Performance of demining sensors and soil properties

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Introduction

- Landmines are buried in soil
- Sensors are required to detect
  - Metal detector ... *Detection*
  - Ground-penetrating radar (GPR) ... *Identification*
  - Both employ EM techniques – *Influenced by soil EM properties*

Investigation on soil magnetic/dielectric properties
  - Prediction of the influence
  - Soil characterisation for demining sensors, *metal detector & GPR*
  - Comparison to field trial results
Soil influence on metal detector

Induced voltage in non-conducting soil:

\[ v^{\text{soil}} = j\mu_0 \omega \pi ab \left[ \frac{\kappa(\omega)}{2 + \kappa(\omega)} \right] m(h) \]

- Magnetic susceptibility \( \kappa \)
- Frequency dependence of magnetic susceptibility \( \kappa(\omega) \)
  Very influential

- Electric conductivity \( \sigma \)
  Has to be very high to be influential as much as susceptibility

Creates additional metal detector responses – *false alarms*

Ground compensation has to be turned on – *loss of sensitivity*
Soil Influence on GPR

Reflection coefficient of GPR signals: \[ \Gamma \approx \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \]

• Dielectric permittivity \( \varepsilon \)
  - Absolute level alone is not so influential on the performance
  - Contrast between soil and target dominates reflectivity
  - Permittivity changes within soil also reflect signals

• Electric conductivity \( \sigma \)
  - Attenuates GPR signal – *shortens penetration depth*
  - Contrast has to be very high to be influential on reflectivity

• Magnetic permeability \( \mu \) (susceptibility \( \kappa \))
  - Has to be extremely high to be influential
Spatial variation of properties

Heterogeneity in:
• magnetic susceptibility may disable the soil compensation of metal detector
  - *false alarms, loss of sensitivity*
• dielectric permittivity causes additional GPR responses
  - *false alarms, miss-identification*

Soil heterogeneity can be quantified by:
  Correlation length: spatial length of changes
  Variability: magnitude of changes

Soil heterogeneity influences detection if ...
• correlation length is similar to target dimension
• variability is high
Soils in ITEP test in Germany in 2009

Laterite – Red-coloured *laterite*, the texture is clay loam
Magnetic sand – Engineered *magnetite* artificially mixed with *coarse sand*
Humus A – *Loam* with *low stone content*
Humus B – *Loam* with high humus and *high stone content*
Soil property measurements

- Spatial variation of $\kappa$ — susceptibility meter (F)
- Frequency dependence of $\kappa$ — susceptibility bridge (L)
- Spatial variation of static $\sigma$ — ERT; electrical resistivity tomography (F)
- Frequency dependence of $\sigma$ — SIP; spectral induced polarisation (L)
- Spatial variation of $\varepsilon$ — TDR; time-domain reflectometry (F)

F: field measurement
L: Lab. measurement

Susceptibility meter
Apparent resistivity measurement
TDR measurement
Magnetic susceptibility

**Frequency dependence of magnetic susceptibility**

<table>
<thead>
<tr>
<th></th>
<th>Laterite</th>
<th>Magnetic sand</th>
<th>Humus A</th>
<th>Humus B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute value</td>
<td>Very high</td>
<td>Very high</td>
<td>-</td>
<td>Very low</td>
</tr>
<tr>
<td>Frequency dependence</td>
<td>High (6 %)</td>
<td>Very low (0.1 %)</td>
<td>High (7 %)</td>
<td>Very low (1 %)</td>
</tr>
<tr>
<td>Spatial variation</td>
<td>Small (8.4 %)</td>
<td>Small (7.4 %)</td>
<td>-</td>
<td>Large (38.9 %)</td>
</tr>
</tbody>
</table>

**Relative spatial variability of magnetic susceptibility**

*Serious Influence on metal detector in Laterite is expected*
Spatial variation of electric conductivity

Spatial variation:  *Magnetic sand* < *Laterite*, *Humus A* < *Humus B*

*Absolute level:* Not high in all soils
Frequency dependence of electric conductivity

- Measured by SIP (spectral induced polarisation) method (up to 6 kHz)
- Extrapolated by the Cole-Cole model (Cole and Cole, 1941)

\[ \rho(\omega) = \rho_0 \left\{ 1 - m \left[ \frac{1 - \frac{1}{1 + (j\omega\tau)^c}}{1 + (j\omega\tau)^c} \right] \right\} \]

\( \rho_0, m, \tau, c: \) model parameters

Frequency dependence of electric conductivity

<table>
<thead>
<tr>
<th></th>
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<th>Humus B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin depth [m]</td>
<td>2.2 – 12.3</td>
<td>10.5 – 31.6</td>
<td>-</td>
<td>1.3 – 5.0</td>
</tr>
<tr>
<td>Attenuation constant [dB/m]</td>
<td>0.7 – 4.0</td>
<td>0.3 – 0.8</td>
<td>-</td>
<td>1.7 – 6.8</td>
</tr>
</tbody>
</table>

Conductivity is not high in all soils ... no serious influence is expected
## Spatial variation of dielectric permittivity

Laterite, **humus**:  
- high in average  
- large spatial variation

Magnetic sand:  
- low in average  
- very small spatial variation

<table>
<thead>
<tr>
<th>Source</th>
<th>Laterite</th>
<th>Magnetic sand</th>
<th>Humus B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>High (14.9)</td>
<td>Low (4.8)</td>
<td>High (20.1)</td>
</tr>
<tr>
<td>Correlation length [m]</td>
<td>0.38</td>
<td>0.26</td>
<td>0.15</td>
</tr>
<tr>
<td>Variation</td>
<td>Large (18 %)</td>
<td>Very small (4 %)</td>
<td>Large (19 %)</td>
</tr>
</tbody>
</table>

**Serious influence on GPR in Humus B is expected**
Estimated soil impact on sensors

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$\kappa$</td>
<td>Very high</td>
<td>Very high</td>
<td>Very low</td>
<td>Very low</td>
</tr>
<tr>
<td>(\kappa(\omega))</td>
<td>Very high</td>
<td>Very low</td>
<td>High</td>
<td>Very small</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>$\varepsilon$, $\theta$</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>$\varepsilon(r)$</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Very large</td>
</tr>
<tr>
<td><strong>MD</strong></td>
<td><strong>Very severe</strong></td>
<td><strong>Moderate</strong></td>
<td><strong>Neutral</strong></td>
<td><strong>Neutral</strong></td>
</tr>
<tr>
<td><strong>GPR</strong></td>
<td><strong>Moderate</strong></td>
<td><strong>Neutral</strong></td>
<td><strong>Severe</strong></td>
<td><strong>Very severe</strong></td>
</tr>
</tbody>
</table>

- $\kappa$: Magnetic susceptibility
- $\kappa(\omega)$: Frequency dependence of magnetic susceptibility
- $\sigma$: Electric conductivity
- $\varepsilon$, $\theta$: Permittivity (dielectric constant), water content
- $\varepsilon(r)$: Spatial variation of permittivity

Metal detector:
- Humus B < Humus A < Magnetic sand < Laterite

GPR:
- Magnetic sand < Laterite < Humus A < Humus B
Detector performance in blind test

5 commercial metal detectors & dual sensor system (MD+GPR)
 Approx. 400 targets (landmines, metal pieces)

Performance of metal detector
+ POD (Probability of detection):
  How many mines detected … 0 % (no mines) 👎
               … 100 % (all mines) 👍
- FAR (False alarm rate):
  How many false alarms produced in unit area

Performance of dual sensor (GPR)
+ FAR reduction:
  How many false alarms reduced by GPR … 0 % (no FA reduced) 👎
                                    … 100 % (all FA reduced) 👍
- POD loss:
  How many mines falsely rejected by GPR … 0 % (no mines rejected) 👎
                               … 100 % (all mines rejected) 👎
Detector performance and soil influence

If soil influence is estimated correctly...

- **Negative feature** – increases (FAR, POD loss)
- **Positive feature** – decreases (POD, FAR reduction)

Soil types in the order of difficulty

If soil influence is estimated incorrectly...

- **No correlation with soil types**

Soil types in the order of difficulty
MD performance and soils

POD – how many mines/metals found
FAR – how many false alarms obtained per a square metre

Difficult soil: Lower POD, higher FAR
Easy soil: Higher POD, lower FAR

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>POD</th>
<th>Magnetic sand</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Laterite</td>
<td>64%</td>
<td>85%</td>
<td>82%</td>
<td>84%</td>
</tr>
<tr>
<td>Magnetic sand</td>
<td></td>
<td>85%</td>
<td></td>
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<td></td>
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Positive feature
MD performance and soils

**POD** – how many mines/metals found

**FAR** – how many false alarms obtained per a square metre

*Difficult soil: Lower POD, higher FAR*

*Easy soil: Higher POD, lower FAR*

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Difficult soil: Lower POD, higher FAR

Easy soil: Higher POD, lower FAR

**Negative feature**
MD performance and soils

POD – how many mines/metals found
FAR – how many false alarms obtained per a square metre

Difficult soil: Lower POD, higher FAR
Easy soil: Higher POD, lower FAR

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<tr>
<td>Laterite</td>
<td>64 %</td>
<td>85 %</td>
<td>1.39 m²</td>
</tr>
<tr>
<td>Humus A</td>
<td>82 %</td>
<td>0.86 m²</td>
<td>1.06 m²</td>
</tr>
<tr>
<td>Humus B</td>
<td>84 %</td>
<td>0.70 m²</td>
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**DS (GPR) performance and soils**

FAR reduction – how many metals/false alarms reduced by GPR

POD loss – how many mines falsely rejected

- **Difficult soil:** Higher POD loss
- **Easy soil:** Lower POD loss

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<td><strong>FAR reduction</strong></td>
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<tr>
<td><strong>POD loss</strong></td>
<td>6.6 %</td>
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*Positive feature*
DS (GPR) performance and soils

FAR reduction – how many metals/false alarms reduced by GPR
POD loss – how many mines falsely rejected

Difficult soil: Higher POD loss
Easy soil: Lower POD loss

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Negative feature
**DS (GPR) performance and soils**

FAR reduction – how many metals/false alarms reduced by GPR

POD loss – how many mines falsely rejected

**Easy soil:** Lower POD loss

**Difficult soil:** Higher POD loss

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GPR measurements in the test soils

Laterite (Moderate)
Curves are not so clear, but still recognisable

Magnetic sand (Neutral)
Very clear hyperbolic curves at all depths

Humus B (Very severe)
Curves are disturbed and not clear
Some are unrecognisable at all

Radar system: GSSI 1.5 GHz
Target: Gyata-64 at 5-25 cm
Summary

- Geophysical investigations in a field test
- Soil characterisation for sensors based on the geophysical investigations
- Characterisation agrees with test results

*Geophysical investigations are useful to predict performance/applicability of sensors*

**MD:** Magnetic Susceptibility (absolute level, frequency dependence)

**GPR:** Dielectric permittivity (spatial variation)

Application scenario:
1. Geophysical investigations besides a mined area
2. Characterisation/assessment of soils
3. Selection of an appropriate clearance method for the area

*Ensures the safety and efficiency of the clearance operation*