Advanced Methods to Identify Asphalt Pavement Delamination (R06D)

Minnesota DOT Evaluation: Calibration and Signal Analysis

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MnDOT

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Activity analysis and applications: Ken Maser
Advanced Analysis: Shongtao Dai
Calibration/Validation Topics

- Highway Speed GPS accuracy (MnROAD)
- Controlled Laboratory Tests (Metal Plate and HDPE plastic)
  - Sampling Rate
  - Metal Calibration
  - Air Calibration
Highway Speed GPS accuracy (MnROAD)
GPS accuracy: Implications for Implementation
## Examiner Results: MnROAD

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Core Condition</th>
<th>Qualitative GPR Signal Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>shallow slight deter/strip</td>
<td>direct shallow anomaly</td>
</tr>
<tr>
<td>2</td>
<td>insignificant</td>
<td>strong backwall</td>
</tr>
<tr>
<td>3</td>
<td>none/sound condition</td>
<td>strong backwall</td>
</tr>
<tr>
<td>4</td>
<td>lg crack/deterioration</td>
<td>backwall shadow</td>
</tr>
<tr>
<td>5</td>
<td>deterioration (coring caused?)</td>
<td>backwall shadow/little direct</td>
</tr>
<tr>
<td>6</td>
<td>slight shallow/bottom deterioration</td>
<td>backwall shadow</td>
</tr>
<tr>
<td>7</td>
<td>shallow slight deter/delam</td>
<td>direct shallow anomaly</td>
</tr>
<tr>
<td>8</td>
<td>minimal middepth stripping</td>
<td>slight shaddowing</td>
</tr>
<tr>
<td>9</td>
<td>slight deterioration/strip</td>
<td>direct reflection (deeper than distress)</td>
</tr>
<tr>
<td>10</td>
<td>shallow slight deter/delam</td>
<td>banding/shaddowed backwall</td>
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</table>
Examiner Results: MnROAD Sound Pavement, Clear Signal

<table>
<thead>
<tr>
<th>Cell 1</th>
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<tbody>
<tr>
<td><strong>Core ID</strong></td>
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<tr>
<td>3</td>
</tr>
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</table>

**Diagram:**
- Image of a cross-section showing GPR signal analysis with a strong backwall indicator.
- A core sample with a tape measure showing a depth of 2.427 ft.
## Examiner Results: MnROAD

Deteriorated Pavement, Unclear

<table>
<thead>
<tr>
<th>Core ID</th>
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<th>Qualitative GPR Signal Assessment</th>
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</thead>
<tbody>
<tr>
<td>9</td>
<td>slight deterioration/strip</td>
<td>direct reflection (deeper than distress)</td>
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</table>
## Examiner Results: MnROAD

### Cell 15

<table>
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<th>Core Condition</th>
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<tbody>
<tr>
<td>1</td>
<td>mid-depth strip/delamination</td>
<td>slight anomaly/shaddowed backwall</td>
</tr>
<tr>
<td>2</td>
<td>clear stripping</td>
<td>direct anomaly</td>
</tr>
<tr>
<td>3</td>
<td>crumbled stripping</td>
<td>direct anomaly</td>
</tr>
<tr>
<td>4</td>
<td>slight strip/deterioration</td>
<td>slight anomaly/shaddowed backwall</td>
</tr>
<tr>
<td>5</td>
<td>no significant distress</td>
<td>strong backwall</td>
</tr>
<tr>
<td>6</td>
<td>clear stripping</td>
<td>direct anomaly</td>
</tr>
<tr>
<td>7</td>
<td>clear stripping</td>
<td>direct anomaly</td>
</tr>
<tr>
<td>8</td>
<td>slight deterioration</td>
<td>edge of anomaly</td>
</tr>
</tbody>
</table>
Controlled Laboratory Tests: Sampling Rate

Effect of Oversampling

- Oversampled
- Normal

GPR Response vs. Samples
Controlled Laboratory Tests: Sampling Rate

Effect of Oversampling - Zoom

![Graph showing the effect of oversampling on GPR response over samples.](image)
Controlled Laboratory Tests: Air Calibration

Extract “Air Wave”
– Face antenna away from the surface
– Eliminate portion of the signal that is only affected by the antenna
Controlled Laboratory Tests: Metal Calibration

4'x8' Metal Surface Reflection Amplitude
– Placed in the center of the antenna array
– Use the amplitude of the surface reflection to characterize the signal magnitude
Controlled Laboratory Tests: Metal Calibration

4'x8' Metal Surface Reflection Amplitude
- Placed in the center of the antenna array
- Rotated 180 degrees and placed in the center of the antenna array

\[
\varepsilon_{HMA} = \left(1 + \frac{A_0}{A_P}\right)^2
\]

Metal Reflection Amplitude
- Metal Amplitude 0 deg
- Metal Amplitude 180 deg
Controlled Laboratory Tests: HDPE Plastic

HDPE Surface Reflection Amplitude
- Plastic Sheet (HDPE) Calibration
- Manufacturer Dielectric Listed: 2.30
- Known Dielectric can be used to evaluate effectiveness of air, metal, and oversampling calibrations

\[ \varepsilon_{HMA} = \left( 1 + \frac{A_0}{A_P} \right)^2 \left( 1 - \frac{A_0}{A_P} \right) \]
Controlled Laboratory Tests: HDPE Plastic Dielectric

\[ \varepsilon_{HMA} = \left( 1 + \frac{A_0}{A_P} \right)^2 \]

- PlasticDielectric_Before Air Removal
- Plastic Dielectric After Air removal
Controlled Laboratory Tests: HDPE Plastic Dielectric Test

Prior to air calibration

Test Setting Combinations

- OrigPair1
- OrigPair2
- OrigPair3
- OrigPair4
- OrigPair5
- OrigPair6
- OrigPair7
- OrigPair8
- OrigPair9
- OrigPair10
- OrigPair11
- OrigPair12
- OrigPair13
- OrigPair14
- OrigPair15
- OrigPair16
- OrigPair17
- OrigPair18
- OrigPair19
- OrigPair20
- OrigPair21
Controlled Laboratory Tests: HDPE Plastic Dielectric Test

After air calibration

Test Setting Combinations:
- NoAirPair1
- NoAirPair2
- NoAirPair3
- NoAirPair4
- NoAirPair5
- NoAirPair6
- NoAirPair7
- NoAirPair8
- NoAirPair9
- NoAirPair10
- NoAirPair11
- NoAirPair12
- NoAirPair13
- NoAirPair14
- NoAirPair15
- NoAirPair16
- NoAirPair17
- NoAirPair18
- NoAirPair19
- NoAirPair20
- NoAirPair21
Controlled Laboratory Tests: HDPE Plastic Dielectric Test

- **Dielectric Standard Deviation**

  - Test Settings Combination
    - WithAirCalibration
    - No Air Calibration

  - Graph shows a comparison between dielectric standard deviation for different test settings combinations with and without air calibration.
Controlled Laboratory Tests: HDPE Plastic Dielectric Test

![Graph showing dielectric standard deviation vs. test settings combination for two conditions: With Air Calibration (orange dots) and No Air Calibration (blue dots). The graph indicates a comparison of the standard deviation values across different test settings combinations, highlighting the variability in dielectric properties under the two conditions.](image)
• 3D Radar equipment can integrate the GPS with the GPR data with high accuracy even at highway speed
  – Useful to integrate an external GPS connected to a virtual reference station or other correction method to get full potential of equipment
  – This allows for selection of validation cores fully based on GPS data
  – Improved accuracy and efficiency of selecting core validation locations

• Incorporation of oversampling, metal, and air calibration into analysis can improve 3D radar signal
  – 3D Radar is working on incorporating some of these calibration options, but none are currently available in examiner and require outside analysis.
  – Oversampling can improve digital representation of the true analogue signal which is important for amplitude calculations and filtering technique applications
  – Metal and air calibrations are critical to addressing antenna to antenna variation and reducing signal noise
Evaluation of Stripping using 3D Radar Data

1. Review SHRP2 Research Data from NCAT
2. Activity Analysis Algorithm for Automated Detection
3. Application to MnROAD Data
4. Application to TH 7 data
Debonding at 2” depth

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|   |   |   |   |   | O | O | O |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 3 |   |   |   |   |   |   |   | X |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 4 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 5 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 6 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 7 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 8 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 10|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 11|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 12|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

Gray = bag house dust; delamination depth = ~ 2 in.; O = locations where point-load methods were conducted; X = verification core; S = standpipe.

FIGURE 15 Section 5: HMA Pavement, Full Width Delamination (STA 1+15 to 1+40).

Stripping at 2” depth

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|   |   |   |   |   |   |   |   | X |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2 |   |   |   |   |   |   |   |   | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| 3 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 4 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 5 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 6 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 7 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 8 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 9 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 10|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 11|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 12|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

Dark gray = RAP; bottom of delamination = ~ 2 in.; RAP thickness = ~ 0.75 in.; O = locations where point-load methods were conducted; S = standpipe.

FIGURE 16 Section 6: HMA Pavement, Partial Stripping (STA 1+40 to 1+65).
Stripping at 5” depth

Debonding at 5” depth

FIGURE 18 Section 8: HMA Pavement, Partial Stripping (STA 1+90 to 2+15).

FIGURE 19 Section 9: HMA Pavement, Wheel Path Delamination (STA 2+15 to 2+40).

Dark gray = RAP; bottom of delamination = ~ 5 in.; RAP thickness = ~ 0.75 inches; O = locations where point-load methods were conducted; X = verification core; S = standpipe.

Gray = bag house dust; tan = paper; delamination depth = ~ 5 in.; O = locations where point-load methods were conducted; X = verification core; S = standpipe.
NCAT Test Track

Section 5 – Debond placed at 2" depth

Section 6 RAP placed at 2" depth

Section 8 - RAP placed at 5" depth

Section 9 – Debond at 5" depth

= water introduced

“Stripped” areas

Possible RAP material overshoot
3D Radar System at NCAT in October 2016
2016 NCAT Data

Section 6 RAP placed at 2" depth

3D Depth Slice at 2"

Section 8 RAP placed at 5" depth

3D Depth Slice at 5"
Vehicle Mounted Equipment For Highway Application
MnROAD Data – Vehicle Interference

File 6-16-16-012

Pavement surface

Clutter bands
Same Data with background removal below surface
Analysis Methods

- 3D Radar “Examiner”
  - Processes and displays raw GPR data to facilitate interpretation
- ExploreGPR
  - Conducts quantitative analyses using data generated by “Examiner”
Activity Algorithm

Intact  Delaminated  Delaminated

AC Surface
Zone of Interest
AC Bottom
Activity Analysis on NCAT Test Sections

Section 6 RAP placed at 2" depth

3D GPR Depth Slice at 0.6ns.

Activity Analysis (0.6 - 1.0 ns)

Section 8 RAP placed at 5" depth

3D GPR Depth Slice at 2ns.

Activity Analysis (1.5 - 2.5 ns.)

Section 3  Section 4  Section 5  Section 6  Section 7  Section 8  Section 9  Section 10
Correlation with Stripping on Well Documented In-Service Roads:

- MnROAD Test Sections
- TH 7 in Clara City, MN
MnROAD Analysis:
Cells 1 and 15 – GPR Data

Cell 1

Cell 15
MnROAD Analysis

Cell 01 - Activity 0.5 - Layer 1

Passing Lane, RWP

Driving Lane, LWP

Reflection Activity Scale

1.2 1.5 1.8 2.1 2.4 2.7 3

Cell 15 - Activity 0.5 - 2.5 ns

Passing Lane, RWP

Driving Lane, LWP

Reflection Activity Scale

1.2 1.5 1.8 2.1 2.4 2.7 3
### MnROAD Analysis

#### Cell 1

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Core Condition</th>
<th>Confirm?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>shallow slight deter/strip</td>
<td>yes</td>
</tr>
<tr>
<td>2</td>
<td>insignificant</td>
<td>yes</td>
</tr>
<tr>
<td>3</td>
<td>none/sound condition</td>
<td>yes</td>
</tr>
<tr>
<td>4</td>
<td>lg crack/deterioration</td>
<td>close</td>
</tr>
<tr>
<td>5</td>
<td>deterioration (coring caused?)</td>
<td>close</td>
</tr>
<tr>
<td>6</td>
<td>slight shallow/bottom deterioration</td>
<td>no</td>
</tr>
<tr>
<td>7</td>
<td>shallow slight deter/delam</td>
<td>yes</td>
</tr>
<tr>
<td>8</td>
<td>minimal middepth stripping</td>
<td>no</td>
</tr>
<tr>
<td>9</td>
<td>slight deterioration/strip</td>
<td>yes</td>
</tr>
<tr>
<td>10</td>
<td>shallow slight deter/delam</td>
<td>yes</td>
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</table>

#### Cell 15

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Core Condition</th>
<th>Confirm?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>mid-depth strip/delam</td>
<td>close</td>
</tr>
<tr>
<td>2</td>
<td>clear stripping</td>
<td>yes</td>
</tr>
<tr>
<td>3</td>
<td>crumbled stripping</td>
<td>yes</td>
</tr>
<tr>
<td>4</td>
<td>slight strip/deterioration</td>
<td>no</td>
</tr>
<tr>
<td>5</td>
<td>no significant distress</td>
<td>close</td>
</tr>
<tr>
<td>6</td>
<td>clear stripping</td>
<td>yes</td>
</tr>
<tr>
<td>7</td>
<td>clear stripping</td>
<td>yes</td>
</tr>
<tr>
<td>8</td>
<td>slight deterioration</td>
<td>yes</td>
</tr>
</tbody>
</table>

**Correlation Result:**

11 confirm
4 close
3 not confirmed
TH 7 in Clara City, Mn

• 16 mile section, 1 lane in each direction
• Pavement thickness ~ 10 inches
• Pavement has regular transverse cracking, spaced 10 – 30 feet
• 2 Cores were taken near each MP, one over a crack and one 2 feet away
• Many cores showed evidence of stripping
• 3D Radar data was collected – Dec. 2016 and May 2017
  • Dec 2016 – many short files directly over the cores
  • May 2017 – long files covering multiple core areas
TH-7 GPR Data at Core Locations
Activity Analysis at 2 Levels using ExploreGPR

Upper Level Activity

Lower Level Activity
Analysis Results

Local Analysis

File 2016-12-02-004 reflection activity

Threshold = 1.5 x mean

File 2016-12-02-002 reflection activity

Threshold = 1.5 x mean
Analysis Results

Larger Scale Analysis
## Analysis Summary – 75% correct

<table>
<thead>
<tr>
<th>MM</th>
<th>Core number</th>
<th>Condition</th>
<th>activity&gt;threshold</th>
<th>Assessment</th>
<th>MM</th>
<th>Core number</th>
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<th>Assessment</th>
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<tbody>
<tr>
<td>91</td>
<td>2000</td>
<td>stripped</td>
<td>yes</td>
<td>correct</td>
<td>99</td>
<td>2017</td>
<td>stripped</td>
<td>no</td>
<td>false negative</td>
</tr>
<tr>
<td>91</td>
<td>2001</td>
<td>stripped</td>
<td>yes</td>
<td>correct</td>
<td>100</td>
<td>2018</td>
<td>intact</td>
<td>yes</td>
<td>false positive</td>
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<td>92</td>
<td>2002</td>
<td>intact</td>
<td>no</td>
<td>correct</td>
<td>100</td>
<td>2019</td>
<td>stripped</td>
<td>yes</td>
<td>Correct</td>
</tr>
<tr>
<td>92</td>
<td>2003</td>
<td>stripped</td>
<td>yes</td>
<td>correct</td>
<td>101</td>
<td>2020</td>
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<td>yes</td>
<td>Correct</td>
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<td>93</td>
<td>2004</td>
<td>stripped</td>
<td>no</td>
<td>false negative</td>
<td>101</td>
<td>2021</td>
<td>stripped</td>
<td>yes</td>
<td>Correct</td>
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<tr>
<td>93</td>
<td>2005</td>
<td>stripped</td>
<td>no</td>
<td>false negative</td>
<td>102</td>
<td>2022</td>
<td>stripped</td>
<td>yes</td>
<td>Correct</td>
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<td>2006</td>
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<td>no</td>
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<td>2026</td>
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<td>96</td>
<td>2010</td>
<td>intact</td>
<td>yes</td>
<td>false positive</td>
<td>105</td>
<td>2028</td>
<td>stripped</td>
<td>yes</td>
<td>Correct</td>
</tr>
<tr>
<td>96</td>
<td>2011</td>
<td>stripped</td>
<td>yes</td>
<td>correct</td>
<td>105</td>
<td>2029</td>
<td>stripped</td>
<td>yes</td>
<td>Correct</td>
</tr>
<tr>
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<td>2012</td>
<td>stripped</td>
<td>yes</td>
<td>correct</td>
<td>106</td>
<td>2030</td>
<td>intact</td>
<td>no</td>
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<td>2013</td>
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<td>yes</td>
<td>correct</td>
<td>106</td>
<td>2031</td>
<td>stripped</td>
<td>yes</td>
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<td>98</td>
<td>2014</td>
<td>intact</td>
<td>no</td>
<td>correct</td>
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<td>2032</td>
<td>stripped</td>
<td>yes</td>
<td>Correct</td>
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<td>98</td>
<td>2015</td>
<td>stripped</td>
<td>yes</td>
<td>correct</td>
<td>107</td>
<td>2033</td>
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<td>99</td>
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<td>correct</td>
<td>107</td>
<td>2033</td>
<td>stripped</td>
<td>yes</td>
<td>Correct</td>
</tr>
</tbody>
</table>
Conclusions

• Activity analysis reasonably quantifies locations of moisture damage and stripping
• Can be applied to long segments of pavement
• Threshold is arbitrary – core correlation is needed to set the threshold
• Core condition has been visual and qualitative – could benefit from quantitative testing such as indirect tensile testing.
Stripping Detection through Signal Analysis of 3D GPR Waveform
Acknowledgement

FHWA/SHRP2 (3D GPR equipment and funding)
3D Radar
NCAT
MnDOT District Offices
Using GPR to Detect Potential Stripping

- Looking at GPR images
  - Very subjective to the person analyzing the image
  - Time-consuming and labor intensive
- GPR can not definitively identify stripping
- GPR image consists of a lot of time-history waveforms
- Each waveform contains some information about the pavement
- A Perfect (homogenous and uniform) Layered System
Real Signal Contains Noise
- Noise makes “disturbed” waveform less visible
Purpose:

Evaluate different signal analysis methods to minimize noise and enhance “disturbed” signal by defect.
Eventually use computer to automatically pick the potential defects.
Signal Analysis Methods from Acoustic Emission (AE)

- AE is used for detecting earthquake
- First arrival of P wave used to estimate hypocenter location

\[ S_2 = \sigma^2 = \frac{\sum_{i=1}^{N} (Y_i - \bar{Y})^2}{N - 1} \]

\[ S_4 = \text{kurtosis} = \frac{\sum_{i=1}^{N} (Y_i - \bar{Y})^4}{(N - 1)\sigma^4} - 3. \]

\[ S_6 = \frac{\sum_{i=1}^{N} (Y_i - \bar{Y})^6}{(N - 1)\sigma^6} - 15. \]

A first arrival identification system of AE Signals
Maximum Energy Ratio

- Energy before and after the first arrival in a small time window has a large difference

\[
R_p = \frac{\sum_{i=p+1}^{p+M} Y_i^2}{\sum_{i=p-M}^{p-1} Y_i^2}
\]

(Shah and Labuz, 1995)
## NCAT Test Sections

<table>
<thead>
<tr>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
<th>Section 5</th>
<th>Section 6</th>
<th>Section 7</th>
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<tbody>
<tr>
<td>Top 2-inch lift</td>
<td></td>
<td>Full bond</td>
<td>Full bond</td>
<td>Full bond</td>
<td>Partial stripping</td>
<td>No bond</td>
<td>Full bond</td>
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<tr>
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<td>Full bond</td>
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</tr>
<tr>
<td>Existing surface</td>
<td>PCC</td>
<td>PCC</td>
<td>HMA</td>
<td>HMA</td>
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[Image of a road with a marked section]

[Image of a truck on a paved road]
Non-stripped Location

- **Original Signal**
  - Depth, ft. below AC surface

- **Energy-based R value**
  - Depth, ft. below AC surface

- **Kurtosis S₆ value**
  - Depth, ft. below AC surface

- **Standard Deviation S₂ value**
  - Depth, ft. below AC surface
Stripped Location

- Original Signal
- Energy-based R value
- Kurtosis $S_6$ value
Raw signal c-scan compared to the filtered data c-scan

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C-scan at design depth (~0.4 ft)
Analysis Results

Energy

S4

S6
ExploreGPR: Activity Method
(Dr. Ken Maser)

- Energy method in ExploreGPR
On-going effort

Energy, S4 and S6 analysis approaches successful in identifying stripping at a controlled section at NCAT

Need to be evaluated on multiple field projects where the stripping is more variable

Goal: Use different methods to analyze signal. If all or most methods indicate a common area with “unusual” activity, the area is worth to be investigated further, could be “stripping”.

Summary