Background

- Ground Penetrating Radar (GPR) is a special kind of RADAR
- Purpose of using GPR:
  - Detect targets buried in a dielectric medium
  - Estimate their depths
- GPR applications: geophysics, archeology, law enforcement, evaluation of civil structures (buildings, bridges, pavements)

Use of GPR for Pavement Evaluation

- Flexible pavements:
  - Detect changes in pavement structures (layers)
  - Estimate layer thicknesses (can be used as input for FWD)
  - Detect subsurface distresses
  - Detect moisture presence
- Rigid pavements and bridge decks:
  - Measure concrete slab thickness
  - Detect voids or loss of support under slabs
  - Detect rebar locations and estimate cover depth
EM Properties of Materials

Interaction of a Material with Applied Electric (E) and Magnetic (H) Fields:

- Polarization
- Conductivity
- Magnetic Permeability
- Permittivity / Dielectric Constant

\[ \varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \]

Dielectric Constant Values

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
</tr>
<tr>
<td>Water</td>
<td>81</td>
</tr>
<tr>
<td>Concrete</td>
<td>3-18</td>
</tr>
<tr>
<td>HMA</td>
<td>3-10</td>
</tr>
<tr>
<td>Limestone</td>
<td>5-9</td>
</tr>
<tr>
<td>Granite</td>
<td>4-6</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>3-5</td>
</tr>
<tr>
<td>Saturated Sand</td>
<td>20-30</td>
</tr>
<tr>
<td>Silts</td>
<td>5-30</td>
</tr>
<tr>
<td>Clays</td>
<td>5-40</td>
</tr>
</tbody>
</table>

GPR Types

Three main types of GPR systems:

- Frequency modulated GPR
- Synthetic pulse GPR
- Pulsed (or impulse) GPR
  - Most common type of GPR systems
  - Principle: Transmit a short pulse (1 ns or less) and record the reflected pulses from layers
**GPR Antennas**

- **Ground-coupled:** the antenna is in contact with the ground surface
- **Air-coupled:** the antenna is 1 to 2 ft above surface
- **Monostatic:** one antenna used as Tx and Rx
- **Bistatic:** one antenna is used for Tx and another one for Rx

**Ground Penetrating Radar System**

- **Air-Coupled Antenna**
- **Ground-Coupled Antenna**
- **Transceiver**
- **Control Unit**

**Typical GPR Response (scan)**

- **Driving Direction**
- **Layer 1**
- **Layer 2**
- **Subgrade**
- **Base**
Data Collection

GPR System Description

Locating Reinforcement
Typical Problems with GPR Data Interpretation

- GPR doesn’t provide “real” images of the subsurface
- Dielectric properties unknown
  - Dielectric properties change with depth/moisture presence
- Sufficient contrast between layer dielectric constants should exist
- Material “loss” reduces GPR detectability of bottom layer interfaces
- Thin pavement layers are difficult to resolve
- Extensive amount of data is collected
- GPR results are operator dependent
Layer Thickness Estimation

- Calculate the thickness $d_i$ of the $i^{th}$ layer.

$$d_i = \frac{c t_i}{2 \sqrt{\varepsilon_{r,i}}}$$

- $c$ is the speed of light in free space (0.3m/ns)
- $t_i$ is the reflection amplitude from interface
- $\varepsilon_{r,i}$ is the relative permittivity or dielectric constant of layer $i$

Preprocessing

Enhance signal quality:
- Noise filtering
- Coupling pulse removal
- Depth resolution enhancement

GPR (UWB 1GHz) susceptible to noise: CB radios, cell phones, cell phone towers, etc.
### Noise Filtering

Elliptic low-pass filter: most efficient filter
- Lowest order → fast to run on data
- Lowest transition bandwidth → high performance

![Original Signal and Filtered Signal](chart)

### Coupling Pulse Removal

- $E_t$: Transmitted
- $E_r$: Reflected
- $E_c$: Coupling
- $E_{er}$: End Reflection

![Amplitude vs. Time](chart)

### Cross-correlation

- Normalized Cross-correlation
- $yc(t)$ and $yr(t)$

![Cross-correlation Chart](chart)

### Shifted Signals

- $yc(t)$ and $yr(t)$

![Shifted Signals](chart)
Dielectric Constant Estimation Methods

- Amplitude of reflected signal
- Common Midpoint
- Modified Common Midpoint
- Iteration (most applicable to airport pavements)
- New Modified Common Midpoint

Dielectric Constant Using Amplitude

\[
\epsilon_{r,1} = \left( \frac{1 + \frac{A_r}{A} - \frac{\Delta \epsilon}{\epsilon_{r,1}}}{1 - \frac{A_r}{A} - \frac{\Delta \epsilon}{\epsilon_{r,1}}} \right)\]

\[
\epsilon_{r,2} = \epsilon_{r,1} \left( \frac{1 + \frac{A_r}{A} + \frac{\Delta \epsilon}{\epsilon_{r,1}}}{1 - \frac{A_r}{A} + \frac{\Delta \epsilon}{\epsilon_{r,1}}} \right)\]

\[
\epsilon_{r} = \sqrt{\epsilon_{r,1}^2 + \epsilon_{r,2}^2}\]

Thickness Accuracy

Relative Layer Thickness Error versus Error in Dielectric Constant Estimation for Different Values of \(\epsilon_r\)
Application for Quality Assurance

- SM-12.5 w/ PG 76-22
- IM-19.0 (2) w/ PG 76-22
- IM-19.0 (1) w/ PG 64-22
- BM-25.0 w/ PG 64-22
- 21-B aggregate base
- Lime stabilized subgrade

GPR Data Collection

- GPR surveys were performed on each layer after its construction
- Three surveys were performed per lane and per layer; in total, 36 surveys were performed
- DMI set at 10 scans/m
- For HMA layers, static measurements were taken near core locations

Typical GPR Response

- GPR Scan over 21-B Layer
- GPR Scan over HMA Base
New Pavements (QC/QA)

Classic GPR thickness estimation gives accurate results:

![Graph showing GPR accuracy for new pavements]

GPR Accuracy: New Pavements

![Graph showing GPR accuracy for new pavements]

For exiting pavement, a different method is needed because of changes in dielectric constant profile.
Dielectric Constant Using CMP

Common midpoint (CMP) technique (or common-depth point, CDP) is used as follows:

\[ v_{t1} = 2h \]

\[ v_{t2} = 2\sqrt{h^2 + (x/2)^2} \]

\[ v = \frac{c}{\sqrt{\varepsilon_r}} = \frac{x}{\sqrt{t_2^2 - t_1^2}} \]

\[ \varepsilon_r = \frac{c^2(t_2^2 - t_1^2)}{x^2} \]

\( \nu \): EM velocity in the layer

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Modified CMP Technique

Modified common midpoint technique:

Snell’s law of refraction:

\[ \sqrt{\varepsilon_r} \sin \theta = \sqrt{\varepsilon_r} \sin \theta_1 \quad (1) \]

Using the figure:

\[ 2b_0 \tan \theta_1 + x_1 = x_0 \quad (2) \]

\[ \tan \theta_1 = \frac{x_1}{2b_0} - \frac{x_1}{v_1} \quad (3) \]

\[ v = \frac{x_1}{\sqrt{t_2^2 - t_1^2}} \quad (4) \]

Modified CMP Setup

1. Measure the reflection times \( t_1 \) and \( t_2 \)
2. Calculate the transmission angle \( \theta_t \) using:
3. Find the angle \( \theta_i \) by solving numerically:
4. Solve for \( \varepsilon_r \) using:
5. Compute HMA thickness using \( t_1 \) and \( \varepsilon_{r1} \)
Modified CMP Technique Results: Old Unknown Pavements (I-81 N)

Overlay Thickness

HMA Layer Thickness

Dielectric Constant Using Modified CMP

Drawbacks

• Cannot be used to estimate the dielectric constant of thin layers or layers with high dielectric constants (because \( t_1 \approx t_2 \))
• Results are sensitive to the magnitude of the time difference (\( t_2 - t_1 \))
• It is difficult to accurately measure \( t_1 \) from ground-coupled data

Depth Resolution Enhancement

Measured Signal from: Thin layer interfaces not visible because of reflection overlap

Synthesized Signal
Measured vs. Simulated Signal

Layer Thickness Estimation by Iteration

Resolving Thin Layers
Detection Results

Detected Layer Interfaces

Resolving Thin Layers: Better Results

GPR Data Analysis Results
GPR Thickness Accuracy

Overall Thickness
Individual Thicknesses
Modified CMP Thickness

GPR Data Collection (18 Projects)

GPR Result of Dielectric Constant

Coefficient Variance of Dielectric Constant
Summary

• Errors may result from estimating dielectric constant from surface reflection
• A modified CMP technique can be used to estimate the bulk dielectric constant
• Detection stage is affected by the deconvolution procedures
• For accurate GPR thickness results the reflections from all the layer interfaces should be separated

Summary

Accuracy of GPR results depends on adopted data analysis technique
– For pavements with multiple thin layers or old pavements, use:
  • Deconvolution: individual thicknesses
  • Modified CMP technique: total thickness
– For new pavements: use classic thickness estimation technique
Thank You!