Detection of Buried Land Mines with High-Frequency Seismic Waves

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April 22, 2002
Outline

• Introduction

• Theoretical Model
  – Interaction of Elastic Waves with a Buried Land Mine
  – Resonant Behavior of a Buried Land Mine

• Experimental Model
  – Laboratory Model
  – Field Model

• Elastic Wave Sources and Sensors
  – Focused Antenna Array

• Conclusions
Elastic/Electromagnetic Sensor

Configuration of the Sensor Currently being Studied
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Elastic Waves in the Ground

- To investigate the elastic wave motion in the soil, a numerical model has been developed.
- Scenario:
  - A source on the surface launches elastic waves.
  - The waves propagate along the surface and in the medium.
  - The waves are scattered by an object buried in the ground.
Elastic Waves in the Ground

- Pressure Wave
- Shear Wave
- Rayleigh Surface Wave
- Lateral Wave
- Leaky Surface Wave

Waves in the far field:
3-D model: semi-infinite half-space.
Medium is assumed to be linear, isotropic, lossless.
The transducer (source) is modeled by exciting the normal particle velocity on the surface.
The air-ground interface is modeled by a free-surface boundary condition.
The solution space is surrounded by a Perfectly-Matched-Layer (PML) absorbing boundary.
A discrete numerical grid is introduced.
Material Properties

- In experiments, mines have been buried in sand.
- The material properties of sand can be described by three independent quantities: $\rho$, $c_p$, $c_s$.
- The soil properties of sand have been measured as a function of depth:
  - Due to changes in the water content, the material density changes with depth.
  - Both shear and pressure wave speed vary with depth.
  - “Slow” layer close to the surface. Pressure and shear wave speed increase rapidly beyond the surface layer.
Polarization of Surface Waves Observed in the Models
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Antipersonnel Mine

Model
- Mine is discretized with cubes;
- Main chamber consists of plastic explosives;
- Trigger mechanism (springs, firing pin);
- Small air-filled plastic case;
- Rubber pressure plate;
- Air-chambers

TS-50 Mine
- Plastic explosive,
- Trigger mechanism;
- Plastic case;
- Rubber pressure plate;
- Air-chambers
Mine-Wave Interaction

Source

Mine

80 cm

2 cm
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Detailed Mine Model

- The mine model used thus far is very simple.
- To study the resonance at the mine location, a mine model is created which includes more details of the mine:
  - Case
  - Explosives
  - Rubber Plate
  - Air Chambers
Detailed Mine Model

- Mine buried 2 cm beneath the surface.
- $\varphi = 1400 \text{ kg/m}^3$, $c_p = 250 \text{ m/s}$, $c_s = 40 \text{ m/s}$
Resonance

- Mine buried 1 cm beneath the surface
- Shear wave speed $c_s = 40$ m/s
- The pressure wave speed and the material density are kept constant in the following:
  - $c_p = 250$ m/s
  - $\rho = 1400$ kg/m$^3$
Resonance

- Resonance as a function of the shear wave speed:
- Mine buried at 2 cm
Resonance

- Resonance as a function of burial depth:
- Shear wave speed $c_s = 40 \text{ m/s}$
Resonance

• First resonance:

Resonant Frequency

Quality Factor
Experiment

• TS-50 AP mine at 1 cm
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Experimental Results

- Both anti-tank and anti-personnel mines have been investigated.
  - Anti-Tank Mines
    - Two Inert Mines: VS-1.6 and VS-2.2.
    - Acrylic Plastic: 30 cm by 30 cm by 7.5 cm.
    - Simulated Mine: SIM-30; depths to 30 cm.
  - Anti-Personnel Mines
    - Four Inert Mines: PFM-1, M-14, TS-50, and VS-50.
  - Clutter Items
    - Rocks, Sticks, Cans, Surface Cover (Pine Straw).

- Resonance
  - All of the inert AP and AT mines studied exhibit a resonant response which enhances the response of the mine and can be used to help distinguish it from clutter.
  - Other types of mines are expected to exhibit this type of resonance.
Experimental Results

• Results presented today.
  – Laboratory Experiment: Sandbox
    • Single TS-50 mine
    • Single AT mine surrounded by AP mines and clutter.
  – Field Experiment: Georgia Red Clay: CCRF
    • Single TS-50 mine.
Diagram of the Laboratory Model

Elastic Waves

Elastic Wave Transducer

Region scanned with the radar

Mine

Damp Compacted Sand

6.1 m

5.8 m

1.5 m

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Laboratory Experiment
TS-50 Mine 1cm Deep
TS-50 Mine: 1 cm deep
Raw Measured Data: Focused Antenna 20 cm High;
Radar A with Radar B operating

○ Mine
Signal Processing

• Filter out forward traveling waves, leaving only the reflected waves.
  – Enhance the signature of the mine.
  – Resonance.

• Image.
  – Energy in the reflected wave at times near the time of arrival of the incident wave.
TS-50 Mine: 1 cm deep
Image: Dual Focused Antenna 20 cm High
15 cm of Pine Straw
30 dB Scale

Antenna A

Antenna B
Experimental Results

• Single AT (VS1.6) Mine surrounded by Multiple AP mines and clutter.
  – VS1.6 buried 4 cm deep.
  – VS-50 buried 1 cm deep.
  – TS-50 buried 1 cm deep.
  – PFM-1 buried 1 cm deep.
  – Two rocks buried approximately 2 cm deep.
  – Two metal cans buried 2-3 cm deep.
  – Metal rod buried 2 cm deep.
  – Wood stick buried 2 cm deep.
Minefield Covered with 15 cm of Pine Straw
Photograph of the Uncovered Mines and Rocks.
Single AT Mine Surrounded by AP Mines and Clutter
Raw Measured Data: Focused Antenna 20 cm High; 15 cm of Pine Straw
Single AT Mine Surrounded by AP Mines and Clutter
Raw Measured Data: Focused Antenna 20 cm High; 15 cm of Pine Straw
30 dB Scale

Surface Clean

Surface Covered with 15 cm of Pine Straw

Intensity, dB

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Field Experiment
Georgia Red Clay: CCRF
Field Experiment; CCRF
TS-50 Mine 0.5 cm deep
Field Experiment; CCRF
TS-50 Mine 0.5 cm deep

Focused Antenna 20 cm High; 30 dB Scale
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Elastic Wave Sources and Sensors Development

- Electrodynami"shaker
- Air acoustic source
- Electrical arc source
- Passive air acoustic sensor
- Ultrasonic sensor
- Radar sensor
Array of Stand off Sensors

- Requirements
  - Standoff
  - Spatial resolution
  - Sensitivity
  - Speed
    - Linear $N$ element array: $N$ times faster
    - Planar $N$ by $N$ array: $N^2$ times faster
  - Surface roughness
  - See though surface vegetation/clutter
  - Cost
Current Radar Sensor

Elastic Wave Source

Elastic Wave

Elastic Wave Beam

Radar Beam

Lens-Focused Corrugated Horns
Focused Antenna

Lens-Focused Corrugated Horn
Conclusions

• The technique shows great promising.
  – System detects both simulated AP and AT mines.
  – System discriminates between mine and some common types of clutter.
  – Focused antenna and array perform well.
  – System seems to be robust in varying soil conditions.

• Ongoing investigations.
  – Focused antenna array.
  – Alternative sensor arrays.
  – Signal processing techniques.
  – Mechanical properties of soils (wave speeds vs depth, nonlinearities, etc.).
  – Range of soil types.