Use of Elastic Waves for the Detection of Buried Land Mines

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Abstract — A prototype system that employs seismic surface (Rayleigh) waves and non-contact displacement sensors for the detection of buried landmines is being developed. The operating principle of this system is to interrogate the ground surface motion, resulting from a remote seismic source, in a region surrounding, and immediately above, a mine using a two-dimensional array of non-contact sensors. The data from this array is then processed in the space and time domains to form images. These images emphasize specific features of the ground motion, which have been linked empirically, through both numerical modeling and experimental studies, to the presence of landmines. The images formed in this way show a large contrast (~30 dB) between mines and background reverberation and a large contrast (>20 dB) between mines and mine-sized clutter objects. They also appear to be robust in simulations of realistic burial scenarios involving a variety of mine sizes and depths along with clutter objects in close proximity.

INTRODUCTION

Seismic/elastic techniques show considerable promise for the reliable detection of all types of buried mines, even low-metal anti-personnel mines. The reason for this is that mines have mechanical properties that are significantly different from soils and typical forms of clutter. For example, the shear wave velocity is approximately 20 times higher in the explosive and the plastics used in typical mines than in the surrounding soil. In addition, mines are complex mechanical structures with a flexible case, a trigger assembly, air pockets, etc. This complex structure gives rise to structural resonances, non-linear interactions, and other phenomena that are atypical for both naturally occurring and man-made forms of clutter. This phenomenology can be used to distinguish a mine from clutter.

A mine detection system has been developed at Georgia Tech that employs sensors, which measure local seismic displacements without physically contacting the soil surface [1]. The non-contact nature of these sensors allows interrogation of the soil surface near or immediately above a mine. This substantially increases the measurable effects of the mine's presence over schemes which rely on elastic waves scattered by the mine to propagate to a remote sensor location [2].

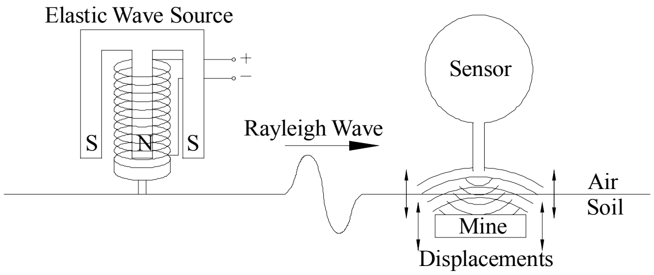

Fig. 1. Diagram of the mine detection system.

A laboratory prototype for the mine detection system is currently being studied. In the prototype, the two-dimensional array of sensors is formed synthetically by scanning a single sensor over the measurement region and exciting the ground with identical seismic signals for each measurement location. The configuration of this system is shown in Fig. 1. In the experimental model, the soil is modeled by a tank that is approximately 6 m wide, 6 m long and 1.5 m deep filled with damp compacted sand. The source depicted here is a 100 lb. electrodynamic shaker that has been coupled to the ground using an elongated foot attached to the shaker head (moving coil). The long dimension of the foot is parallel to the excited wave fronts. This was found to preferentially excite surface waves and to direct energy toward the measurement region rather than the side walls of the tank in which the tests are conducted. The shaker is free standing so that the ground is driven against the tail mass (permanent magnet).

As the Rayleigh wave propagates across the minefield, it excites motion of compliant objects such as mines and is scattered from inhomogeneties, which include both mines and clutter. The amplitude of the Rayleigh wave displacement decreases exponentially with depth and only the soil near the surface is interrogated by this signal. The depth of soil that is examined is a function of the frequency of the source. For the laboratory system this is typically in the 100 to 1,000 Hz range. Somewhat lower frequencies may be used in a field system that is not limited by reverberation in a restricted tank volume, as the laboratory system is.

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The motion of the mine is different from the motion of the surrounding soil and clutter, because of the unique mechanical characteristics of a mine. Both antipersonnel (AP) and antitank (AT) mines with pressure sensing triggers exhibit structural resonances within the bandwidth of the current interrogation signal. These are excited by the passage of a Rayleigh wave. A consequence of this is that the motion above this type of mine is amplified relative to the incident motion and persists in time following the passage of the incident wave. The resonance is damped due to loss effects in the soil and energy that is radiated into the soil.

Numerical models have been developed which mimic the experimental observations of resonant mine behavior. These are three-dimensional finite-difference time-domain (3-D FDTD) models, which represent the soil as a linear, isotropic, elastic, half-space with material properties that have been determined from the experimental studies. In the numerical model, mines are represented as simplified structures with the approximate size, shape, and density of the actual mine and a closed air cavity to simulate a pressure-sensing trigger. Both the stiffness and the mass of the overlying soil and the case of the mine influence the resonant behavior. The models have also shown that the surface motion excited above a resonant mine greatly exceeds that of natural clutter objects such as rocks with a wide range of sizes and material properties.

DATA PROCESSING

The data acquired with the laboratory mine detection system is recorded as a transfer function (surface displacements relative to the input drive signal) in the frequency domain. As such, the raw data are four-dimensional (two spatial dimensions over which the synthetic array is formed and two dimensions for the amplitude of the surface displacements as a function of frequency). A meaningful image-processing algorithm must reduce this data to the two spatial dimensions and a third representing the probability of the presence of a buried land mine. Some authors have suggested that, under similar circumstances, the amplitude of measured displacement at a point is sufficient to represent this third dimension [3]. The imaging scheme that is currently employed with the laboratory system is considerably more complex than this approach as it exploits features of the observed phenomena to enhance the background contrast over that which can be achieved with this simpler scheme.

The current imaging algorithm, which has been described in a previous paper [4], first synthesizes the response of the system to a differentiated Gaussian pulse, which typically has a center frequency of 450 Hz. The data is filtered temporally and spatially to remove low and high frequency noise. Then, the forward-propagating waves are filtered out leaving only the back-scattered waves. Two data sets are created: the first data set is the energy at each spatial position in the back-scattered waves at times of arrival near the incident wave, while the second data set is the energy that propagates back toward the seismic source from each spatial position. Finally, taking the product of these two data sets forms the image.

MULTIPLE MINE BURIAL SCENARIO

Previous papers have demonstrated the feasibility of detecting both AP and AT mines using the laboratory system and of distinguishing these from buried clutter [1]. Recent investigations have focussed on imaging individual mines in close proximity to each other while distinguishing them from clutter. A common practice of mine warfare is to plant multiple AP mines in close proximity to AT mines. The AP mines thereby protect the AT mine from sappers who can more easily detect the larger object and remove it with little personal danger. This poses a unique detection problem in that it requires a system to operate with sensitivity appropriate to both mine types simultaneously. Also, the system must be capable of distinguishing individual targets and rejecting ghost images formed by multiple scattering effects.

To address this scenario experimentally, an experiment was performed in which an AT mine was surrounded by four AP mines and four AP mine-sized clutter objects. The AT mine was an inert VS-1.6 mine. It was surrounded by an improbable assortment of AP mines: M-14, TS-50, VS-50, and PFM-1 mines. The arrangement of this burial and the relative scale of the objects can be seen in Fig. 2.

The image formed from the data taken over the multiple mine burial is shown in Fig. 3. The number of mines present and their relative locations have been accurately depicted. The image of the AT mine is seen to be strongest at the back edge; this is due to the reflection at the back edge being stronger than that at the front. The effects of the rocks are much smaller than those of any of the mines. The largest rock is barely discernable with the 30-dB dynamic range used to generate the image. It can be seen in the lower left of the figure. The reason for this is that the rocks do not exhibit resonances within the frequency range of the incident signal.

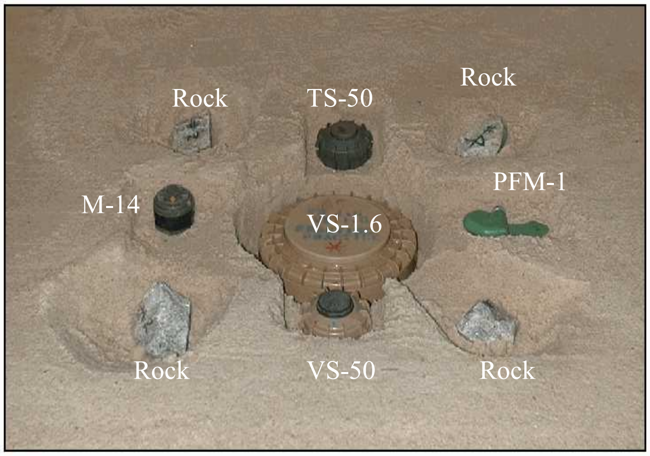

Fig. 2. VS 1.6 AT mine surrounded by TS-50, PFM-1, VS-50, and M-14 AP mines and rocks. The burial depths are 4.5 cm for the VS-1.6; 2cm for the TS-50, VS-50, and PFM-1; and 0.5cm for the M-14. The burial depths for the rocks were 3.5cm, 1.5cm, 2cm, and 1cm (clockwise, starting with the upper left rock).

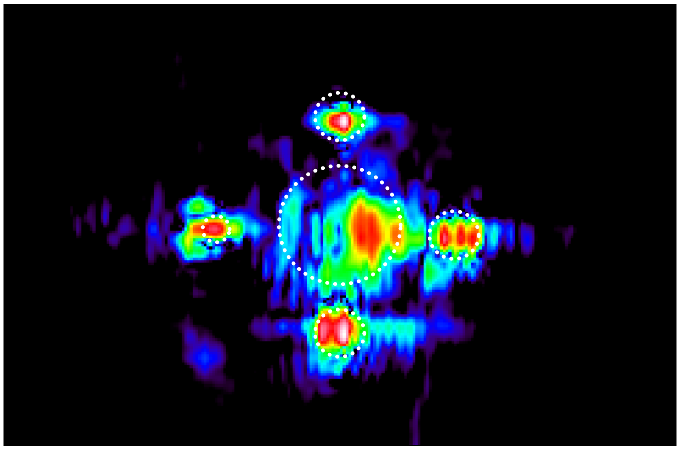

Fig. 3. Image formed of AT mine surrounded by AT mines and rocks. Dynamic range is 30 dB. Physical dimensions are 120 cm by 80 cm.

Processing artifacts of the removal of forward propagating waves from the data cause the images of the individual mines to be smeared horizontally. This does not, however, mask the presence of the AP mines to the left or right of the AT mine. Nor does the seismic shadow (forward scattered signature) of the AT mine appear to degrade the image of the PFM-1 AP mine directly behind it.

This scenario was modeled numerically using the 3-D FDTD model [5]. The image in Fig. 4 was formed using these model results as input to the imaging algorithm. The similarities between this image and the experimental image are readily apparent. The model underestimates the signatures of 3 of the 5 mines. This is partially due to the lack of some important details in the model regarding the mechanical structure of these mines. Another factor may be that the depth profile of the material properties in the sand used for the model only approximately represents the actual depth profile, altering the surface motion at the mine locations. The numerical model is linear but experiments have shown that the sand is highly nonlinear and this creates increasing loss at increasing frequencies; thus, the response in the numerical model is biased toward higher frequencies enhancing the response of the smaller mines. Hence, the response of the AT mine is less pronounced in the numerical results. It can also be argued, that these numerical results show that the imaging algorithm can be significantly improved. The image from the numerical results has obvious clutter, but the numerical model has no unspecified clutter or noise. Thus, the clutter in the image must be an artifact of the algorithm that produced it.

The model does, however, predict the placement of the mine's image at the back of the true extent of the mine, just as it has occurred in the experiment. It is possible that the enhancement in the experimentally measured mine signature is due to the trenching effect of its burial. This was the focus of a previous theoretical and experimental study [6].

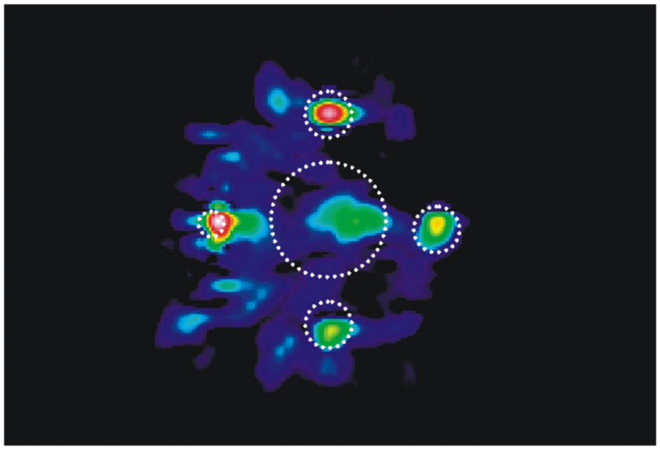

Fig. 4. Image formed from numerical simulation of data from the multiple mine burial scenario on a 30-dB scale.

CONCLUSIONS

Imaging of multiple mines buried in close proximity in the presence of clutter has been demonstrated using a seismic imaging system. The results of this experiment are in good agreement with a numerical model. Both model and experiment show the system's ability to individually image small AP mines in close proximity to a much larger AT mine. Model and experiment also demonstrate that natural mine-sized clutter, in similarly close proximity, does not pose a serious problem for system operation.

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