SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

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

Brad Miller, Mackin Engineering Company

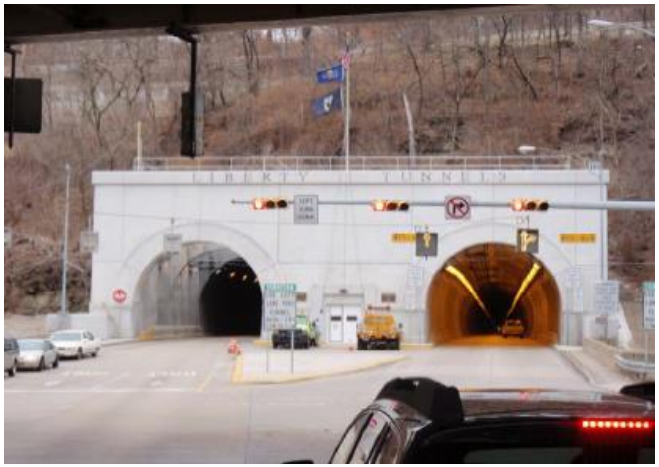
September 14, 2016

U.S. Department of Transportation
Federal Highway Administration

American Association of State Highway and Transportation Officials
AASHTO

Project:

- Condition Assessment of Liberty & Armstrong Tunnels in Pittsburgh, PA using High-Speed Mobile Scanning and Hand-held Non-Destructive (NDT) Technologies



Liberty Tunnel

Armstrong Tunnel

Background:

- 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:

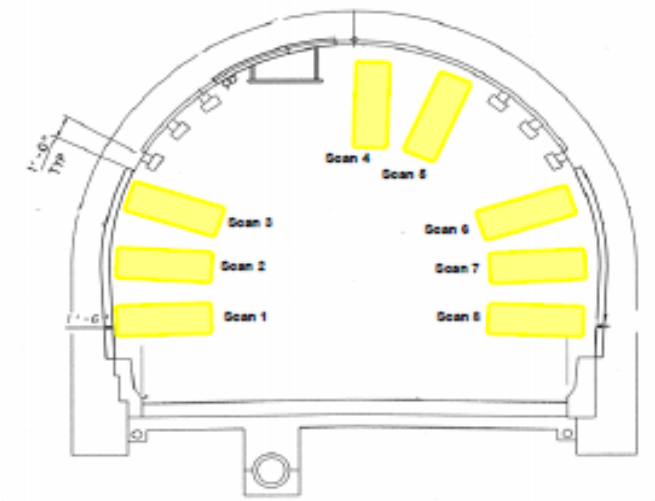
- Completion of field work:
  - September 21: SPACETEC (Liberty & Armstrong)
  - September 22: Penetradar GPR (Liberty)
  - September 23: Penetradar GPR (Liberty)
  - September 24: Penetradar IRT/Video (Liberty & Armstrong)
  - September 25: Penetradar GPR (Armstrong)
  - November 5: Advanced Infrastructure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

Project Approach:

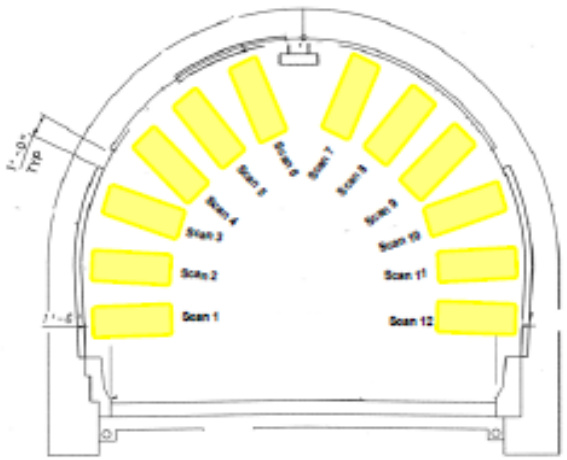
- Penetradar Corporation:
  - GPR/IRT/Video
  - Detects delaminations, voids behind liner, moisture within and behind liner, cracks, debonded tiles.

Project Approach:

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



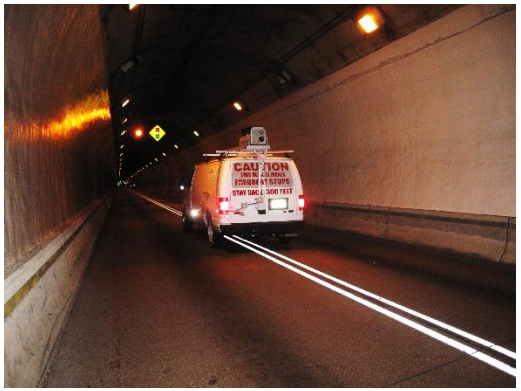
Liberty Tunnel - GPR Scans



Armstrong Tunnel - GPR Scans

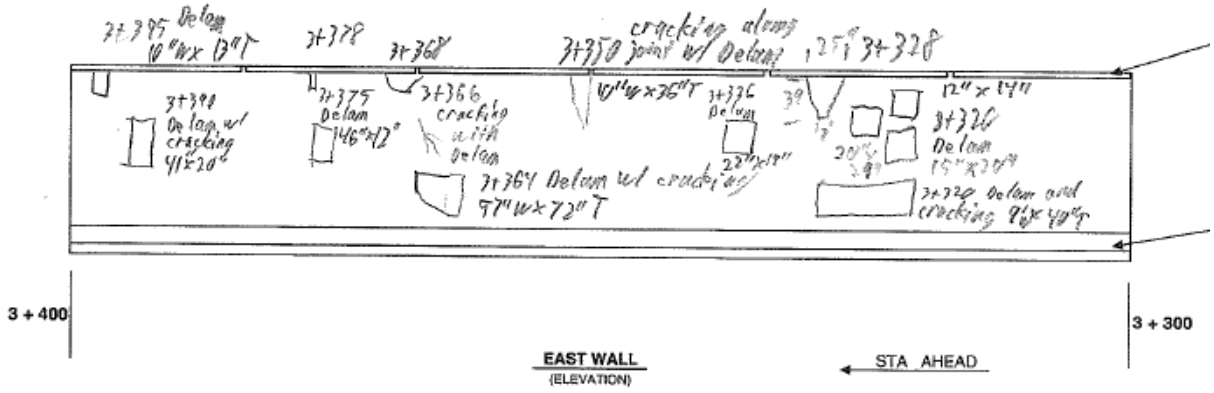
Project Approach:

- 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.

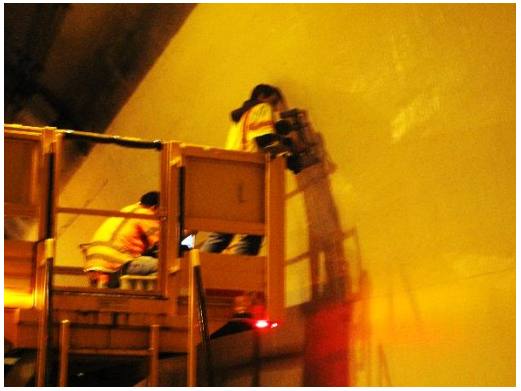


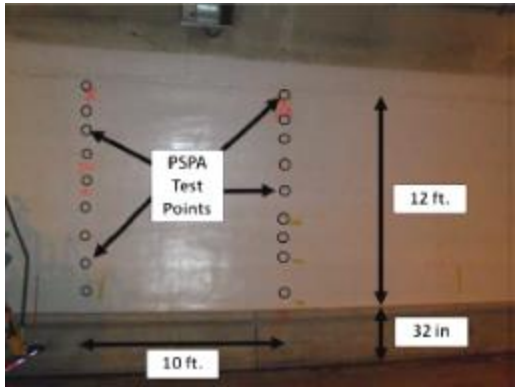
Project Approach:

- 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



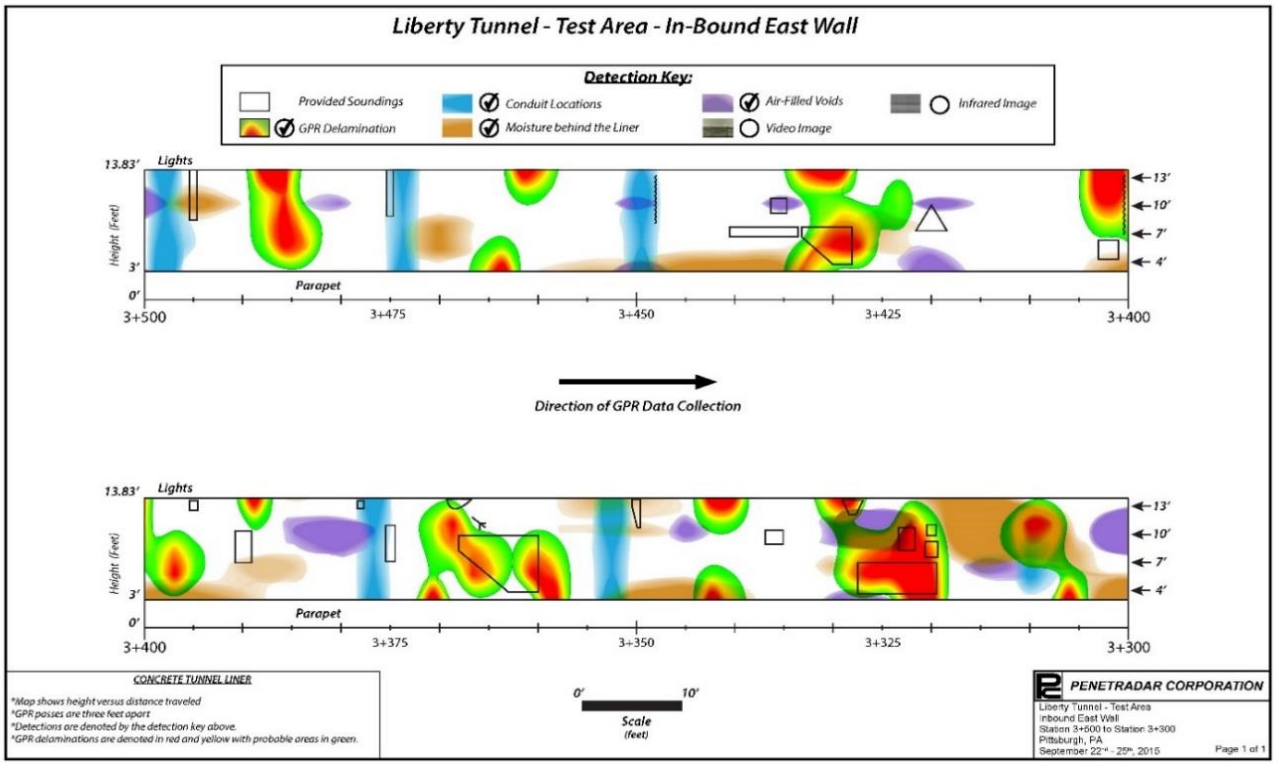


Project Approach:

- 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:

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



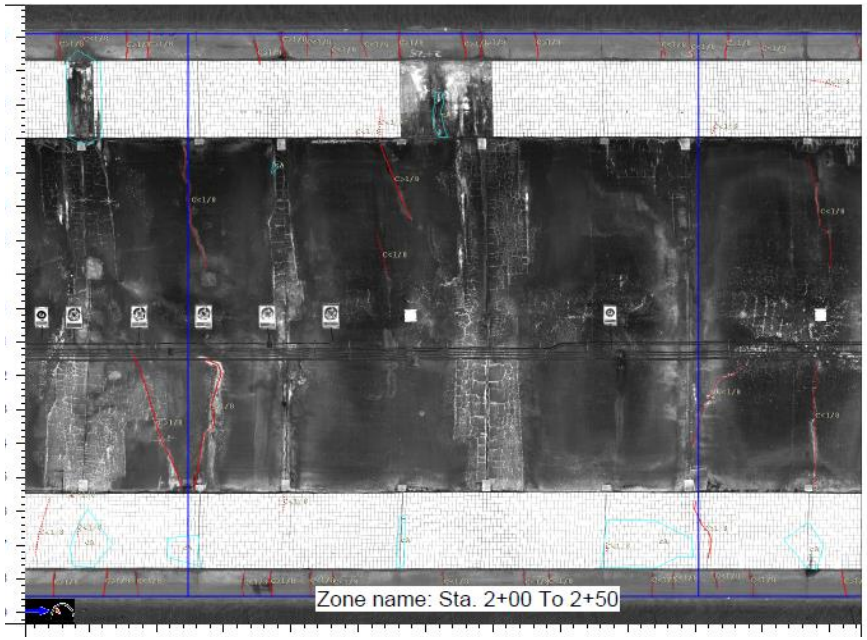
Results:

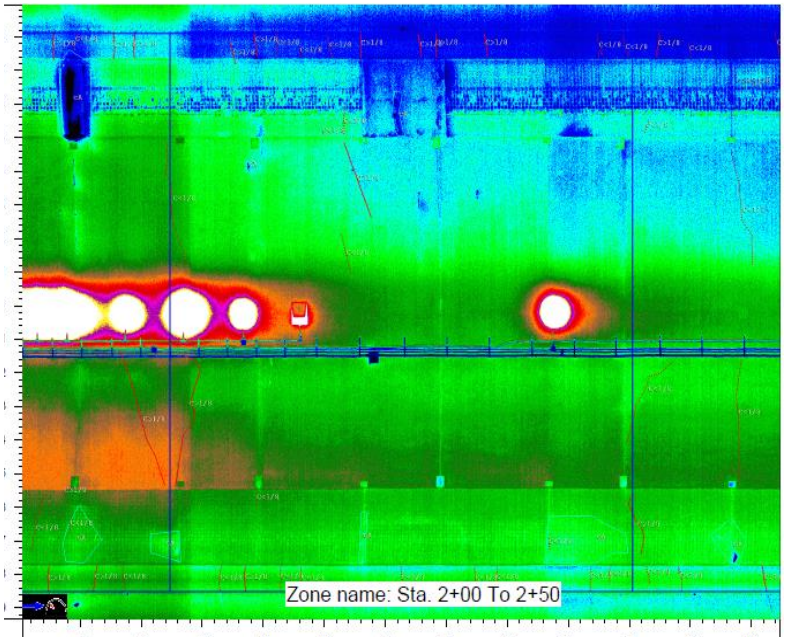
- Penetradar GPR/IRT/Video:
  - Penetradar also provided table comparing GPR detections to 2014 inspection findings for the “test section”.

Delamination	*Soundings*	*GPR*
Area (%)	7.2	11.9
Area (Square Feet)	156	257
GPR Detection Percentage of Sounding Delaminations	73.2	
GPR Detection Percentage of Sound Areas	90.4	
Voids Behind the Liner	*GPR*	
	Percentage	*Area (SQFT)*
Moisture Areas or Water-Filled Voids	10.2 %	220
Air-Filled Voids	6.2 %	135

Results:

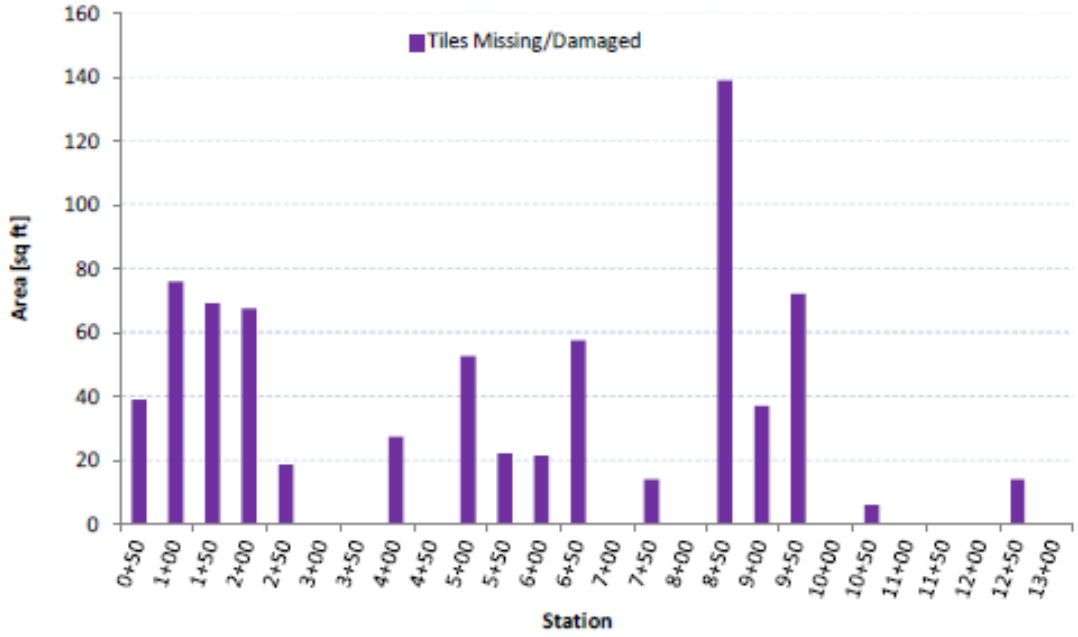
- AID 3-D Laser /IRT/Video (SPACETEC):
  - AID provided unfolded plan views of 3-D laser and thermal images for each tunnel (typical Armstrong scans show below).





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).



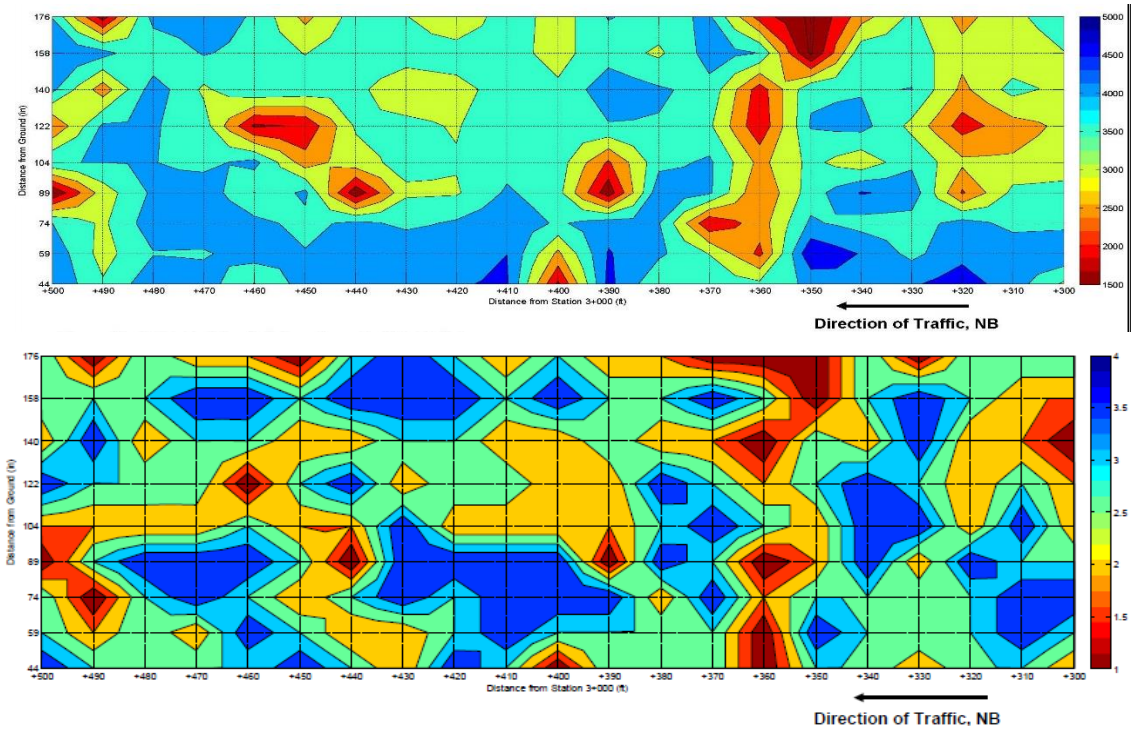
Results:

- 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

Distance from Ground, in	Station and Seismic Modulus (ksi)						
	3+300	3+310	3+320	3+330	3+340	3+350	3+360
176	3853	3355	2835	3617	2780	1410	2247
158	3475	3110	3170	3760	3850	1400	3993
140	3340	3677	2875	4015	3950	3925	2240
122	3103	2780	2280	3363	4183	4040	2103
104	3250	3070	3125	3880	3135	3640	2850
89	3660	3640	2427	4345	4545	3755	2525
74	3867	3865	4200	3760	3805	4080	2745
59	4427	4315	4370	3860	4465	4920	2370
44	3420	4253	4730	4445	4490	4125	3620
Average	*3599*	*3563*	*3335*	*3894*	*3911*	*3477*	*2744*
Stdev	*404*	*531*	*883*	*339*	*614*	*1229*	*656*
COV, %	*11%*	*15%*	*26%*	*9%*	*16%*	*35%*	*24%*

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).

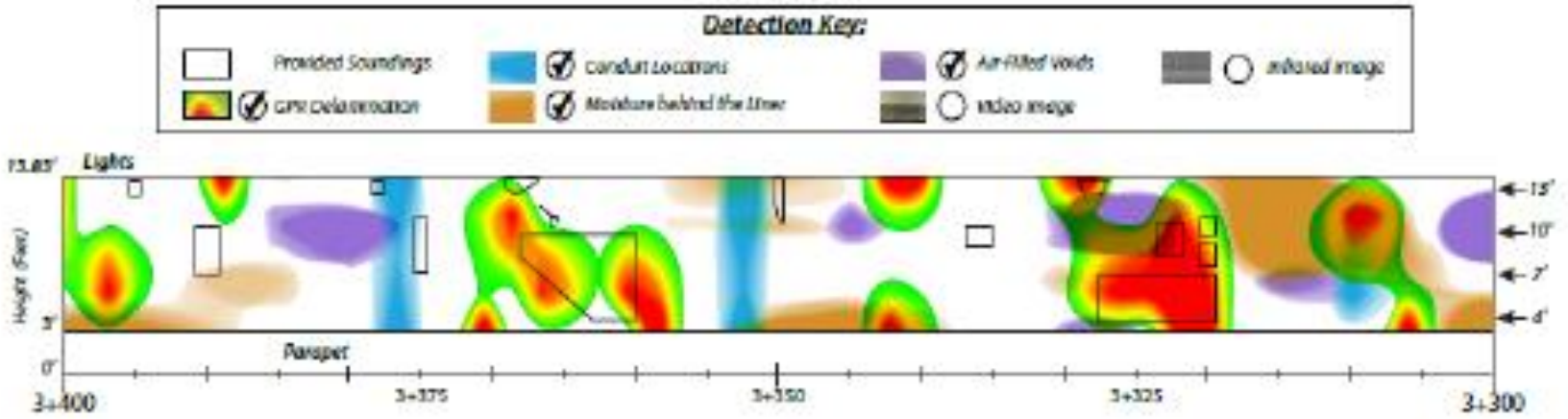


Results:

- 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:

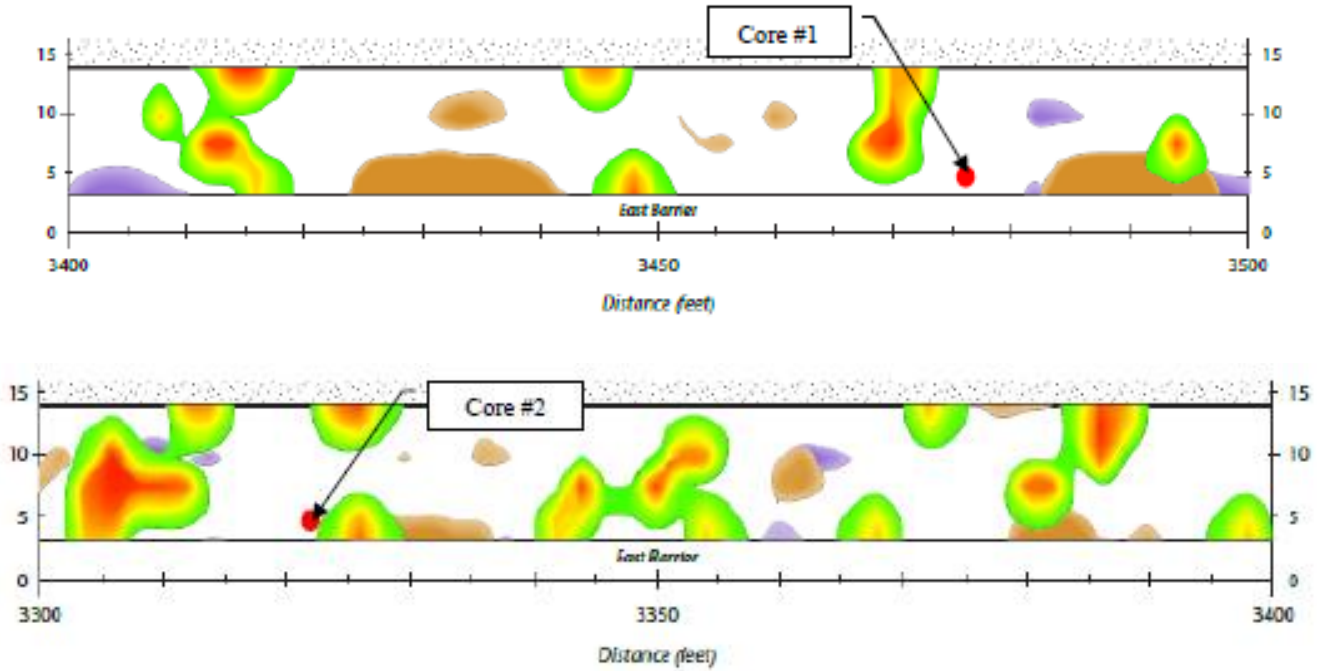
- Comparison of NDT to Physical Inspection (Liberty):



GPR correlated reasonably well with hammer soundings

Results:

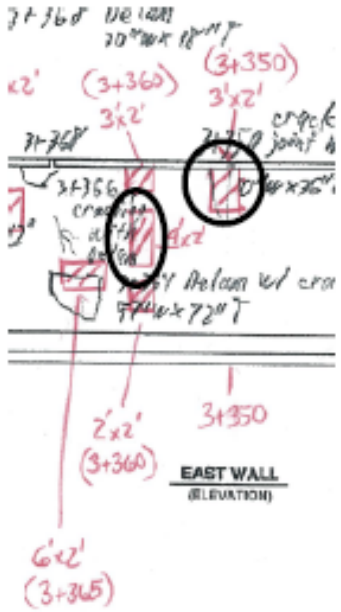
- Comparison of NDT to Physical Inspection (Liberty):

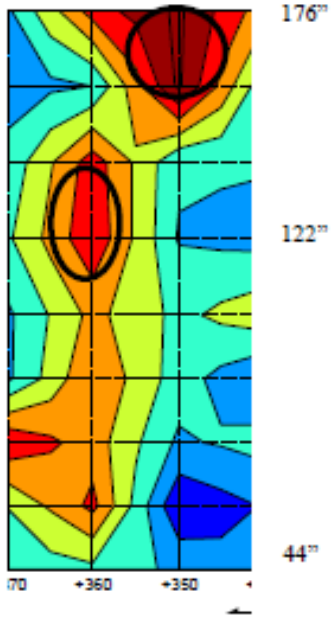


GPR consistent with location of concrete core samples.

Results:

- Comparison of NDT to Physical Inspection (Liberty):



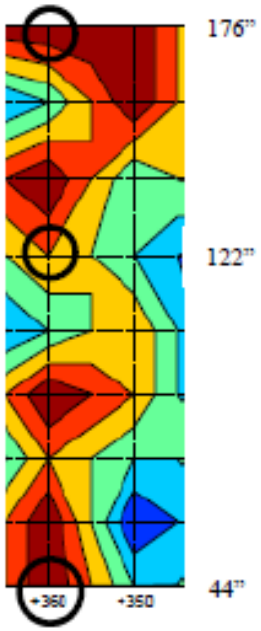


3+350	3+360	
1410	2247	176"
1400	3993	
3925	2240	
4040	2103	122"
3640	2850	
3755	2525	
4080	2745	
4920	2370	
4125	3620	44"
3477	*2744*	
1229	*656*	
35%	*24%*	

PSPA (USW) results matched well with hammer soundings.

Results:

- Comparison of NDT to Physical Inspection (Liberty):

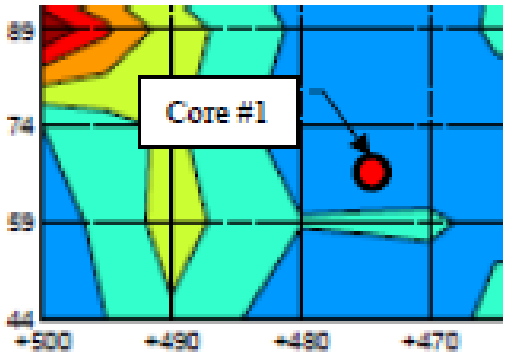


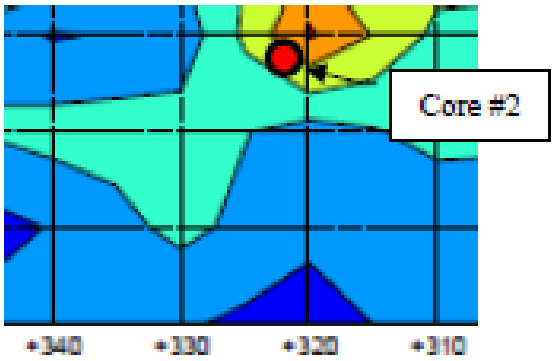
3+350	3+360	
1	1	176"
1	3	
3	1	
3	2	122"
2	3	
2	1	
3	2	
4	1	
3	1	44"

PSPA (IE) results matched well with hammer soundings.

Results:

- Comparison of NDT to Physical Inspection (Liberty):





Coring locations plotted on PSPA (USW) mappings.

Results (Overall):

- Penetradar:
  - 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):

- Penetradar:
  - 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:

Delamination	*GPR*	
	Percentage	*Area (SQFT)*
West Wall	4.1	2919
East Wall	4.3	3060
Ceiling	3.6	1281
Total	4.1	7260
Moisture Areas or Water-Filled Voids	*GPR*	
	Percentage	*Area (SQFT)*
West Wall	12.4	8766
East Wall	16.9	11946
Ceiling	7.6	2676
Total	13.2	23388
Air-Filled Voids	*GPR*	
	Percentage	*Area (SQFT)*
West Wall	6.8	4776
East Wall	8.2	5803
Ceiling	2.8	992
Total	6.5	11571

GPR Results – Liberty Tunnel

Results (Overall):

- Penetradar Summary Tables:

Attenuation	GPR	
	Percentage	Area (SQFT)
West Wall – Total	25.0	6794
Low Attenuation (-6 dB to -7 dB)	*14.1*	*3832*
Medium or High Attenuation (-7 dB or more)	*10.9*	*2962*
East Wall – Total	25.5	7590
Low Attenuation (-6 dB to -7 dB)	*7.9*	*2352*
Medium or High Attenuation (-7 dB or more)	*17.6*	*5238*
Total	25.3	14384
Low Attenuation (-6 dB to -7 dB)	*10.9*	*6184*
Medium or High Attenuation (-7 dB or more)	*14.4*	*8200*
Dielectric Constant (Moisture Content - %)	**Percentage**	**Area (SQFT)**
West Wall	Average Dielectric Constant 9.6 Average Moisture Content 4%	
<8.0 (2%)	19.3	4495
8.0-14.0 (2% - 10%)	75.0	17469
>14.0 (10%+)	5.7	1328
East Wall	Average Dielectric Constant 12.2 Average Moisture Content 8%	
<8.0 (2%)	6.4	1656
8.0-14.0 (2% - 10%)	72.0	18634
>14.0 (10%+)	21.6	5590
Total	Average Dielectric Constant 11.0 Average Moisture Content 6%	
<8.0 (2%)	12.5	6151
8.0-14.0 (2% - 10%)	73.4	36103
>14.0 (10%+)	14.1	6918

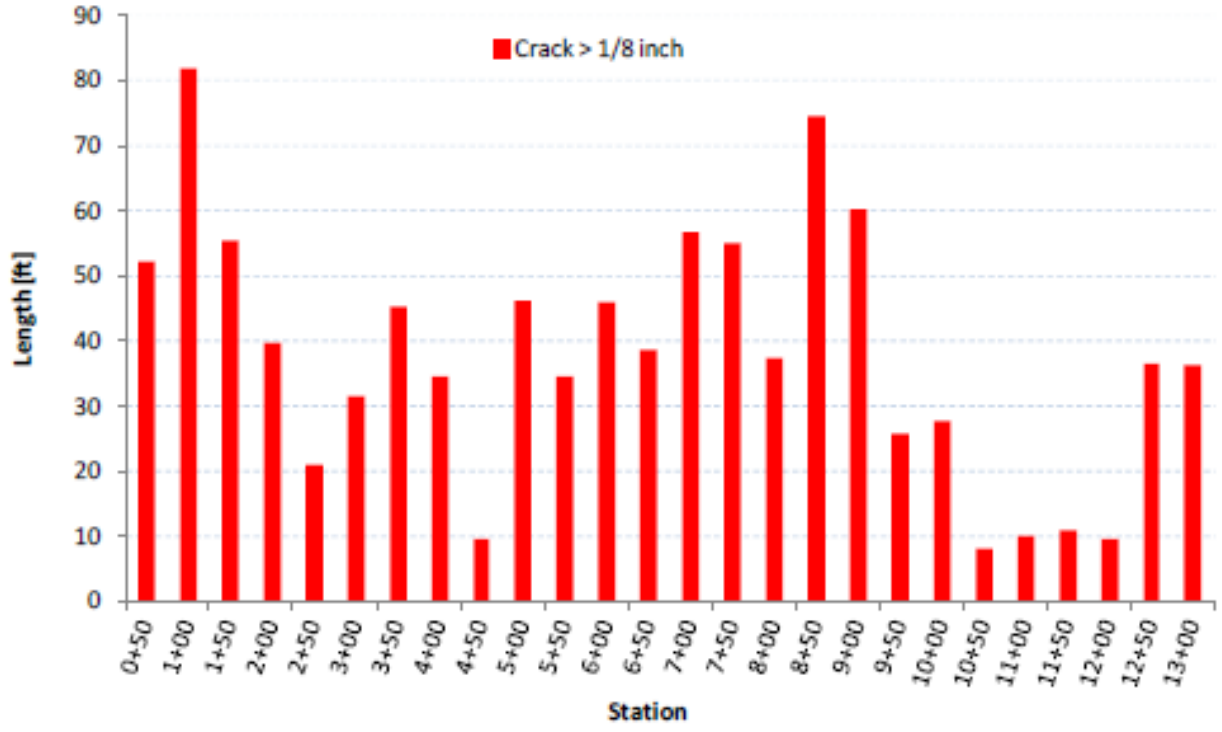
GPR Results – Armstrong Tunnel

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):

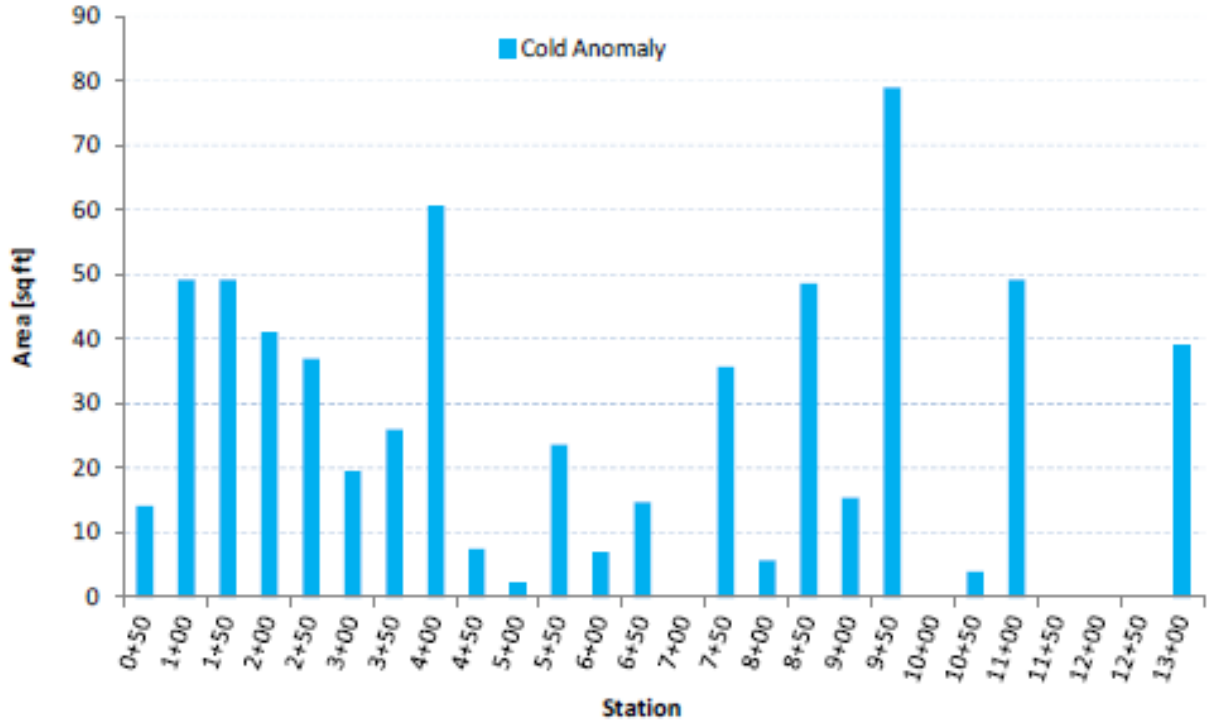
- AID/SPACETEC Summary Tables:



Crack Distribution (example) - Armstrong

Results (Overall):

- AID/SPACETEC Summary Tables:



Cold Anomaly (example) - Armstrong

Conclusions:

- Penetradar:
  - 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.
- Penetradar (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
- Penetradar roughly 2 times greater & SPACETEC 25% greater that 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???