soil interrogation modes – the acoustic mode – and show that in spite of our limited knowledge of soil it is still possible to develop inexpensive and robust systems capable of remote reconnaissance missions in various forms of soil under varying weather conditions. A deeper understanding of mechanical energy propagation in soil will only allow us to finesse the present approach and hence develop it to the level of sophistication that is available in electromagnetic modalities.

II. THE UNUSUAL (NONLINEAR) ACOUSTICS OF SOIL

Electromagnetic waves penetrate well into soil [3]. However, to detect buried objects that are ~ 10-15 cm in length scale, small wavelength electromagnetic waves are essential and for such wavelengths attenuation is known to become an issue [3]. Further, the non metallic nature of most of the buried landmines can also adversely affect the intensity of the backscattered electromagnetic waves at the soil surface.

Surprisingly, acoustic mine detection works very differently. Experiments reveal that acoustic waves do not follow the wave equation [5]. Newtonian dynamics based simulations of mechanical energy propagation through granular beds show that mechanical energy propagates almost ballistically through such beds [6]. Hence, sound

waves with frequencies $\sim 10^2$ Hz moving at velocities $\sim 10^3$ m/s (at a wavelength ~ 10 m) can allow detection and imaging of objects that can be as small as $\sim 10^{-2}$ m. This is the underlying reason why acoustic waves emerge as a competitive mode for finding small buried objects at shallow depths.

A. Impulse Studies

Elastic grains of quartz or sand repel upon compression according to Hertz law [7]. For two identical spheres of radius R , located at position \mathbf{r}_i and \mathbf{r}_j where Y , σ denote the Young's modulus, Poisson's ratio, respectively, the Hertz potential describes the grain-grain repulsion upon compression as $V(\delta_{ij}) = a\delta_{ij}^{5/2}$, where $a = (2/5D)(R/2)^{1/2}$, $D \equiv (3/2)[(1-\sigma^2)/Y]$ and the grain overlap parameter $\delta_{ij} \equiv 2R - (|\mathbf{r}_i - \mathbf{r}_j|) \geq 0$, where (i,j) are neighbors in contact. We have carried out studies in which a select collection of grains at the

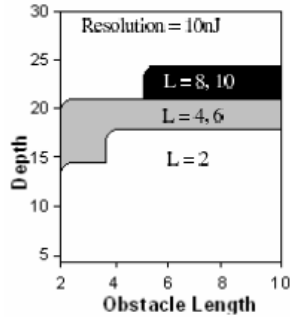


Fig. 1. Results of a small scale study in which the Obstacle Length refers to the sides of a square inclusion, Depth refers to the placement of the inclusion under the surface and L refers to the impulse area. The lengths are measured in grain diameter. Resolution means any energy < 10 nJ is invisible. The “phase diagram” suggests that while larger impulse areas allow us to look deeper, they also make it easier to miss small objects. Thus, detection should ideally start off with small impulse areas and then progressively use increased impulse areas.

surface of a granular bed has been subjected to an impulse. Newton's equations are then solved for every grain in the granular bed [6,8]. Studies reveal that the energy pulse propagates into the bed much like a torch beam emanates in a cone shaped fashion from the lamp. The propagating mechanical energy is easily backscattered by any buried object along its way. If sufficient amount of backscattering reaches the surface then the buried object may become detectable by appropriate surface based sensors. Our simulation based studies on how impulses backscatter from small buried inclusions reveal encouraging results as shown in Fig. 1. The primary finding is that large surface area impulses are unable to readily detect objects that are of smaller surface area than the impulse area itself. Thus, it is best to interrogate a soil surface with impulse areas that are smaller than the expected object area. Gradually, the impulse area can be increased as one looks for progressively larger objects. This non-trivial conclusion is based upon extensive simulations using granular beds with $\sim 10^5$ grains [6,8]. Effects such as that of ambient backscattering at the surface in empty beds have been subtracted off in performing these

studies. Effects of typical restitutive losses during grain-grain interactions have also been accounted for in our analyses [6]. There are a limited number of available experimental studies on impulse propagation in 3D granular beds. Our simulation based results agree well with available literature [9,10]. More systematic experiments are, however, needed to check the detailed features in the simulation based predictions and such studies are being planned.

B. Continuous Wave Studies

It has been known presumably since 1950s and has been reiterated often that shallow soil can be transparent to acoustic signals in the typical frequency window of 100-300 Hz or so [11]. Not only do the signals penetrate into shallow soil, any buried inclusion efficiently backscatters the signals in such a way that when the backscattered signals are received by a sensor array placed in gentle contact with the soil surface it becomes possible to glean enough information to learn about the nature of the backscatterer. The approach is typically able to find objects that are just about several centimeters across. Acoustic detection seems to work well for dry and wet soils and for sand, clay and loam, a feature

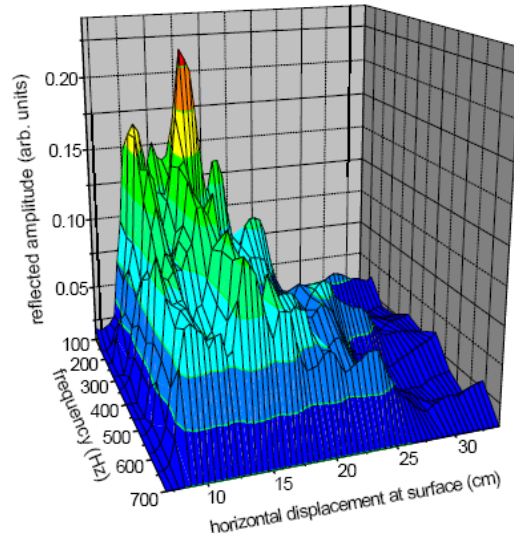


Fig. 2. We show the backscattered amplitude of sound waves at the surface of a nominally dry laboratory based sand bed of dimensions 1 m^3 . The sound waves were sent across most of the surface using a vibrating plate that touched the bed surface. A plastic circular shaped anti-personnel land mine of diameter 15 cm is placed at a depth of 10 cm from the bed surface and at 15 cm from the edge of one of the sides. Sound waves across a range of frequencies are introduced into the bed. It is found that maximum backscattering (as shown by the peak) from the buried mine occurs in the frequency range between 150 and 300 Hz. To represent the available data in a 3D plot, the position of the land mine is only given in terms of one coordinate, i.e., how far the mine is from one edge of the cube. The other axis has been integrated over.

that is not true for the widely used ground penetrating radar (GPR) based approaches. The frequencies and amplitudes that are transmitted through various soil types vary

significantly. Nevertheless, existing experiments and our work suggest that acoustic transparency of soil seems to hold up to frequencies of several hundred Hz but typically not quite as high at 1 kHz.

Recent field experiments conducted by one of us (LEG) show that for given soil types, certain applied frequencies – which we call “preferred frequencies” – yield the greatest proportion of returned energy [12]. These experiments were done for three different soil types, sand, clay loam and silt loam at three distinct locations. The studies were conducted using a new “controlled frequency acoustic-seismic source” (CASS). The CASS allows for modulation of the source signal frequency, amplitude, and load time: 60-1000 Hz; 5 and 10 volts peak-to-peak (Vpp); and 0, 5, and 10 s, respectively. Combining successive iterations while varying only one variable at a time yielded approximately 140 different initial conditions at each site each, with a total of 420 different initial conditions. Soil temperatures were 10, 14, and 11° Celsius (+/- 0.5° degrees during the experiments); air temperatures were 6.6, 13.8, and 10.4° Celsius (+/- 1.5° during the experiments); and soil moisture was 7.1%, 2.7%, and 3.3% for the sand, clay loam, and silt loam, respectively. The studies suggest that sandy soil, clay loam, and silt loam at various test sites have preferred frequencies of 300-330, 100-140 and 140-260 Hz, respectively. These preferred frequencies are robust enough to be valid at different seasons and hence under varying soil moisture conditions. Further experiments are under way to prove preliminary results that buried objects – regardless of the object’s composition – will always disrupt this resonance like process and yield a specific change in the preferred frequency response and that this change can be measured and mapped in detail. There are no detailed theoretical or simulational studies of propagation of continuous wave signals through granular beds. Such studies are currently in progress.

III. GROUND BASED SENSORS

Seismic measurements require a seismic source to



Fig. 3. The photo shows geophones laid out for studying acoustic transmission properties when the ground is water saturated. The experiments were done by Gilcrist. Studies have revealed that the preferred frequency transmission ranges vary somewhat for different types of soil.

generate the waves to be measured. Examples of common seismic sources are seisguns, hammers, small explosives, and rifle ammunition shot into the ground [1]. When one plans to use a wireless network to transmit backscattering from the ground into a remote tower, it is important to minimize power consumption and make the seismic source autonomous. Spark plugs have been shown to be a viable source. The measurements were effective within 1 m of the earth’s surface and reliable within 2-3 m of the source. A spark plug or similar technology can be integrated into an automated wireless network of geophones [13]. The set up of spark plugs and geophones shown in Fig. 3 above reveal a

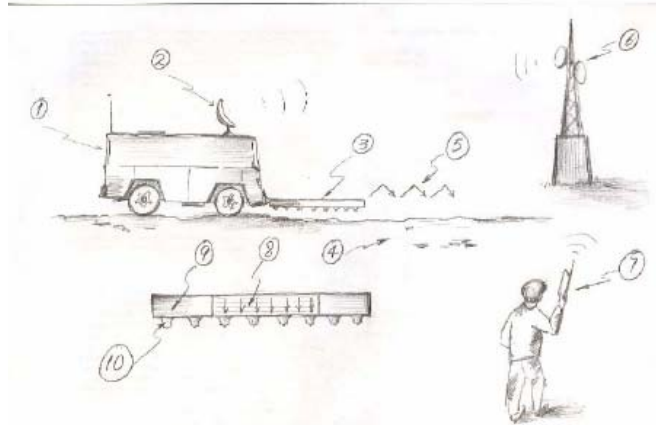


Fig. 4. Artist’s conception of IED reconnaissance in progress, “1” is the armored vehicle, “2” is the vehicle transmitter/receiver, “3” is the front end with technology platform, “4” shows buried inclusions, “5” shows the manner in which the platform is being moved, “6” shows the reception/transmission tower, “7” shows the PED, “8” shows the acoustic generator/speaker, “9” shows areas where the electronics is assembled and “10” shows the ground contact sensors.

typical set up for acoustic sensing with wires. This set up can be readily adapted for wireless transmission from the geophones and for use from a ground based reconnaissance vehicle as illustrated in the sketch in Fig. 4.

The typical geophones used in our field work are of standard specifications with a natural frequency of 10 Hz, maximum coil motion of 2 mm peak-to-peak, and a coil resistance of 375 ohms. The only power required by each sensing node is that of the RF transmitter, which is 2mA @ 3V for a transmission distance of 100 m.

IV. COORDINATION OF SENSORS

For goal-directed intelligent coordination of sensors and for smart fusion of data received from different sources (e.g., SIGINT from ground sensors, ISR from satellite imagery, and HUMINT from human workers) we are developing a model-based deductive framework. Our framework builds on recent advances in wireless sensor networks, computational logic (decision procedures, deduction), non-monotonic reasoning (default and case-based reasoning) [15], artificial intelligence (causality [16] and automated plan recognition)

and behavioral reasoning [17]. It will obtain information gathered using level 1 data fusion (e.g., from Kalman filters [14]), perform model-based deductive reasoning based on it and generate intelligent decisions. These decisions are communicated to relevant authorities using our SINS distributed infrastructure [19].

V. SUMMARY

In closing we note that we have highlighted the problem of detection of shallow buried objects such as landmines and IEDs in various soil types and under various soil conditions and have mentioned the inherent challenges associated with detecting these buried objects. Our work over the past decade suggests that mechanical energy backscattering based approaches present a viable way to find these objects. Finally, we have mentioned that the sensor and communication technologies are now in place to remotely detect, filter and transmit sensor data to a command and control center for possible remote detection of these objects using this ground contact acoustics based approach.

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