SHRP2 Project R06G: High-Speed NDT Methods for Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings

Liberty and Armstrong Tunnels, Pittsburgh, PA

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September 14, 2016
Project:

• Condition Assessment of Liberty & Armstrong Tunnels in Pittsburgh, PA using High-Speed Mobile Scanning and Hand-held Non-Destructive (NDT) Technologies
The second Strategic Highway Research Program (SHRP2) was created to find strategic solutions to three national transportation challenges:

- Improving highway safety,
- Reducing congestion,
- Improving methods for renewing roads and bridges.

SHRP2 Research was focused on 4 areas: Safety, Renewal, Reliability, and Capacity.

R06G Project (a “renewal” project) focused on High-Speed NDT Methods for Mapping Defects Behind and Within Tunnel Linings
Background:

- R06G Research Effort Completed January 2013.
- Next step for R06G → Successful Implementation and Deployment of Research that was performed.
- Round 4 of Implementation Assistance Program (IAP) led by FHWA.
- Pennsylvania was 1 of 2 states to selected to receive FHWA grant money to evaluate tunnels under R06G Project.
Objectives:

• Demonstrate and evaluate the usage and ability of high-speed mobile scanning NDT methods and hand-held NDT methods to detect deterioration in concrete tunnel linings.

• District 11-0 wanted to evaluate as many NDT methods as possible with available grant money – GPR, IRT, 3-D Scanning, Video, PSPA.

• Perform physical inspection tasks (hammer soundings, delamination wheel, concrete cores) to validate NDT findings.

• Identify limitations and “lessons-learned”.
Objectives:

Why Liberty & Armstrong Tunnels?

- Not on interstates.
- Armstrong → CIP arch with tile-lined walls; good range of deterioration.
- Liberty → CIP arch with synthetic fiber reinforced repairs and galvanized WWF (2011).
- Tunnel types conducive to NDT methods used
Project Approach:

- Solicit RFPs from vendors:
  - Penetradar Corporation (Niagara Falls, NY)
  - Advanced Infrastructure Design (Hamilton, NJ), which used SPACETEC (Germany)

- Penetradar performed high-speed mobile scanning using air-coupled GPR, Infrared Thermography (IRT), and video image recording

- SPACETEC performed high-speed mobile scanning using IRT, 3-D laser scanning, and video recording
Project Approach:

- AID also performed point-by-point NDT using Portable Seismic Property Analyzer (PSPA) on limited area of Liberty Tunnel for IE and USW testing.

- Mackin Engineering performed physical inspection (hammer soundings, concrete cores, etc.) on the limited area of Liberty Tunnel.

- Northbound (Inbound) Tunnel bore for each tunnel completely closed to traffic (10:00pm to 5:30am)
Project Approach:

• Completion of field work:
  - September 21: SPACETEC (Liberty & Armstrong)
  - September 22: Penetradar GPR (Liberty)
  - September 23: Penetradar GPR (Liberty)
  - September 24: Penetradar IRT/Video (Liberty & Armstrong)
  - September 25: Penetradar GPR (Armstrong)
  - November 5: Advanced Infrastructure PSPA Testing & Physical Inspection (Liberty)
Project Approach:

- Penetrادar Corporation:
  - GPR/IRT/Video
  - Detects delaminations, voids behind liner, moisture within and behind liner, cracks, debonded tiles.
Project Approach:

- Penetradar Corporation:
  - Multiple passes required for GPR (3-6 ft widths)
  - For IRT/Video, 3 passes required in each tunnel.
Project Approach:

• **SPACETEC:**
  
  - 3-D Laser scanning/IRT/Video
  - Detects delaminated and debonded areas, spalls, cracks, efflorescence, and water infiltration. Can also detect changes in shape, bulges, etc.
Project Approach:

- Initial Report on Liberty “Test Section”:

  - Mackin reviewed 2014 Liberty Tunnel inspection findings to identify a small area (200LF) that exhibited repaired areas, delaminations, cracks, etc. to correlate data.

  - The “test section” (East Wall Station 3+300 to 3+500) was sent to AID and Penetradar within 3 days following completion of scanning.
Project Approach:

- Initial Report on Liberty “Test Section”:
  - NDT detections from initial reports were used to confirm whether the “test section” was appropriate.
  - Once confirmed, follow-up testing was scheduled to perform hand-held NDT with PSPA (for IE and USW testing) and physical inspection.
  - Follow-up testing scheduled for November 5th
  - No follow-up testing was performed at Armstrong
Project Approach:

- PSPA Testing:
  - PSPA used to perform Impact-Echo (IE) and Ultrasonic Surface Wave (USW) analysis at “test section”.
  - Test grid established to conduct PSPA testing over 200LF (10’ spacing; 9 locations vertically).
  - 189 total test points – 5 hours
Project Approach:

- Physical Testing:
  - Traditional hammer sounding was performed on the “test section” using 45-foot bucket truck.
  - Delam2000 – Rotary percussion tool also used to sound concrete.
  - Cores were taken at Station 3+475 (sound) and 3+321 (unsound).
Results:

- Penetrador GPR/IRT/Video:
  - Penetrador provided interactive map to toggle on/off various defects (“test section” shown below as example).
Results:

- Penetrarad GPR/IRT/Video:
  - Penetrarad also provided a table comparing GPR detections to 2014 inspection findings for the “test section”.

<table>
<thead>
<tr>
<th>Delamination</th>
<th>Soundings</th>
<th>GPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (%)</td>
<td>7.2</td>
<td>11.9</td>
</tr>
<tr>
<td>Area (Square Feet)</td>
<td>156</td>
<td>257</td>
</tr>
<tr>
<td>GPR Detection Percentage of Sounding Delaminations</td>
<td>73.2</td>
<td></td>
</tr>
<tr>
<td>GPR Detection Percentage of Sound Areas</td>
<td>90.4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voids Behind the Liner</th>
<th>GPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>Area (SQFT)</td>
</tr>
<tr>
<td>Moisture Areas or Water-Filled Voids</td>
<td>10.2 %</td>
</tr>
<tr>
<td>Air-Filled Voids</td>
<td>6.2 %</td>
</tr>
</tbody>
</table>
Results:

- AID 3-D Laser /IRT/Video (SPACETEC):
  - AID provided unfolded plan views of 3-D laser and thermal images for each tunnel (typical Armstrong scans show below).
Results:

- AID 3-D Laser /IRT/Video (SPACETEC):
  - AID also quantified various defects (cracks, warm/cold anomalies, debonded tiles) using bar charts (typical data for debonded tiles at Armstrong show below).
Results:

- Advanced Infrastructure hand-held PSPA:
  - AID tabulated seismic modulus results using USW method from PSPA testing.
  - Based on correlations with hammer soundings during testing, AID concluded that seismic moduli lower that 2,750 ksi were suspected as being delaminated.

<table>
<thead>
<tr>
<th>Distance from Ground, in</th>
<th>3+300</th>
<th>3+310</th>
<th>3+320</th>
<th>3+330</th>
<th>3+340</th>
<th>3+350</th>
<th>3+360</th>
</tr>
</thead>
<tbody>
<tr>
<td>176</td>
<td>3853</td>
<td>3355</td>
<td>2835</td>
<td>3617</td>
<td>2780</td>
<td>1410</td>
<td>2247</td>
</tr>
<tr>
<td>158</td>
<td>3475</td>
<td>3110</td>
<td>3170</td>
<td>3760</td>
<td>3850</td>
<td>1400</td>
<td>3993</td>
</tr>
<tr>
<td>140</td>
<td>3340</td>
<td>3677</td>
<td>2675</td>
<td>4015</td>
<td>3850</td>
<td>3925</td>
<td>2240</td>
</tr>
<tr>
<td>122</td>
<td>3103</td>
<td>2780</td>
<td>2280</td>
<td>3363</td>
<td>4183</td>
<td>4040</td>
<td>2103</td>
</tr>
<tr>
<td>104</td>
<td>3250</td>
<td>3070</td>
<td>3125</td>
<td>3880</td>
<td>3135</td>
<td>3640</td>
<td>2850</td>
</tr>
<tr>
<td>89</td>
<td>3660</td>
<td>3640</td>
<td>2427</td>
<td>4345</td>
<td>4545</td>
<td>3755</td>
<td>2525</td>
</tr>
<tr>
<td>74</td>
<td>3867</td>
<td>3865</td>
<td>4200</td>
<td>3760</td>
<td>3805</td>
<td>4080</td>
<td>2745</td>
</tr>
<tr>
<td>59</td>
<td>4427</td>
<td>4315</td>
<td>4370</td>
<td>3860</td>
<td>4465</td>
<td>4920</td>
<td>2370</td>
</tr>
<tr>
<td>44</td>
<td>3420</td>
<td>4253</td>
<td>4730</td>
<td>4445</td>
<td>4490</td>
<td>4125</td>
<td>3620</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>3599</strong></td>
<td><strong>3563</strong></td>
<td><strong>3335</strong></td>
<td><strong>3894</strong></td>
<td><strong>3911</strong></td>
<td><strong>3477</strong></td>
<td><strong>2744</strong></td>
</tr>
<tr>
<td><strong>Stdev</strong></td>
<td><strong>404</strong></td>
<td><strong>531</strong></td>
<td><strong>883</strong></td>
<td><strong>339</strong></td>
<td><strong>614</strong></td>
<td><strong>1229</strong></td>
<td><strong>656</strong></td>
</tr>
<tr>
<td><strong>COV, %</strong></td>
<td><strong>11%</strong></td>
<td><strong>15%</strong></td>
<td><strong>26%</strong></td>
<td><strong>9%</strong></td>
<td><strong>16%</strong></td>
<td><strong>36%</strong></td>
<td><strong>24%</strong></td>
</tr>
</tbody>
</table>
Results:

• Advanced Infrastructure hand-held PSPA:
  - AID also developed contour maps of seismic moduli results from USW analysis (top) and debonding condition from IE analysis (bottom).
Results:

• Comparison of NDT results and Physical Inspection results at “test section”:
  - Penetradar GPR detections correlated reasonably well with hammer soundings.
  - No usable data was obtained from Penetradar or SPACETEC IRT scans due to lack of temperature variation in middle of tunnel.
  - PSPA testing correlated well with hammer soundings.
Results:

• Comparison of NDT to Physical Inspection (Liberty):

GPR correlated reasonably well with hammer soundings
Results:

- Comparison of NDT to Physical Inspection (Liberty):

  GPR consistent with location of concrete core samples.
Results:

- Comparison of NDT to Physical Inspection (Liberty):

  PSPA (USW) results matched well with hammer soundings.
Results:

- Comparison of NDT to Physical Inspection (Liberty):

PSPA (IE) results matched well with hammer soundings.
• Comparison of NDT to Physical Inspection (Liberty):

Coring locations plotted on PSPA (USW) mappings.
Results (Overall):

• Penetrador:
  - GPR analysis for Liberty completed using decorrelation method to remove surface reflection – effective for detecting shallow delaminations.
  - 4.1% delaminated, 13.2% water-filled voids or high concentration of moisture behind liner, and 6.5% air-filled voids behind liner.
  - For Armstrong, GPR analysis focused on measuring signal attenuation and dielectric content.
  - Probable deterioration noted as being -6dB to -8dB of max. signal.
Results (Overall):

- Penetrador:
  - At Armstrong, -6dB in 25% of west wall and 25.5% of east wall.
  - East wall worse than west wall due to larger area of high attenuation (-8dB).
  - Average dielectric constant of west wall was 9.6 (4% moisture by volume) and east wall was 12.2 (8% moisture by volume).
  - For scale, low = less than 2%, moderate = 2%-10%, high = 10% or greater.
Results (Overall):

- Penetradar Summary Tables:

**GPR Results – Liberty Tunnel**
Results (Overall):

- **Penetrador Summary Tables:**

<table>
<thead>
<tr>
<th>Attenuation</th>
<th>GPR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percentage</td>
</tr>
<tr>
<td>West Wall - Total</td>
<td>25.0</td>
</tr>
<tr>
<td>Low Attenuation (6 dB to -7 dB)</td>
<td>14.1</td>
</tr>
<tr>
<td>Medium or High Attenuation (-7 dB or more)</td>
<td>10.9</td>
</tr>
<tr>
<td>East Wall - Total</td>
<td>25.5</td>
</tr>
<tr>
<td>Low Attenuation (6 dB to -7 dB)</td>
<td>7.9</td>
</tr>
<tr>
<td>Medium or High Attenuation (-7 dB or more)</td>
<td>17.6</td>
</tr>
<tr>
<td>Total</td>
<td>25.3</td>
</tr>
<tr>
<td>Low Attenuation (6 dB to -7 dB)</td>
<td>10.9</td>
</tr>
<tr>
<td>Medium or High Attenuation (-7 dB or more)</td>
<td>14.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dielectric Constant (Moisture Content - %)</th>
<th>Percentage</th>
<th>Area (SQFT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Dielectric Constant</td>
<td>9.6</td>
<td></td>
</tr>
<tr>
<td>Average Moisture Content</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>&lt;8.0 (2%)</td>
<td>19.3</td>
<td>4405</td>
</tr>
<tr>
<td>8.0-14.0 (2% - 10%)</td>
<td>75.0</td>
<td>17469</td>
</tr>
<tr>
<td>&gt;14.0 (10%+)</td>
<td>5.7</td>
<td>1328</td>
</tr>
<tr>
<td>East Wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Dielectric Constant</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>Average Moisture Content</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>&lt;8.0 (2%)</td>
<td>6.4</td>
<td>1656</td>
</tr>
<tr>
<td>8.0-14.0 (2% - 10%)</td>
<td>72.0</td>
<td>18634</td>
</tr>
<tr>
<td>&gt;14.0 (10%+)</td>
<td>21.6</td>
<td>5500</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Dielectric Constant</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>Average Moisture Content</td>
<td>6%</td>
<td></td>
</tr>
<tr>
<td>&lt;8.0 (2%)</td>
<td>12.5</td>
<td>6151</td>
</tr>
<tr>
<td>8.0-14.0 (2% - 10%)</td>
<td>73.4</td>
<td>36103</td>
</tr>
<tr>
<td>&gt;14.0 (10%+)</td>
<td>14.1</td>
<td>6918</td>
</tr>
</tbody>
</table>

GPR Results – Armstrong Tunnel
Results (Overall):

- AID/SPACETEC:
  - Typical defect detections at Liberty included open surface cracks, thermal anomalies, previous repair areas, and honeycombing.
  - The majority of IRT scanning at Liberty did not yield useable results due to lack of temperature variation.
  - For Armstrong, typical defect detections included open surface cracks, thermal anomalies, missing/damaged tiles, efflorescence, cracked patches, and ceiling deterioration.
Results (Overall):

- AID/SPACETEC Summary Tables:

![Crack Distribution (example) - Armstrong](image)
Results (Overall):

- AID/SPACETEC Summary Tables:

Cold Anomaly (example) - Armstrong
Conclusions:

- Penetrador:
  - Effective at detecting defects related to delaminations, moisture, and voids.
  - Combination of GPR/IRT/Video enables defects to be detected at the surface, within the liner, and behind the liner.
  - Shallow delaminations (1”+/−) are difficult to detect with GPR.
  - GPR cannot be used on steel liners or on tunnels with steel fiber reinforced repairs. Wire mesh fabric reinforcement should be discussed with vendor.
Conclusions:

• AID/SPACETEC:
  - SPACETEC’s combination of 3-D laser scanning/IRT/Video was effective at detecting cracks, tile debonding, and moisture-related defects.
  - SPACETEC able to produce detailed summary of visible crack locations, widths, & densities
  - SPACETEC’s combination of NDT is not capable of detecting defects through liner thickness.
  - PSPA testing is effective, but only practical over small, limited areas.
Conclusions:

• General:
  - No single NDT method can detect all defects.
  - Except near portals, IRT does not appear to effective for very long tunnels or ones that are in relatively good condition. Temperature variation very important.
  - IRT seems better suited for tunnels with moisture-related anomalies and tile linings.
  - IRT only indicates “presence” of anomaly.
Conclusions:

• General:
  - Some level of physical inspection is required regardless of NDT method.
  - Still some questions regarding depth of delamination, but GPR seems better suited for detecting concrete tunnel defects.
  - No NDT testing performed on air shafts, fire passages, or portal facades. In addition, GPR scanning could not be performed where conduits, hangers, etc. attach to ceiling.
Cost:

- Factors that affect cost include: tunnel dimension/geometry, type of NDT method(s), MPT requirements, data processing and report requirements, mobilization, etc.

- Penetrador (Liberty & Armstrong Inbound combined):
  - GPR (scanning & report) = $56,533 ($0.897/LF)
  - IRT (scanning & report) = $38,180 ($1.763/LF)
  - Video (scanning & report) = $26,275 ($1.213/LF)
  - Mobilization = $2,805

Total = $123,793
Cost:

- SPACETEC (Liberty & Armstrong Inbound combined):
  - Scanning & report = $79,412 ($10.18/LF)
  - Contingency cost for additional scanning = $6,800 per day.
  - Stand-by cost (delays, etc.) = $3,000 per day

- PSPA:
  - Total cost $14,384 (inclds. testing, report, mobilization, etc.) and based on 50-100 test points.
  - $143 to $286 per test point.
Cost:

- Other costs for scanning (Liberty):
  - MPT = $16,400 ($4,100 per day)
  - Equipment Truck = $2,000 ($500 per day)

- Other Costs for PSPA and Physical Inspection (Liberty):
  - MPT = $4,100
  - Equipment Truck = $500
  - Tool Truck = $850 (for coring)
  - Bucket Truck = $375 (hammer sounding)
  - District 11-0 supplied lift truck for PSPA testing and performed lab testing for cores
Cost:

• Compared to typical inspection of Liberty Inbound bore:
  - Engineering = $37,744 (average of 2 inspections)
  - Support Services = $13,600 ($6,800 per day)
  - Total = $51,344

• Penetradar (using 5,900LF and above unit costs):
  - GPR+IRT+Video = $95,013
  - MPT = $13,800 (3 days)
  - Total = $108,813
Cost:

• SPACETEC (using 5,900LF and $10.18/LF):
  - IRT+3-D scan+Video = $60,062
  - Support Services = $4,600 (1 day)
  - Total = $64,662

• Penetrador roughly 2 times greater & SPACETEC 25% greater than traditional inspection.
Recommendations/Discussion:

• Important to select NDT method(s) that are appropriate for tunnel type and known deterioration.

• Communicate with vendors – specify what information is needed and how it is to be presented.

• Plan ahead – identify time needed for RFPs, testing, final report, etc.

• MPT requirements - single lane, closure, detours, etc.

• NDT scanning should be performed on additional tunnels to obtain larger sampling of information and further correlation
Recommendations/Discussion:

- Concrete core samples recommended for correlating NDT results.
- Best application -> 1 or 2 NDT methods + physical sounding (e.g. GPR & 3-D + soundings).
- Planned rehab projects, in-depth inspections, initial inspections.
- NDT costs may reduce significantly with repeated inspections since base line testing and reporting are complete.
Recommendations/Discussion:

• As an additional exercise, beneficial to confirm NDT findings by field verification for entire tunnel.

• Establish limits for what needs repair based on severity of NDT findings – red, orange, yellow, all the above?

• The full potential and ultimate success of using NDT for tunnels will only be realized through continued development and use.
Questions/Comments:

- Questions/Comments???