Experimental Measurements for a Seismic Landmine Detection System

Gregg D. Larson\textsuperscript{(a)}, James S. Martin\textsuperscript{(a)}, Waymond R. Scott, Jr.\textsuperscript{(b)}, and George S. McCall II\textsuperscript{(c)}

Georgia Institute of Technology
\textsuperscript{(a)}Woodruff School of Mechanical Engineering
\textsuperscript{(b)}School of Electrical and Computer Engineering
\textsuperscript{(c)}Georgia Tech Research Institute
Atlanta, GA 30332-0405

ABSTRACT

Experimental and numerical models have been utilized at Georgia Tech in the research and development of a seismic landmine detection technique which generates seismic waves in the soil using a surface-coupled electrodynamic transducer and detects normal surface displacements with a non-contact radar sensor. As the numerical models have shown a strong dependence upon material properties of the soil as a function of depth, experiments have been conducted at six field sites and in the experimental model to quantify the effect of different soil conditions upon the operation of the seismic landmine detection system and to measure depth-dependent material properties. Measurements have been made with and without buried anti-personnel and anti-tank mines to determine the effects that landmines have upon the propagation of seismic waves. Surface waves have been measured using the non-contact radar sensor as well as triaxial accelerometers and geophones. Post-processing has included the examination of particle motion in three dimensions, the identification of individual wave types through polarity tracking and dispersion curves, and the extraction of individual propagating waves. The field sites include wet and dry sand at a beach, a roadbed at a U. S. Government facility in a temperate climate, frozen ground, clayey soil with and without rocks, and a silt-sand mixture in a coastal region.

Keywords: Landmine detection, Seismic, Acoustic

1. Introduction: Seismic Landmine Detection Technique

In recent years, landmine detection research undertaken at Georgia Tech has included the research and development of a seismic landmine detection technique with a balanced approach utilizing numerical models, experimental models, and field experiments\textsuperscript{1-6}. The prototype system, shown in Figure 1, uses a surface-contacting electrodynamic source to excite seismic waves that propagate through the region of interest. The source-to-ground coupling has been designed to preferentially excite Rayleigh surface waves as they best interrogate the near-surface layers. As the seismic waves propagate through the soil, they interact with buried objects (i.e., landmines, rocks, sticks, shrapnel, etc.) and are scattered and reflected. Interactions of the seismic waves with buried landmines, however, create a distinct detection cue in that the landmines are excited and exhibit resonant oscillations that persist well after the seismic waves have passed the burial location. The resonance of the landmine-soil system results in increased motion of the surface directly over the landmine, which, in turn, indicates the presence of a landmine. The seismic landmine detection system measures the normal surface displacements of the soil surface using a non-contact radar sensor. Further details of the system are available in the literature.

The development of the laboratory models and the 3-D finite-difference time-domain (FDTD) models was done synergistically to leverage the knowledge gained from one effort in the other. For example, when it was observed that a loosely-packed region around a recently buried landmine increased the measured surface displacements in the laboratory model, the same conditions were modeled using the FDTD models to verify the experimental results\textsuperscript{7}. Similarly, variations in depth-dependent properties (i.e., density, compressional wave speed, and shear wave speed) of the numerical model demonstrated changes in the modeled surface displacements that were attributed to the changes in
material properties in the numerical model. Subsequent sampling of the material properties in a borehole in the laboratory model, shown in Figure 2a, and a borehole measurement with accelerometers confirmed that the surface wave propagation was highly dependent upon the material properties of the near-surface layers of the soil.

In light of the dependence of the surface wave propagation upon the material properties beneath the soil surface in the laboratory model, a series of field experiments were conducted to characterize seismic propagation effects at field sites with diverse soils and environmental conditions. Field measurements were conducted in wet and dry sand at a beach site in Monterey, California; a sand-silt-clay mixture with high stiffness in Smyrna, Georgia; a sand-silt-clay-rocks mixture with high stiffness in Woodbury, Georgia; a coastal region with a sand-silt mixture on Skidaway Island, Georgia; frozen ground in Hanover, New Hampshire; and a roadbed site at a U. S. Government test facility in a temperate climate. The main goal of the field measurements was to transition the system development from the laboratory to more typical field settings by characterizing the propagation of seismic waves in realistic soils, providing experimental data to be used for hardware development, numerical modeling, and signal processing research.

Field measurements were done to characterize the propagation of seismic waves using triaxial geophones and accelerometers, shown in Figure 2b, as well as a field-operable prototype of the radar sensor mounted in a three-axis, computer-controlled positioner, shown in Figure 2c. A typical field array of geophones and accelerometers is shown in Figure 2d with a closeup of the installed sensors in the inset photograph. The use of triaxial sensors provided insight into the particle motion in three orthogonal directions at different propagation distances and depths. The additional information provided by measuring the motion in three axes allowed the examination of data using hodograms and polarity tracking. In the laboratory model, a bi-level array of accelerometers was installed so that surface and sub-surface motion could be measured; this allowed the observation of the change in direction of the particle motion of the Rayleigh wave with increasing depth. This type of measurement using a bi-level array at field sites was not possible as the existing soil fabric would have been destroyed by the installation of the sensors. Post-processing of the data allowed for extraction of individual seismic waves from the data and inversion of near-surface material properties.
2. Field Experiments

In the following sections, several field measurements will be discussed in terms of development of the seismic landmine detection system. Specifically, overall system measurement speed, determination of material properties of the near-surface layers, and ground input impedance in different soils will be addressed.
2.1. Coastal Region at Skidaway Island, Georgia

Two types of experiments were conducted at the Skidaway Institute of Oceanography on Skidaway Island, Georgia. The first set of experiments investigated the effect of measurement time upon the landmine detection system’s ability to measure surface wave motion and to successfully detect buried landmines. The second set of experiments was done to determine the shear wave speed profile as a function of depth in the near-surface layers at the site.

2.1.1. Measurement Time Experiments

Based upon the observation that the field sites tended to be quieter in terms of ambient seismic noise than the laboratory model, the decimation of long time records in the frequency domain was completed using a two-dimensional scan of a buried anti-tank (AT) mine to determine the necessary measurement time for successful detection of a buried landmine at a field test site. It was demonstrated analytically that the measurement time could be reduced from the standard 4.096 seconds to as short as 0.064 seconds while still detecting the landmine. To validate this result in real time experimentally, a set of measurements were undertaken to test the prototype system’s limits in regards to measurement time. In the first test, measurements were conducted on a 2m long scan region using varying time length signals. The data for a 2 m scan over a region with no buried landmines with measurement times which ranged from 0.064 to 4.096 seconds are presented in Figure 3 as waterfall plots. The measurement times for each waterfall are indicated above the data. In the waterfall plots, each trace represents the measured surface displacement at a given distance from the seismic source. The trace at the bottom of each column was measured 115 cm from the seismic source. With 2 cm separation between adjacent measurements, the trace at the top of each column was measured 315 cm from the seismic source for a total scan length of 2 m. In Figure 3, the surface waves are readily apparent in all four waterfalls. As the measurement time decreases, the effect of the ambient seismic noise becomes more noticeable as the signal-to-noise ratio (SNR) decreases.

![Figure 3: Waterfall comparison of different length chirps](image-url)
These measurements were repeated with a TS-50 anti-personnel (AP) landmine buried 0.25 inches deep, 50 cm into the scan region; the data recorded with measurement times of 4.096, 1.024, and 0.256 seconds are shown in Figure 4. The shaded region in the waterfalls indicates the location of the buried landmine. In all three waterfalls, the resonance of the landmine can be observed to continue after the seismic waves have passed the burial location. Thus, shorter measurement times can be used to detect the presence of buried landmines in field settings.

![Image showing the detection of TS-50 Anti-Personnel Landmine with Three Different Measurement Times](image)

Figure 4: Detection of TS-50 Anti-Personnel Landmine with Three Different Measurement Times

In previous experiments, measurements have been made with a scanning method where the radar sensor was moved to a location, the seismic source generated a transient signal, the surface displacements were measured, and the process was repeated until the entire scan region had been measured. With this point-by-point measurement technique, as the interrogation time decreases, the measurements approach the limit of becoming a continuous measurement. To test the present system in a continuous-scanning mode, a set of measurements were conducted on a 1.22 m by 0.8 m scan region with a TS-50 AP landmine buried 0.25 inches deep in the middle of the scan region. The seismic source continuously generated a 0.256 second frequency-swept chirp from 60 Hz to 1000 Hz while the radar sensor was moved over the scan region to measure the surface displacements as a function of time and location. For comparison purposes, a point-by-point measurement was conducted over the same region using a 0.064 second frequency-swept chirp from 60 Hz to 1000 Hz. The point-by-point measurement had to be stopped before finishing the entire scan region as rainfall flooded the test area; thus, the measurement only covered a 0.78 m by 0.8 m region but did include the TS-50 landmine.

The data from these measurements are presented as images in Figure 5 on a 30 dB scale. In both of these images, the seismic source was located to the left of the presented scan region. Both images indicate the location of the buried landmine in the presence of ambient noise. In Figure 5a, the point-by-point measurement shows increased noise at the right side of the scan region; this can be attributed to the increased propagation distance to this portion of the scan region (and resulting lower SNR) and to the increasing height of the water table due to the rain. In Figure 5b, the continuous-scanning measurement exhibits greater noise throughout the scan region. This increased noise is due to...
increased electrical and mechanical noise of the prototype system. The continuous motion of the stepper motors introduced added vibrations in the positioner resulting in motion of the radar sensor relative to the ground. There was increased electrical noise due to cross-talk interference between the stepper motor control signals and the measurement signals. As the positioner was designed for point-by-point measurements, the noise caused by operating the positioner in a continuous scanning mode was not unexpected; redesigning the positioner and controllers for continuous scanning would significantly improve the performance by reducing the added noise. In spite of this added noise, the system successfully detected the presence of the buried landmine.

Figure 5: Image Comparison of Detection of TS-50 AP Mine with (a) 0.064 second Measurement Time with Point-by-Point Measurement and (b) 0.256 second Measurement Time with Continuous Measurement

2.1.2. Inversion of Shear Speed Profile

Two separate field experiments at Skidaway Island, Georgia, were conducted with the accelerometers and geophones to determine the sub-surface structure through inversion techniques. Skidaway Island is a coastal area in southern Georgia with many distinct layers present in the soil structure. From numerous surface array measurements at two proximate locations with geophone and accelerometer arrays, a composite dispersion relation was determined as shown in Figure 6a. The corresponding inverted shear speed profile is shown in Figure 6b. Thinner layers were used closer to the surface due to the inherent properties of the Rayleigh wave and its interrogation depth variation. The general increase in the shear speed with increasing depth is to be expected as the soil is compacted due to overburden. However, the occurrence of slower speeds beneath the surface is an interesting feature, most likely caused by the presence of grass roots in the near-surface layers.

2.2. Sand/Silt/Clay/Rock Soil at Woodbury, Georgia

Surface waves are primarily shear-like in nature, and their propagation speeds are close to the speed of bulk shear waves. For this reason, it is impractical to invert the stratification of compressional wave speeds by the techniques used for determining the shear speed structure from measured surface waves. However, borehole and trenching techniques are appropriate for inverting the compressional wave speed profile. Trenching proved to be more effective than borehole measurements because the triaxial sensors were extremely sensitive to orientation and surface coupling, both of which were difficult to control within the confinement of a shallow borehole. A trench measurement was conducted in a field experiment at the Woodbury Research Facility of the Georgia Tech Research Corporation in
Woodbury, Georgia. The facility was built upon an area that was graded and prepared for construction in 1975 and has remained unchanged since that time; the top four to six inches of soil was graded while the deeper soil was untouched. The soil is a mixture of sand, silt, and clay with large amounts of rocks; the soil structure presents a medium with a high stiffness and a large number of inhomogeneities. The near-surface layers can be seen in the trench shown in the photograph in Figure 7a. An accelerometer array was installed from 12.5 cm below the surface to a depth of 125 cm in a trench at the site, shown in Figure 7b, to measure the compressional wave speed as a function of depth. A surface-coupled electrodynamic transducer was located at various distances from the trench to generate the seismic waves.

Based upon ray theory, the compressional wave speed was determined as a function of depth by matching the measured first-arrival times with computed arrival times based upon wave speeds in multiple layers of the soil. The measured delays from a variety of source locations were used to numerically invert the compressional wave structure by tracing incident ray paths and using the Nelder-Mead simplex search algorithm to select an appropriate stratification while repeatedly bisecting the presumed structure in order to seed the search; this method is quite similar to those used for the inversion of deep earth structures from earthquake data. The final compressional wave speed profile is shown in Figure 8. The major sources of error appear to be from the accuracy of the manual arrival time evaluations and from the choice of source locations for the experiment.

2.3. Input Impedance at Various Field Sites

To interrogate the soil for the presence of buried landmines, a seismic landmine detection system must be capable of generating Rayleigh surface waves in the region to be investigated. As the amplitude of the Rayleigh wave decays exponentially with depth, it is well suited to investigating the near-surface layers for the presence of buried landmines. As the penetration distance is proportional to the wavelength, lower frequencies will interrogate deeper layers than higher frequencies. Measurements conducted at the field sites included the determination of the ground input impedance. This measurement was accomplished with an accelerometer mounted on the seismic source’s foot to measure the acceleration imparted to the ground by the source and a current probe to measure the current provided to the source by the power amplifier. As the seismic source is an electrodynamic transducer, the input current is proportional to the excitation force. Thus, the ground input impedance was found from the ratio of the acceleration of the source foot to the input excitation force when the seismic source was placed on the ground. Data from four of the field sites are shown in Figure 9: (a) the Cobb County Research Facility of the Georgia Tech Research Institute in

![Figure 6: Near-surface Soil Structure at Skidaway Island, Georgia: (a) Dispersion Relation of Rayleigh Surface Wave and (b) Inverted Shear Speed Profile.](image)
Smyrna, Georgia; (b) the Woodbury Research Facility of the Georgia Tech Research Corporation in Woodbury, Georgia; (c) the Skidaway Institute of Oceanography on Skidaway Island, Georgia; and (d) a U. S. Government test facility in a temperate climate. The vertical axis is the measured acceleration of the source divided by the driving current, which is proportional to the force, in uncalibrated units. It is clear from the figure that the source and soil coupling together behave like a single-degree-of-freedom spring-mass system. The stiffness that dominates the low-frequency region is contributed by the soil whereas the mass includes both the moving mass of the source and the radiation mass and is relatively site-independent. Sites exhibiting higher resonances had higher soil moduli and required larger excitation signals to achieve comparable seismic displacements to the sites with softer soils.

Figure 7: Trench Measurements at Woodbury, Georgia: (a) Accelerometers Installed in Trench and (b) Surface-coupled Seismic Source

Figure 8: Compressional Wave Speed Profile from Ray-tracing Inversion of Trench Data at Woodbury, Georgia
3. Conclusions

Field measurements have provided additional knowledge concerning the operation of a seismic landmine detection system in typical soils and environmental conditions. Anti-personnel and anti-tank landmines have been successfully detected in soils at field sites and at U. S. Government testing facilities. Seismic propagation effects have been studied in a variety of soils and conditions with the non-contacting radar sensor and surface-contacting accelerometers and geophones. The use of triaxial sensors has allowed the examination of particle motion and polarity of the propagating waves for wave type identification in these studies. Measurements of ambient seismic noise at the field test sites have demonstrated lower ambient noise levels at the field sites as compared to the laboratory model. Thus, shortening the measurement time for field tests has been shown to be possible with no loss of detection capabilities for the system. Further, a continuous scanning mode has been tested with comparable results to measurements made using the standard point-by-point method in spite of hardware-related noise issues. Modifications to the hardware would significantly improve the results. Examination of the particle motion in order to extract individual waves has led to a better understanding of the seismic wave motion and improved signal processing for the system in general.
ACKNOWLEDGEMENTS

This work was supported in part by the Office of Naval Research under Contract Number N00014-01-1-0743 and in part by the U. S. Army Research Office under Contract Number DAAD19-02-1-0252.

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