FINAL REPORT

Strategic Highway Research Program (SHRP2) – Project R06G: High-Speed Nondestructive Testing Methods for Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings

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

Submitted to:

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PENETRADAR CORPORATION

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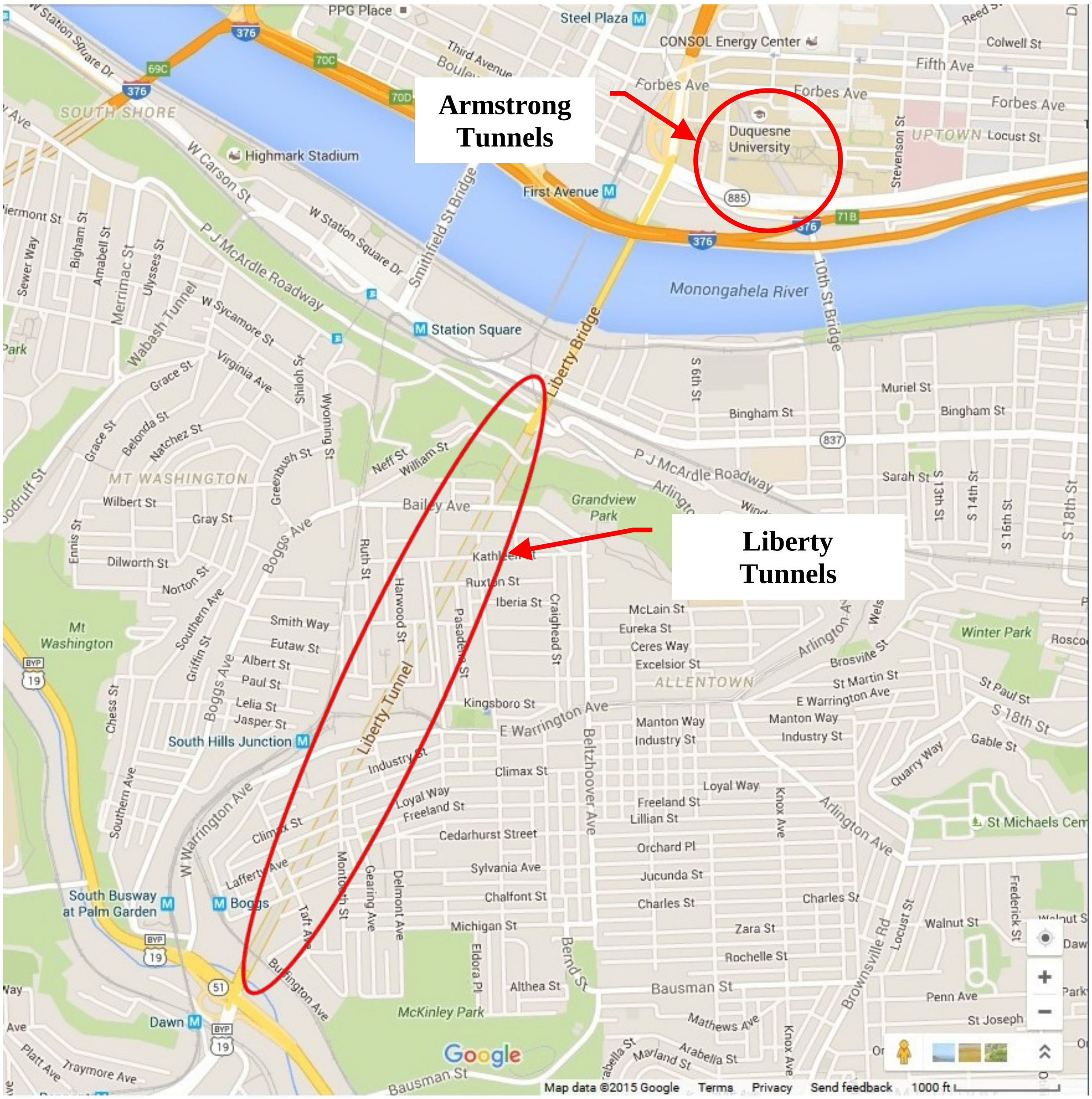
Location Map



Liberty and Armstrong Tunnels, Pittsburgh, PA

Executive Summary

This report presents the results from the non-destructive testing (NDT) that was performed to evaluate the tunnel lining condition of Liberty and Armstrong Tunnels in Pittsburgh, PA. This work was done as a part of the Implementation Assistance Program led by the Federal Highway Administration (FHWA) for the second Strategic Highway Research Program (SHRP2).

The SHRP2 Program was created to find strategic solutions to three national transportation challenges: improving highway safety, reducing congestion, and improving methods for renewing roads and bridges. Under the SHRP2 Program, research was focused in four areas - safety, renewal, reliability, and capacity. The SHRP2 R06G project (a "renewal" project) focused on High-Speed Nondestructive Testing Methods for Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings. This project had five objectives:

- To identify NDT technologies for evaluating the condition of various types of tunnel linings and tunnel lining finishes;
- To evaluate the applicability, accuracy, precision, repeatability, ease of use, capacity to minimize disruption to vehicular traffic, and implementation and production costs of the identified technologies;
- To conduct the required development in hardware or software for those techniques that show potential for technological improvement within the time limitations of this project;
- To prove the validity of the selected technologies/techniques for detecting flaws within or verifying conditions of the targeted tunnel components; and
- To recommend test procedures and protocols for successfully implementing these techniques.

The goals of this field testing effort were to demonstrate and evaluate the usage and ability of high-speed mobile scanning NDT methods and hand-held NDT methods to detect deterioration and defects in concrete tunnel linings. In conjunction with the NDT methods selected for this project, traditional physical inspection techniques (hammer sounding, concrete coring, etc.) were also performed on a limited area of the northbound Liberty Tunnel bore in order to validate the NDT findings.

The high-speed mobile scanning was performed by Penetradar Corporation and Advanced Infrastructure Design (AID), which used SPACETEC scanning technology. AID also performed point-by-point non-destructive evaluation using a Portable Seismic Property Analyzer (PSPA) to conduct Impact-Echo and Ultrasonic Surface Wave testing. Physical testing (hammer sounding, concrete coring, etc.) was performed by Mackin Engineering Company.

On-site activities at Liberty and Armstrong Tunnels were completed while the tunnels were completely closed to traffic from 10:00pm to 5:30am on the following dates:

- Monday, September 21, 2015: Advanced Infrastructure Design/SPACETEC – Liberty and Armstrong Tunnel.
- Tuesday, September 22, 2015: Penetradar GPR – Liberty Tunnel
- Wednesday, September 23, 2015: Penetradar GPR – Liberty Tunnel
- Thursday, September 24, 2015: Penetradar IRT, Image recording – Liberty and Armstrong Tunnel.
- Friday, September 25, 2015: Penetradar GPR – Armstrong Tunnel
- Thursday, November 5, 2015: Advanced Infrastructure Design Hand-held NDT Testing (Impact-Echo & Ultrasonic Surface Wave) using a Portable Seismic Property Analyzer. In addition to NDT testing, Mackin Engineering Company performed physical testing and concrete coring.

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Penetradar Corporation's high-speed mobile scanning technique incorporates Ground Penetrating Radar (GPR) in conjunction with infrared thermography (IRT) and video image recording that is performed simultaneously. The combination of these three (3) technologies allows for defects to be detected through the thickness of the tunnel lining as well as at the surface and also shows high-resolution visual imaging of the lining at a particular location.

Air-coupled ground penetrating radar scans were performed at the Liberty & Armstrong Tunnels to detect areas of delaminated concrete, voids behind liners, and moisture within and behind the liner. The GPR survey was performed by using a specialized vehicle installed with a non-contacting horn antenna that was placed in close proximity to the tunnel wall surface (a standoff distance of about one foot when in operation). An electromechanical boom mounted to the front of the vehicle was used to position the antenna and maintain the constant standoff distance. Continuous GPR scans were made as the vehicle traveled at a rate of approximately 10 mph along the length of the tunnel, and scans were made in areas that were accessible to the GPR antenna (i.e. away from traffic barriers, conduit hangers, etc.). Eight passes were used to complete the scanning in the northbound Liberty tunnel and twelve (12) passes were made in the Armstrong tunnel. A high-resolution antenna (1GHz to 2GHz) was used to detect thin, shallow depth defects, and separate passes using a low-resolution antenna (500MHz) were performed to detect deterioration and defects through the full thickness of the tunnel liner. The collected GPR data was analyzed to identify and report delamination and/or deterioration of the liner, air and//or water filled voids behind the liner, and moisture in the concrete liner. The report provided the percent of tunnel wall that is delaminated or deteriorated, the percent of water or air filled voids detected and the percent of tunnel area where high moisture was identified. Areas of delamination, debonding, voids and moisture were graphically shown on colorized topographical mappings (in PDF format) showing the location and spatial extent.

The infrared thermographic (IRT) inspection of the Liberty & Armstrong Tunnels was performed using a high resolution thermal camera installed onto the special test vehicle that recorded real-time infrared images of the tunnel surface. Three IRT passes, sufficient to cover the entire surface, were made to complete the scanning along the length of each tunnel. The IRT inspection was performed at speeds of approximately 10-15 mph, and each scan as referenced according to linear distance along the tunnel length. The IRT data was analyzed to identify cracks in the liner and areas of suspected water flow, debonded tiles and/or delaminated concrete. The results of the inspection were presented in a report that provides the percent of the detected flaws and distance-scaled, thermal images of the inside tunnel in plan-view format, showing the location and extent of detected flaws. The visual image recording was performed using a high resolution, "4K" 4096 x 2160 video recording of the tunnel interior. The video image recording was performed in conjunction with the IRT scans. An overlay was produced from the high resolution video recording which was converted to a distance-scaled, plan-view image. The plan-view overlay image was also provided in PDF format that can be toggled on/off to show detailed surface features for comparison with the subsurface evaluation data from GPR and IRT.

Specific findings from the GPR, IRT, and video scanning that was performed by Penetradar Corporation include the following:

- The GPR data analysis was completed using different methods for Liberty and Armstrong Tunnel: for Liberty Tunnel, the surface echo was removed using a decorrelation method to detect delaminations. By eliminating the surface reflection, it was possible to observe the GPR signal, which would normally be obscured from the concrete delamination. This method was particularly effective for Liberty Tunnel since shallow delaminations were found to exist. Water and air-filled void were detected by observing distinct, reflected signals at the back of the liner. For Armstrong Tunnel, the decorrelation was not used since shallow delaminations were not a significant problem. Instead, GPR delaminations were detected by measuring the GPR signal attenuation and by measuring the dielectric content (moisture content) of the liner. Water and air-filled voids were not evaluated at Armstrong Tunnel.
- The GPR inspection of Liberty Tunnel focused on the detection of delaminations, water-filled voids, and moisture and air-filled voids behind the concrete liner. Overall, concrete delamination was detected in 4.1% of the area tested, water-filled voids or high concentration of moisture was found in 13.2% of the area behind the liner, and air-filled voids were found in 6.5% of the area behind the liner.
- The GPR inspection of Armstrong Tunnel focused on measuring the signal attenuation to predict the condition of the concrete. Signal attenuation at

thresholds ranging from -6 dB to -8 dB of the maximum measured signal strength were used to identify areas of probable deterioration. The west wall was found to have attenuation levels in excess of -6 dB in 25% of the area tested, and the east wall was found to have attenuation levels that exceed the -6 dB threshold in 25.5% of the area tested. However, in comparing the condition of the east and west walls, the east wall was in worse physical condition because there was a larger area of high attenuation (equal to or greater than -8 dB).

- Penetradar indicated that moisture content within a concrete liner can be an indication of deteriorated concrete, honeycombing, moisture accumulation in base layers, or some other incipient problem. At Armstrong Tunnel, the average dielectric constant for the west wall was 9.6, which corresponded to a 4% moisture content by volume. The east wall had an average dielectric constant of 12.2, which corresponded to a moisture content of 8%.
- IRT did not produce definitive results for Liberty Tunnel, except a few locations near the tunnel portals, because very little temperature variation was observed. Even where delaminations were known to exist, IRT was unable to detect the deficiencies.
- The Armstrong Tunnel infrared mappings revealed few distinct detections of thermal variation; however, visual distress was clearly in some of those areas in the form of discolored tile, exposed concrete areas, or visible evidence of moisture on the tunnel liner. In general, the average temperature for the west wall was 78.1 degrees F, and the east wall was 77.2 degrees F. Because of the near 1-degree F average temperature difference between the walls, temperature distribution plots were developed separately for each wall. The average temperature difference between the two sections of the tunnel was attributed to the tunnel construction, and/or the west wall borders the adjacent southbound tunnel bore.

ADVANCED INFRASTRUCTURE DESIGN

SPACETEC technology was utilized by Advanced Infrastructure Design (AID) to scan and map defects at the Liberty and Armstrong tunnels. The scanning was performed using the high-resolution (10,000 pixels per scan) TS360 three-channel scanner mounted to a vehicle that traveled 1-2 mph. The TS360 scanner resided in Freiburg, Germany and scheduled shipment of the equipment was required for this project.

The SPACETEC scanner simultaneously performed infrared thermography, 3-D laser survey (profile data), and visual image recording and collected data in raw format. The thermal data processing included a radiometric correction to compensate for variations of external air temperature along the recording path. This made the thermal images easier to understand, and the variations in the thermal images allowed for the identification of anomalies (debonding, heat sources, moisture, etc.). As a result, the detection of deterioration and moisture was highly dependent on the temperature gradient that exists between the ambient air temperature and tunnel surface during the scanning.

Profile data processing included a correction in length that allowed a single scan (profile) to be uniquely related to a location in the structure. Data processing further included a process that related the measured profile data to the actual tunnel axis. The process automatically detected the positions from the measurement, covering a 360° field of view, and corrected the data accordingly. This process compensated for all effects that were due to the vehicle and the mounting of the scanner on the vehicle. The profile data was useful for detecting clearance problems and for analyzing the surface of the lining with respect to surface defects like protrusions, localized bulging, changes in tunnel shape, etc.

Visual data processing included length and geometric corrections that transform the measured data into the development of the tunnel surface. As a result, each single point of an image is uniquely related to a location in the structure. Also included is a radiometric correction, which is used to achieve constant brightness of the images independently from the distance of the scan-head to the tunnel surface. Detection of cracks and spalls are possible by viewing the visual data.

Particular findings from the SPACETEC high-speed mobile scanning include the following:

- Typical deficiencies detected by the SPACTEC scanning in Liberty tunnel included surface cracks, thermal anomalies, previous repair areas, and honeycombing.
- Typical deficiencies detected by the SPACETEC scanning in Armstrong Tunnel included surface cracks, thermal anomalies, missing/damaged tiles, efflorescence, cracked patches, and ceiling deterioration.
- The majority of the Liberty tunnel IRT scanning did not provide usable results due to the lack of temperature variation. Cold anomalies were detected near the tunnel portals, where variations in air temperature are more substantial.
- Missing and/or debonded tiles in Armstrong tunnel were detected by the IRT scanning.
- For Liberty and Armstrong tunnel, the 3-D laser scanning was able to detect cracks less than 1/8” and greater. In addition, no surface deformations (changes in shape, bulges, etc.) were detected from the profile data.
- In general, IRT scanning provided an indication of the presence of anomalies. But, additional inspection (physical or non-destructive) is required to determine the cause and severity of the anomaly.

Hand-held NDT: A limited area of the Liberty Tunnel was identified in order to conduct additional validation testing using Impact-Echo (IE) and Ultrasonic Seismic Waves (USW) method, which is an offshoot of Spectral Analysis of Surface Waves (SASW). A Portable Seismic Property Analyzer (PSPA) was the seismic device that was used to obtain the data, which is capable of performing both the IE and the USW methods simultaneously. Impact-Echo testing was used to detect discontinuities such as delamination, voids, cracks, and debonding within the concrete tunnel lining. The USW testing was used to measure the seismic modulus of elasticity of the tunnel lining in order to evaluate the integrity of the concrete.

Particular findings from the IE and USW testing that was performed includes the following:

- The PSPA testing that was performed on the Liberty tunnel test section (200 LF section of the east wall) was relatively slow and time-consuming. One hundred eighty-nine (189) test locations were evaluated with the PSPA in approximately 5 hours.
- A good correlation was observed between the seismic modulus from the PSPA testing and areas showing concrete delamination that were identified from the hammer soundings.
- The IE analysis showed good correlation with the areas showing concrete delamination identified from the hammer soundings.
- PSPA testing revealed good correlation with the lab results from the concrete core testing. The concrete cores were subjected to petrographic analysis (*note: chloride ion content was also requested from the laboratory; however, these results were not provided. In addition, compressive strength testing was also anticipated; however, the core samples extracted from the field did not meeting the minimum required core diameter for testing*).

PHYSICAL INSPECTION

The physical inspection task for this project was performed in Liberty Tunnel only. Mackin Engineering Company (Mackin) had previously completed a routine inspection of the northbound Liberty Tunnel bore in 2014. The 2014 inspection was performed using traditional hammer soundings and visual observation of the entire tunnel surface to identify cracks, spalls, delaminations, moisture intrusion, etc., and deterioration was documented using inspection sketches and digital photographs. Using this information, a limited area of the tunnel was selected that exhibited a good sampling of concrete delamination, previous repair locations, cracks, etc. in order to perform the hand-held NDT, concrete coring, and additional hammer soundings. The location selected to perform the follow-up testing was Station 3+300 to 3+500 at the east wall of the inbound tunnel. In order to confirm the appropriateness of this section of the tunnel for additional testing, an initial report of the high-speed mobile scanning results at this location was obtained from Penetradar and SPACETEC.

Mackin performed the additional hammer soundings on this section of the east tunnel wall to confirm the 2014 inspection findings and to determine if changes had occurred from the previous inspection. The updated findings from the hammer sounding inspection could then be compared more accurately to the NDT results. In conjunction with the hammer soundings, Mackin also performed a physical inspection of the test section using an extendable rotary percussion inspection tool (DELAM 2000). Concrete cores were also taken at (1) sound concrete location (Station 3+475) and at (1) unsound concrete location (Station 3+321). The extracted concrete cores were subjected to petrographic analysis (*note: chloride ion content was also requested from the laboratory; however, these results were not provided; compressive strength testing was also anticipated; however, the core samples extracted from the field did not meeting the minimum required core diameter for testing*).

Particular findings from the physical inspection and concrete core testing that was performed include the following:

- Hammer sounding revealed several delaminated concrete areas of various sizes that matched reasonably well with the 2014 inspection findings. Some variation was noted, but this appeared to be due to differences in locating and documenting deterioration between inspectors and not from changes in existing deterioration.
- The rotary percussion tool performed well in identifying unsound concrete areas. However, it was difficult to detect audible differences for very shallow delaminations or at areas that were not highly unsound. This was further complicated by ambient noise from electric generators used for core drilling, vehicle engines from lift trucks, etc. In addition, it was difficult to delineate areas of unsound concrete with marking keel/chalk that were beyond arms-reach without the use of a lift truck. This made accurate documentation of deterioration difficult.
- The petrographic analysis revealed that the core at Station 3+475 consisted of three layers: layer 1 that was comprised of thin white coating on top of a layer of mortar and fine aggregate that varied from 3/16” and 11/32”, layer 2 that was comprised of a slightly thicker white coating and layer of mortar with narrow-graded gravel coarse aggregate and gravel sand fine aggregate with a total thickness of 5/8” to 1 ½”, and layer 3 that consisted of oversized gravel coarse aggregate and gravel sand fine aggregate with a total thickness of 9 ¾” to 10 ½”. The third layer was identified as the original concrete. The petrographic analysis rated the overall condition of layer 1 as “good”, the overall condition of layer 2 as “fair”, and the overall condition of layer 3 as “fair”. The original concrete was rated as “fair” due to the highly variable paste quality, the lack of entrained air, and indications that excess water was present when the paste was plastic.

  Similarly for the core at Station 3+321, the sample consisted of three layers: layer 1 consisted of thin white coating on top of a layer of mortar and fine aggregate that varied from 7/16” and 1/2”, layer 2 that was comprised of a slightly thicker white coating and layer of mortar with narrow-graded gravel coarse aggregate and gravel sand fine aggregate with a total thickness of 13/16” to 25/32”, and layer 3 that consisted of oversized gravel coarse aggregate and gravel sand fine aggregate with a total thickness of 7 5/8” to 8 1/4”. The third layer was identified as the original concrete. In addition, the lab observed that the first layer had separated from the rest of the sample at the top white coating for layer 2, which was consistent with how the core was extracted from the field. The petrographic analysis rated the overall condition of layer 1 as “very good”, the overall condition of layer 2 as “fair”, and the overall condition of layer 3 as “fair”. The original concrete was rated as “fair” due to the highly variable paste quality, the lack of entrained air, and indications that excess water was present when the paste was plastic.

The chloride ion content of each core was not included in the lab test results, and it is not known why this information was not provided.

It can be noted here that, in review of the GPR delamination detections from Penetradar Corporation, minor to moderate concrete delamination and moisture behind the liner was noted within 5’ above the traffic barrier in proximity to Station 3+321, which was consistent with the petrographic analysis and the physical inspection findings. Similarly, moisture behind the liner and no concrete delamination was noted around Station 3+475 within 5’ above the traffic barrier. This also was consistent with the petrographic analysis of the core sample and the hammer soundings.

No correlation could be made when comparing the SPACETEC mobile scanning results to the concrete core samples since no thermal anomalies were detected due to thermal equilibrium that existed at this location during testing.

RECOMMENDATIONS

In review of the NDT methods deployed for this project, it is apparent that not one technology by itself can provide all information needed to ascertain the condition of the tunnel lining. It is important to understand the limitations of each technology as well as have knowledge of existing tunnel conditions for proper planning and to assure the condition assessment will provide desired information. At this time, it appears the best application for the NDT technology is to use one or two mobile scanning methods in combination with traditional hammer soundings. For example, utilizing GPR to supplement traditional hammer soundings to document and assess deterioration for a planned rehabilitation project would be an appropriate application. The GPR mobile scanning could be performed in advance physical inspection, where hammer soundings and visual observation could be used to confirm GPR findings and to inspect areas that were not accessible by GPR. Other examples would include incorporating GPR during in-depth inspection intervals (e.g. every 6 years, 10 years, etc.), or utilizing GPR to facilitate the baseline condition assessment during an initial inspection. At this time, GPR does not appear to be a practical solution over traditional physical methods for biennial inspections because of the cost and time required for data processing. However, cost and time may be reduced significantly during subsequent NDT inspections since test procedures and previous NDT data would be established. These items would need to be investigated and discussed with NDT service providers.

In regard to IRT testing, it is difficult to obtain reliable and useful results for tunnels because the surface of the liner is not directly exposed to active heating and cooling cycles. As a result, the tunnel liner is in relative thermal equilibrium despite seasonal climate changes, which prevents the detection of defects and anomalies. This is further complicated in very long tunnels and by different liner thicknesses that may exist between the exterior walls, the ceiling, and interior walls. In the case of Liberty Tunnel, no usable results were obtained from IRT testing since the tunnel over 1-mile long and is in relatively good condition; however, some thermal anomalies were noted near the tunnel portals. Better results were observed at Armstrong Tunnel due to moisture-related issues (evaporative cooling), tile lined walls, and a shorter length (1300 feet). In any case, IRT only provides an indication of a warm or cool defect – additional inspection is required to determine the type and severity of the defect.

PSPA testing is a good NDT method for assessing concrete deterioration. However, this point-by-point method is time consuming and expensive. As a result, it is not well-suited for the inspection of large surface areas typically associated with tunnels, unless small areas are to be investigated.

Report

INTRODUCTION

The information presented in this report provides a summary of the results of the high-speed mobile NDT scanning that was performed on Liberty and Armstrong Tunnels in Pittsburgh, PA. The mobile NDT scanning was performed on the northbound bore of each tunnel system. This report also summarizes the results of the verification testing that was performed on the limited area of the Liberty Tunnel using hand-hand NDT and traditional physical inspection techniques. The high-speed mobile scanning occurred over a span of five nights, September 21 through 25, 2015, and the verification testing was performed on the night of November 5, 2015. This NDT evaluation of the Liberty and Armstrong Tunnels was conducted under the Federal Highway Administration (FHWA) Round 4 Implementation Assistance Program for the second Strategic Highway Research Program (SHRP2), R06G project. The R06G project focused on the High-Speed Nondestructive Testing Methods for Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings. The objectives of this evaluation were as follows:

- Demonstrate and evaluate the ability of high-speed mobile NDT scanning methods and hand-held NDT methods to assess deterioration in tunnel linings.
- Compare the effectiveness of using NDT methods to detect defects to traditional visual and physical inspection methods that are currently used to assess tunnel conditions.
- Identify limitations and discuss "lessons learned" in order to develop and incorporate relevant NDT methods as an effective asset management tool to managing agencies.

The Liberty and Armstrong Tunnels were selected for this project because the structure types are conducive to the NDT technologies used for the project (i.e. no steel linings, no steel fiber reinforced concrete, etc.), and the tunnel systems were not on interstate highways. The scope of the testing effort included several NDT methods that, when used collectively, would identify and document deterioration in the tunnel linings. For this project, Penetradar Corporation was selected to perform high-speed mobile scanning using a combination of air-coupled ground penetrating radar (GPR), infrared thermography (IRT), and video image recording. Advanced Infrastructure Design (AID) was selected to utilize SPACETEC technology, which uses a combination of infrared thermography, 3-D laser scanning, and video image recording. AID also performed the Impact-Echo (IE) and Ultrasonic Surface Wave (USW) verification testing for this project using a Portable Seismic Property Analyzer (PSPA). In addition, Mackin Engineering Company (Mackin) completed the physical inspection work (hammer soundings, a delamination wheel, and concrete coring) to obtain the "ground-truth" information in order to compare inspection findings to the NDT results.

The format of this report presents the results from each NDT method individually and compares the results of each NDT method to the physical inspection findings that were obtained at the Liberty Tunnel test section. It should be noted that no verification testing using hand-held NDT methods or physical inspection was completed for the Armstrong Tunnel.

TUNNEL DESCRIPTIONS

The Liberty Tunnel system was built in 1926 and is located in the city of Pittsburgh, PA. The tunnel system carries SR 3069 northbound and southbound traffic (two lanes each direction) and exhibits a length of 5,898 ft. The northbound tunnel bore has a curb-to-curb width of 23’-0” and height of 20’-9 ¼” at the arch apex. The average daily traffic (ADT) of the northbound tunnel bore is 17,652 vehicles. The tunnel is comprised of a cast-in-place (CIP) reinforced concrete arch and was rehabilitated in 2011 that included synthetic fiber reinforced shotcrete repairs with galvanized welded wire fabric reinforcing.

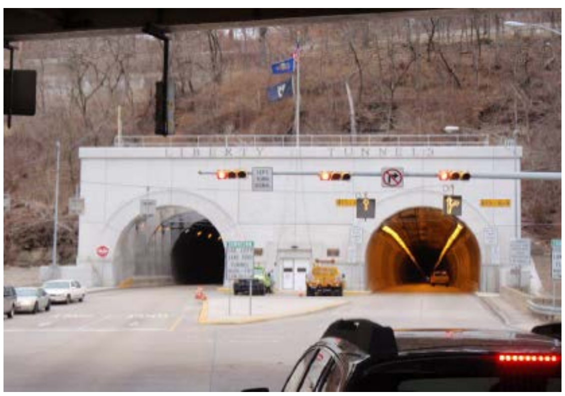

Photo 1: Liberty Tunnel South Entrance

Photo 2: Liberty Tunnel Cross-Section

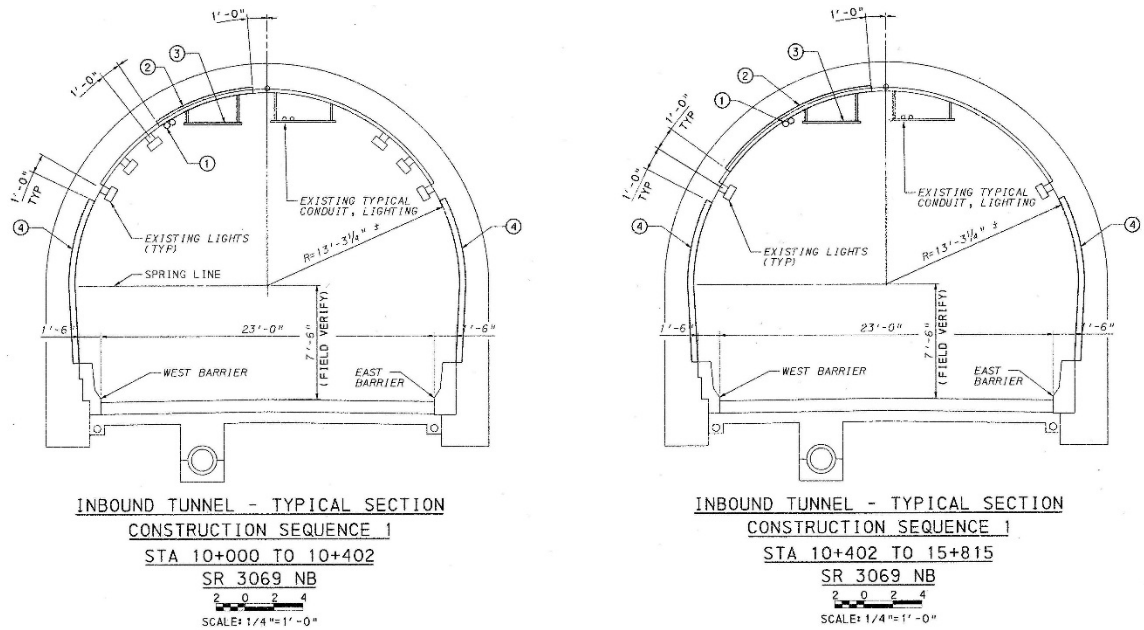

Figure 1: Liberty Tunnel Cross-Section Data (from S-29344)

The Armstrong Tunnel system was built in 1927 and is located in the city of Pittsburgh, PA. The tunnel system carries South 10th Street northbound and southbound traffic (two lanes each direction) and exhibits a length of 1,300 ft. The northbound tunnel bore has a curb-to-curb width of +/- 20'-0" and height of +/- 22'-0" at the arch apex. The average daily traffic (ADT) of the northbound tunnel bore is 9,230 vehicles. The tunnel is comprised of a cast-in-place (CIP) reinforced concrete arch with tile-lined walls and was rehabilitated in 1991.

Photo 3: Armstrong Tunnel South Entrance

Photo 4: Armstrong Tunnel Cross-Section

PROJECT APPROACH

The objective of PennDOT District 11-0 for this SHRP2 project was to evaluate as many NDT technologies as possible with the funding allocated for the project. In consideration of estimated costs, as well as understanding the limitations and advantages of the various NDT methods available, it was determined that GRP, infrared thermography, 3-D laser survey, visual image recording, Impact-Echo and Ultrasonic Surface Wave would offer a sufficient range of NDT technologies capable of evaluating and assessing the tunnel linings.

The project was initiated by soliciting a Request for Proposal (RFP) and cost estimate from Penetradar Corporation and Advanced Infrastructure Design approximately 2-3 months prior to field work being performed. The Penetradar and AID proposals have been included in Appendix A and Appendix B, respectively. The RFP included information such basic tunnel information, desired tests to be performed, traffic control and access requirements, date(s) of on-site activities, and recommended report format (graphical, tabular, etc.). The high-speed mobile scanning was performed during the week of September 21 through September 25, 2015. The high-speed mobile scanning was coordinated and scheduled to ensure work could be completed each night within the specified time frames for the week. The tunnels were completely closed to vehicular traffic from 10:00pm to 5:30am that required proper planning (including a detour plan) and approval from the District 11-0 Traffic Unit. Maintenance and protection of traffic required changeable message boards to be placed in advance of the tunnel closures to alert local traffic. During the week of the high-speed mobile scanning for Liberty Tunnel, Mackin was on site each night to ensure the tunnels were properly closed to traffic, provide overall supervision, and provide any required assistance. As a part of the on-site activities, Mackin stationed the Liberty tunnel bore every 100 feet using a measuring wheel and marking paint for referencing defect locations. Penetradar and SPACETEC also recorded the measured tunnel length in conjunction with the mobile scanning.

Within 3 days of completing the high-speed mobile scanning, Mackin provided Penetradar and AID with the location of the “test section” for Liberty Tunnel so that additional testing could be performed at a future date using hand-held NDT methods (Impact-Echo and Ultrasonic Surface Wave); the test section was also inspected using traditional physical methods, including hammer sounding, a delamination wheel, and extracting concrete cores. To identify the test section, Mackin reviewed the 2014 Inspection Report for an area of the tunnel that was accessible and exhibited a variety of delaminations, cracks, repair areas, etc. The findings from the previous inspection were also used to help validate and correlate the results from the NDT testing. The test section for Liberty Tunnel was limited to Station 3+300 to 3+500 of the east wall from the top of the traffic barrier to the bottom of the lighting system (i.e. the painted portion of the wall segment). Within 3 weeks of the receiving the location of the test section, Penetradar and AID were required to submit an initial report of the mapped defects that were identified at the test section from the high-speed mobile scanning. The initial NDT reports for

Liberty Tunnel were reviewed by Mackin to confirm whether the test section was a good candidate for the hand-held NDT to be performed or whether adjustments were needed. It should be noted that verification testing at a limited area of the Armstrong Tunnel was not performed.

The location of the test section was sent to AID, and the date of the hand-held NDT testing was scheduled for November 5, 2015. The tunnel was completely closed to vehicular traffic from 10:00pm to 5:30am, and the required MPT, detour plan, and changeable message boards were placed with prior approval from the District 11-0 Traffic Unit. AID performed the hand-held NDT testing using the Impact-Echo (IE) and Ultrasonic Surface Wave (USW) methods with a Portable Seismic Property Analyzer (PSPA). The test was applied using a grid system. Test points were established every ten (10) feet of stationing and at nine (9) evenly spaced locations vertically from Station 3+300 to 3+500 at the east wall. This resulted in 189 total test locations. At each test location, the PSPA test was conducted 2 or 3 times to ensure reliable, accurate data was obtained.

In conjunction with the IE/USW testing using the PSPA, Mackin performed a traditional physical and visual inspection of the Liberty Tunnel test section. The concrete surface was hammer sounded and the 2014 inspection sketches were updated for changes. In addition to the hammer sounding, this area of the tunnel was sounded with a rotary percussion tool (i.e. Delam 2000). Inspection access for the hand-held NDT and physical inspection was provided by using PennDOT's lamping truck (a flat-bed hydraulic lift truck) that was used for the IE/USW testing, and a 45-foot reach bucket truck that was used for the physical inspection. The physical inspection tasks also consisted of extracting concrete cores from the east wall at sound and unsound concrete locations. One core was taken from Station 3+475 (sound location) and one core was taken from Station 3+321 (unsound location). The concrete cores were delivered to PennDOT District 11-0 and were subjected to petrographic analysis (*note: chloride ion content was also requested from the laboratory; however, these results were not provided; compressive strength testing was also anticipated; however, the core samples extracted from the field did not meeting the minimum required core diameter for testing*).

The high-speed mobile scanning, hand-held NDT, and physical inspection results are discussed below. In general, the results are organized by discussing test procedures and equipment, the results at the test section for Liberty Tunnel, and the complete results for the entire length of Liberty and Armstrong Tunnel. Following the discussion of the NDT testing and physical inspection results, each NDT method is compared to the physical inspection findings at the test section in order to correlate results. In addition, a discussion of the project costs, conclusions, and recommendations is also provided. The report Appendix includes all supporting information, including vendor proposals, the initial reports for the Liberty Tunnel test section, and the complete NDT results for the Liberty and Armstrong Tunnel.

PENETRADAR MOBILE SCANNING RESULTS

Air-coupled GPR scanning of the Liberty & Armstrong Tunnels was performed to detect areas of delaminated concrete, voids behind the liners and moisture within and behind the liners. Penetradar utilized a specialized vehicle, installed with a non-contacting GPR antenna. The GPR antenna was attached to an electro-mechanical boom that was used to position the antenna and maintain a constant standoff distance of about one foot when in operation. Continuous GPR scans were made in 3 to 6 foot widths as the GPR vehicle traveled at approximately 5-10 MPH along the length of the tunnel. Multiple passes were required to complete the GPR scanning of the entire surface of each tunnel. For the infrared thermography and video inspection, which were performed as separate scans from the GPR inspection, a high resolution thermal camera and a high resolution "4K" 4096x2160 video camera were installed on the specialized test vehicle. The IRT and video cameras simultaneously recorded real-time infrared and digital images of the tunnel surfaces. The IRT and video scanning was performed at speeds of approximately 10 to 15 MPH, and multiple scans were required to complete the inspection of the entire surface of each tunnel.


Photo 5: Penetradar GPR Wall Scan

Photo 6: Close-up of GPR Antenna

Photo 7: Penetradar GPR Ceiling Scan


Photo 8: Penetradar IR and Video Camera

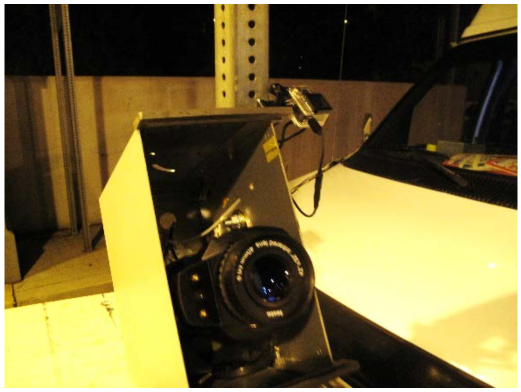
Photo 9: Close-up of IR and Video Camera

Each scan was referenced according to the linear distance along the tunnel length. Penetradar experienced a minor discrepancy in the measured length of Liberty Tunnel. The length of the tunnel according to the stationing on the rehab drawings S-29344 was 5,889 feet, which coincided within one foot of Penetradar's measured tunnel length. The tunnel length determined by Mackin using the measuring wheel measured 5,912 feet, which resulted in a difference of 23 feet. To resolve this discrepancy, Penetradar utilized the GPR data to identify what was believed to be electrical conduit within the wall, and correlated those detections with the physical inspection findings at the test section. Using this technique, the two sets of data were able to be aligned.

The initial report prepared by Penetradar for the test section of Liberty Tunnel is included in Appendix C. The location of concrete delamination, air-voids, water-filled voids or moisture behind the liner, and the location of what was determined to be electrical conduit within the concrete wall were identified using GPR. Each type of defect required different methods of analyzing the GPR waveform to identify these conditions. GPR found 11.9% (257 SF) of the test section to be delaminated, whereas hammer soundings identified 7.2% (156 SF) of the area to be delaminated (based on Penetradar's estimation). GPR also identified 10.2% (220 SF) of the test area exhibited high levels of moisture (or water-filled voids), and air voids were detected in 6.2% (135 SF) of the test area. The voids and moisture were typically found at the interface between the concrete liner and underlying subbase material.

The IRT method did not provide usable results with regard to delamination in the test section as no temperature differential was detected with the infrared camera. This was not unexpected since the test section was well inside the length of the tunnel and was not subjected to air temperature differences. Additional attempts were made to increase the sensitivity of the thermographic images through a "coherent integration" signal processing method, but these attempts were not successful. In addition, no major cracking or water flow was detected with IRT, which did correlate with visual observations. In conjunction with the IRT scanning, a high resolution image of the tunnel wall was generated. This visual image was produced by extracting portions of each video frame and assembling an accurately scaled "plan-view" image of the wall that is viewed on the same scale as the GPR and IRT. The figure below shows typical side-by-side image of the infrared image and visual image at the same location.

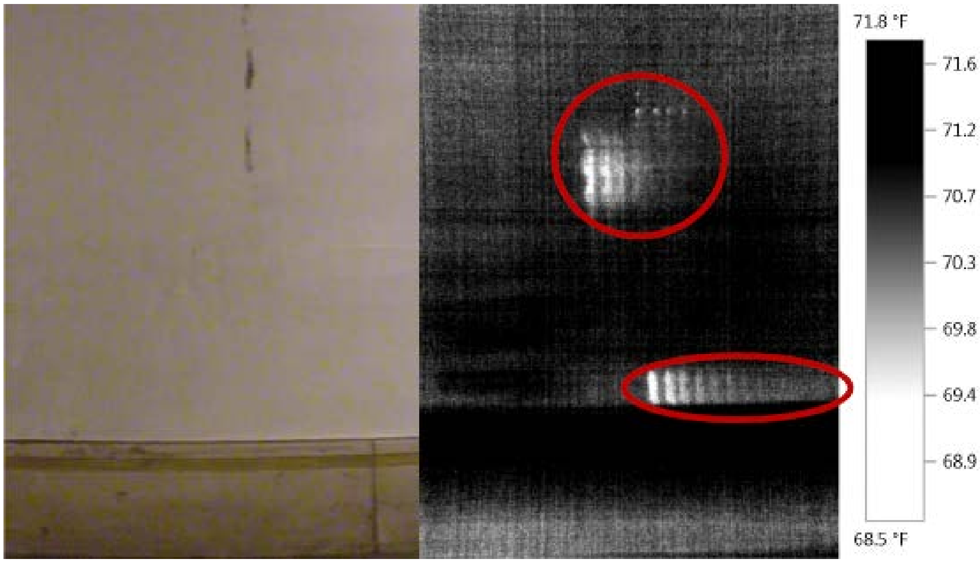

Figure 2: Infrared image on the right shows two areas of thermal differences on the tunnel wall along with the visual image of the same location

The figure below shows the interactive defect map prepared by Penetradar for the Liberty Tunnel test section. The various defects identified by GPR can be toggled on or off to display the various layers (see also Appendix C). The areas delineated as "provided soundings" are from the 2014 Mackin inspection that were provided to Penetradar for the initial report on the test section following the completion of the high-speed mobile scanning.

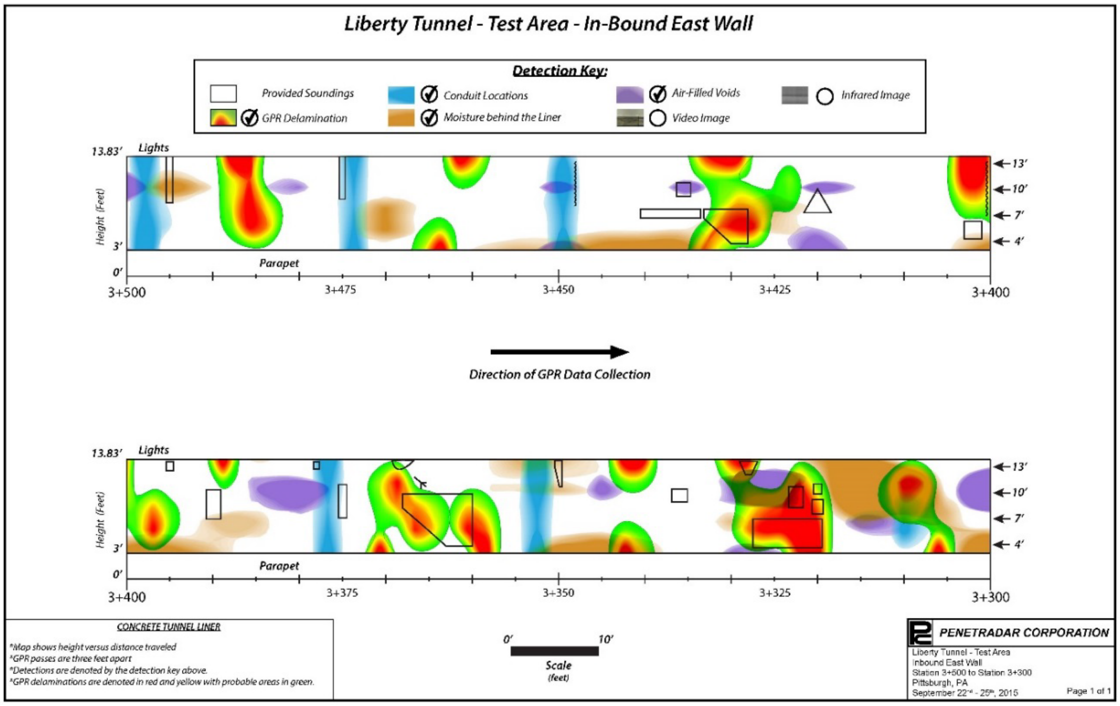

Figure 3: Liberty Tunnel Test Section – Interactive Defect Mapping Report

Since the Liberty Tunnel was recently rehabilitated with hydro-demolition and synthetic fiber reinforced shotcrete repairs, one concern with the GPR detections was whether repairs areas and delaminated areas would be discernable. Penetradar did not observe any significant difference in material property between repair areas and areas that were not repaired. There was no change in reflectivity or dielectric observed, which lead to the conclusion that the material used for repair was electrically similar to the original surrounding material and would not be detected. It should be noted that this is not true in all cases and should be investigated on a case-by-case basis.

The results of the Penetradar scanning for the entire Liberty Tunnel are included in Appendix D. The GPR scanning was divided into three sections due to the various obstructions attached to the interior of the tunnel bore: the east wall (Section 1) extended from the top of the traffic barrier to the bottom of the lighting system at the right side, the ceiling (Section 2) extended from the top of the lighting system at the right side to electrical/ telecommunication conduit system, and the west wall (Section 3) extended from the bottom of the lighting system at the left side to the top of the traffic barrier. Heights were referenced from the bottom of the east traffic barrier.

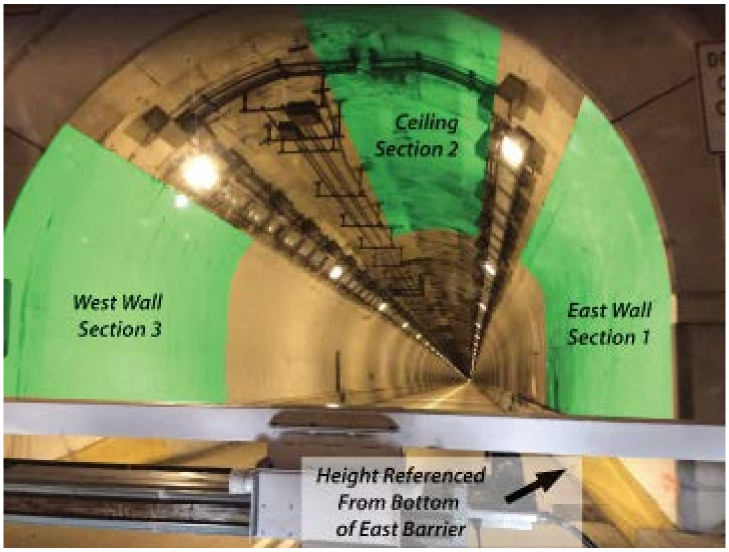

Figure 4: GPR Survey Locations – Liberty Tunnel

The GPR inspection of the Liberty Tunnel focused on the detection of delaminations, water-filled voids, moisture and air-filled voids behind the concrete liner. The GPR waveforms were analyzed using one or more techniques to identify and quantify each type of defect. Delaminations were detected using a decorrelation method to remove the surface echo of the signal. By eliminating the surface reflection, it was possible to observe the signal that would normally be obscured as a result of the delamination. This method was particularly effective for shallow delaminations, which were found in the Liberty Tunnel. After analysis of this data, all detections for delaminations were logged, and a plan-view map was generated taking into account the location and proximity of neighboring scans and detections. Delaminations from the GPR inspection were found uniformly in all parts of the Liberty Tunnel, with detections in 4.1% of the west wall, 4.3% of the east wall and 3.6% of the ceiling section. Overall, delaminations were detected in 4.1% of the tunnel wall area.

To detect water-filled voids or moisture behind the liner at Liberty Tunnel, the GPR waveform was analyzed at the interface between the liner and base material. A distinct signal was observed from the back of the liner, which was measured. Areas of high moisture and/or water-filled voids were determined to exist based on the detection of those reflective signals that exceeded a running mean value over a prescribed distance. The quantity of water-filled voids and/or areas of high moisture ranged from 12.4% in the west wall to 16.9% in the east wall. The ceiling was found to have a much lower percentage of water-filled voids at 7.6%. Overall, 13.2% of the Liberty Tunnel exhibited evidence of water-filled voids or high moisture concentration behind the liner.

The technique used for locating air-filled voids behind the liner was similar to the method utilized for locating water-filled voids. However, the primary difference in the detection of air-filled voids was in the polarity of the reflected signal that occurs at the void. It is this difference in polarity that helped identify an air-void versus a water-filled void. In general, the results for air-filled voids followed the pattern observed for water-filled voids, with a detection rate of 6.8% for the west wall, 8.2% for the east wall, 2.8% for the ceiling section, and an overall detection rate of 6.5% for the entire tunnel.

Table 1 below shows a summary of the GPR detections at the northbound Liberty Tunnel.

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

Table 1: Summary of GPR Tunnel Inspection – Liberty Tunnel

Figure 5 below shows an example pdf image prepared by Penetradar Corporation in which each defect type (delamination, moisture behind the liner, air-filled void, and video image) can be toggled on/off to display specific deterioration. The complete GPR mappings for Liberty Tunnel are included in Appendix D.

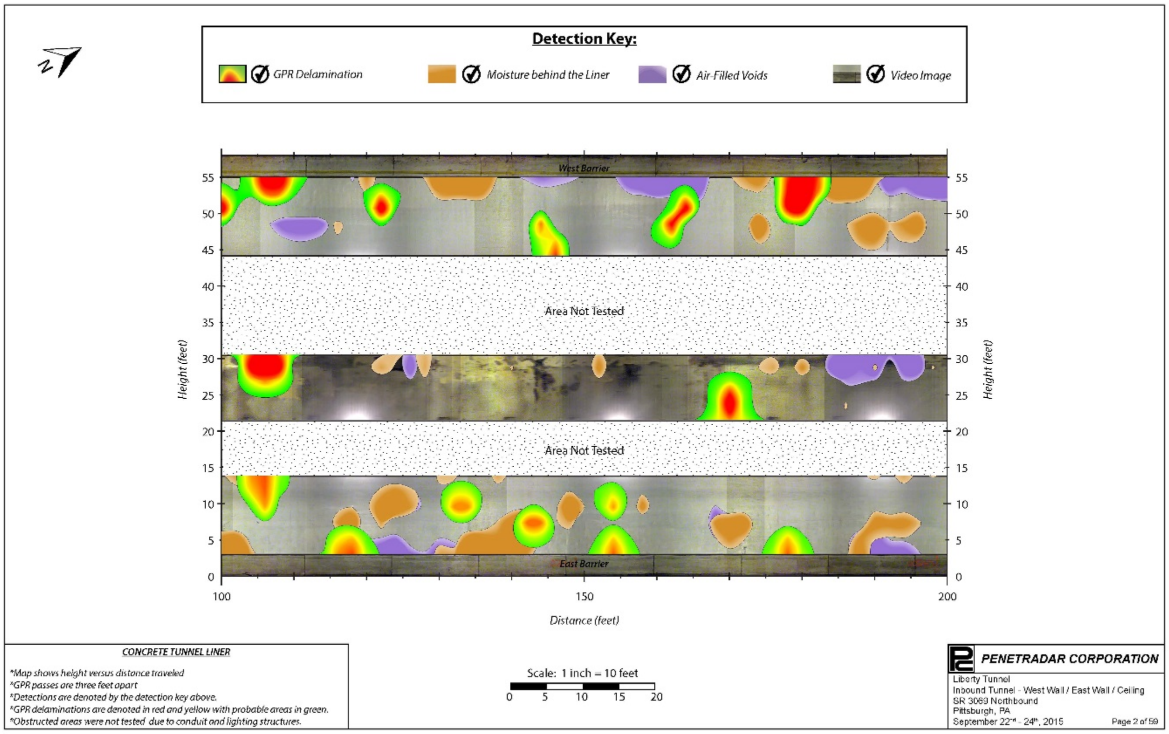

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Figure 5: Example Interactive PDF of GPR Mappings at Liberty Tunnel

Regarding the IRT results at Liberty Tunnel, definitive results could not be produced for the tunnel due to the lack temperature variation between the tunnel lining and ambient air temperature. Better temperature variation was observed near the tunnel portals, and some thermal defects were noted. These defects were presented as thermal “snapshots” derived from the infrared video and are included in Appendix D.

The results of the mobile scanning for Armstrong Tunnel are also presented in Appendix D. The GPR and IRT scanning was divided into two sections due to the lighting obstruction attached to the ceiling of the tunnel bore: the east wall (Section 2) extended from the bottom of the east traffic barrier to the lighting system at the ceiling, and the west wall (Section 1) extended from the lighting system to the bottom of the west traffic barrier. Heights were referenced from the bottom of the east traffic barrier.

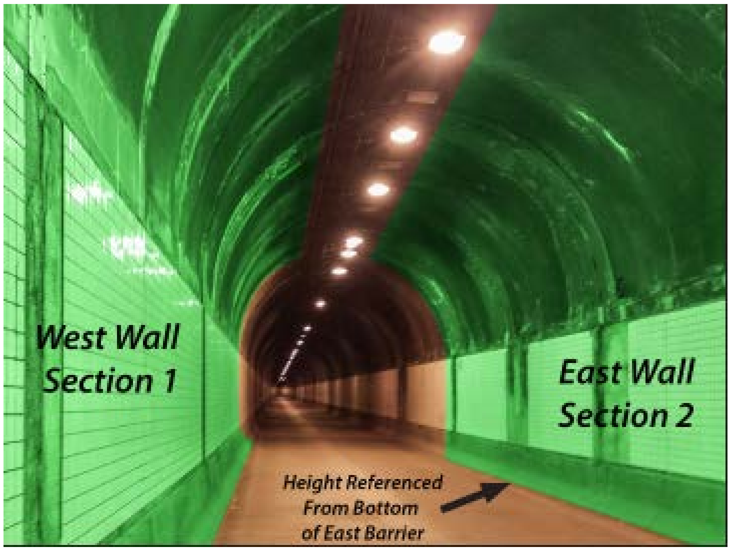


Figure 6: GPR/IRT Survey Locations – Armstrong Tunnel

The Armstrong Tunnel utilized the GPR methods based on ASTM D6087-03 and SHRP C101, which measures signal attenuation to predict the condition of the concrete. The decorrelation method used for the Liberty Tunnel was not applicable to Armstrong Tunnel and did not yield a similar result, suggesting that shallow delamination was not a significant problem in the Armstrong Tunnel.

According to ASTM D6087, signal attenuation can be used as a general indicator of deterioration and delamination in concrete bridge decks. Although tunnel liners are not exposed to the same environmental conditions as bridge decks and the construction method is different, there are enough similarities in the materials comprising these structures to warrant the use of this technique. For Armstrong Tunnel, signal attenuation was continuously measured and thresholds ranging from -6 dB to -8 dB (of the maximum measured signal strength) were applied to the measurements to identify areas of probable defects. Penetradar assigned a scale to classify the different signal attenuation levels, where -6 dB was determined to be “medium”, -7 dB was determined to be “medium to high”, and -8 dB was determined to be a “high” attenuation level.

For the west wall of the Armstrong Tunnel (Section 1), 25.0% (6,794 ft^2) of the area was found to have attenuation levels in excess of -6 dB. A total of 10.9% (2,962ft^2) of the west wall liner exhibited attenuation levels that were classified as “medium or high”, with attenuation levels of greater than -7db. For the east wall of the Armstrong Tunnel (Section 2), attenuation in excess of the -6 dB threshold was found in 25.5% (7,590ft^2) of the area, and 17.6% (5,238 ft^2) of that attenuation considered to be “medium to high” (-7 dB and higher).

Figures 7 and 8 below show the distribution of GPR signal attenuation for the east wall and west wall at Armstrong Tunnel:

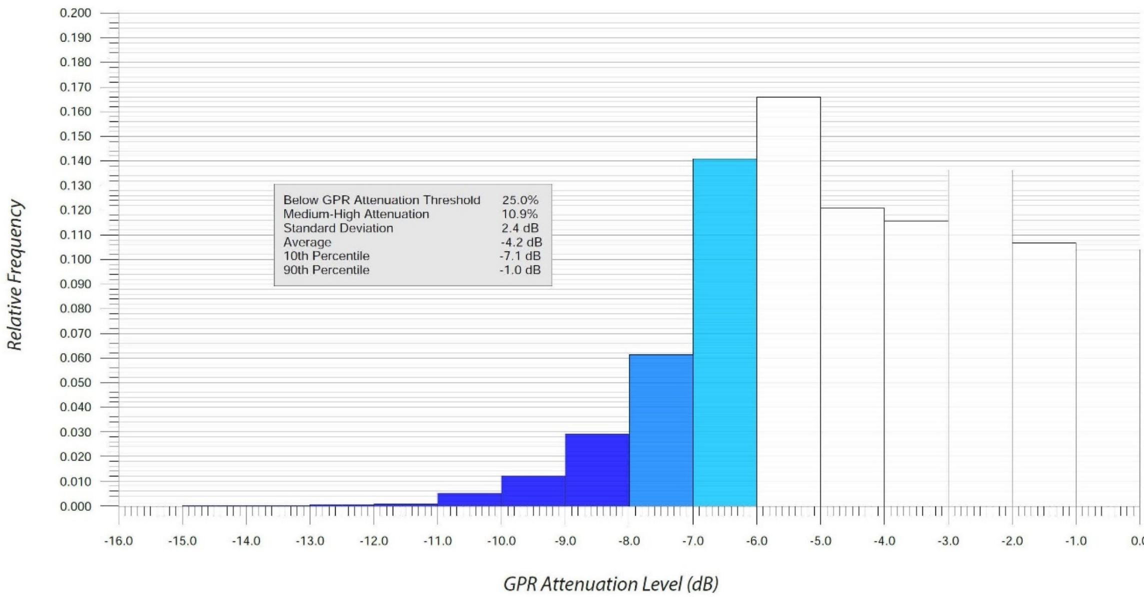


Figure 7: Armstrong Tunnel West Wall - Histogram showing GPR Signal Attenuation

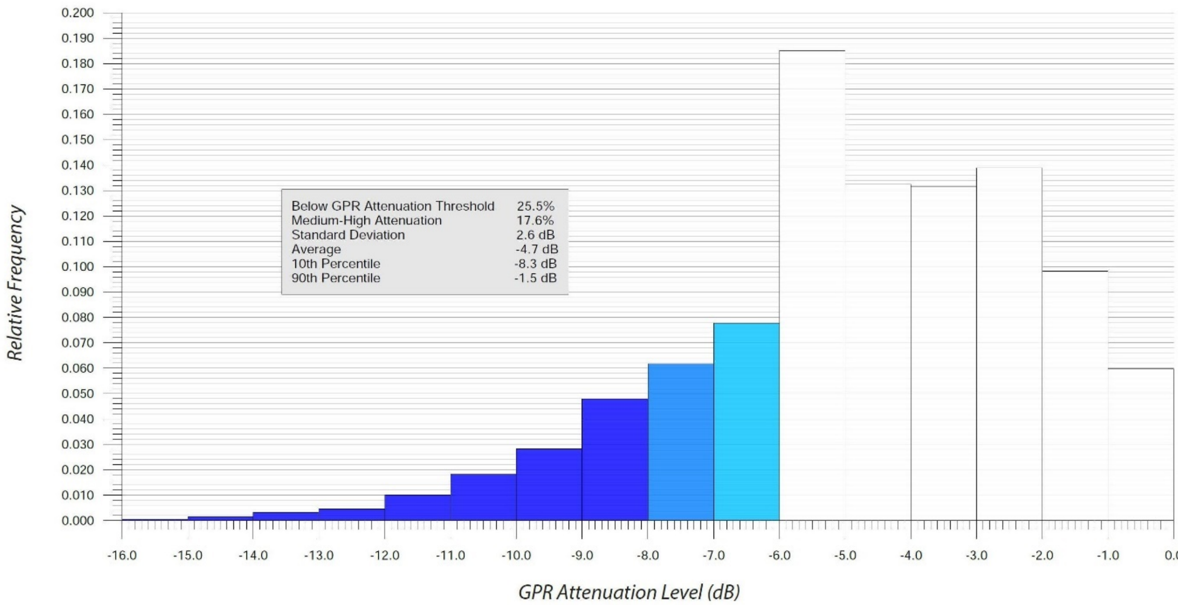


Figure 8: Armstrong Tunnel East Wall - Histogram showing GPR Signal Attenuation

In comparing the attenuation distribution for the east and west walls of the Armstrong Tunnel, Penetradar observed a significant difference in the severity of attenuation even though both sides had roughly the same amount that exceeded the -6 dB threshold. A major difference is seen in the quantity of high attenuation in the east wall (-8 dB and above), which far exceeded the amount detected in the west wall at that level. This would suggest the east wall to be in generally in worse physical condition than the west wall.

The GPR scanning at Armstrong Tunnel was also conducted to measure the dielectric content (moisture content) of the tunnel lining. In tunnels, high levels of moisture within the concrete liner can be an indication of deteriorated concrete, poor concrete consolidation (honeycombing), moisture accumulation in base layers or some other type of incipient problem. GPR, based on its ability to measure the electrical properties of materials, can be used to both identify areas of saturated concrete and quantify the moisture level based on measurement of the dielectric constant of the material. Penetradar was able to estimate the moisture content in concrete based on a linear interpolation of the dielectric constant using two extremes: dry concrete with a relative dielectric constant of 6.25 that represented an approximate low value, and pure water with a dielectric of 81 that represented the maximum. Every other moisture condition lied between these values. The following scale was used by Penetradar to classify low, moderate, and high moisture contents:

Low – < 2% moisture content by volume; dielectric range = less than 8.0
Moderate – 2% to 10% moisture content by volume; dielectric range = 8.0 to 14.0
High – > 10% moisture content by volume; dielectric range = greater than 14.0

After analyzing the GPR data and calculating the relative dielectric constant of the concrete, Penetradar found the west wall to have an average of dielectric constant of 9.6. This value corresponded to roughly 4% moisture by volume. For the west wall, 19.3% of the concrete liner was found to have low moisture content, 75.0% exhibited moderate moisture content, and 5.7% of the concrete exhibited a high moisture content.

The east wall of the Armstrong Tunnel was found to have an average relative dielectric constant of 12.2, which was significantly higher than the west wall. This resulted in an estimated average moisture content of roughly 8%. For the east wall, only 6.4% of the area was determined to have a dielectric value corresponding to low moisture content (less than 2% moisture content by volume). Approximately 72% of the east wall was determined to have moderate moisture content, with a dielectric range of 8.0 – 14.0. The major difference between the west and east walls was in the amount of area with high moisture content. Concrete with high moisture content (dielectric constant greater than 14.0) was found in 21.6% of the east wall, which is over three times greater than what was found in the west wall. This suggests that the east wall may be in worse physical condition than the west wall.

Figures 9 and 10 below show the distribution of the relative dielectric constant of concrete for the east wall and west wall at Armstrong Tunnel.

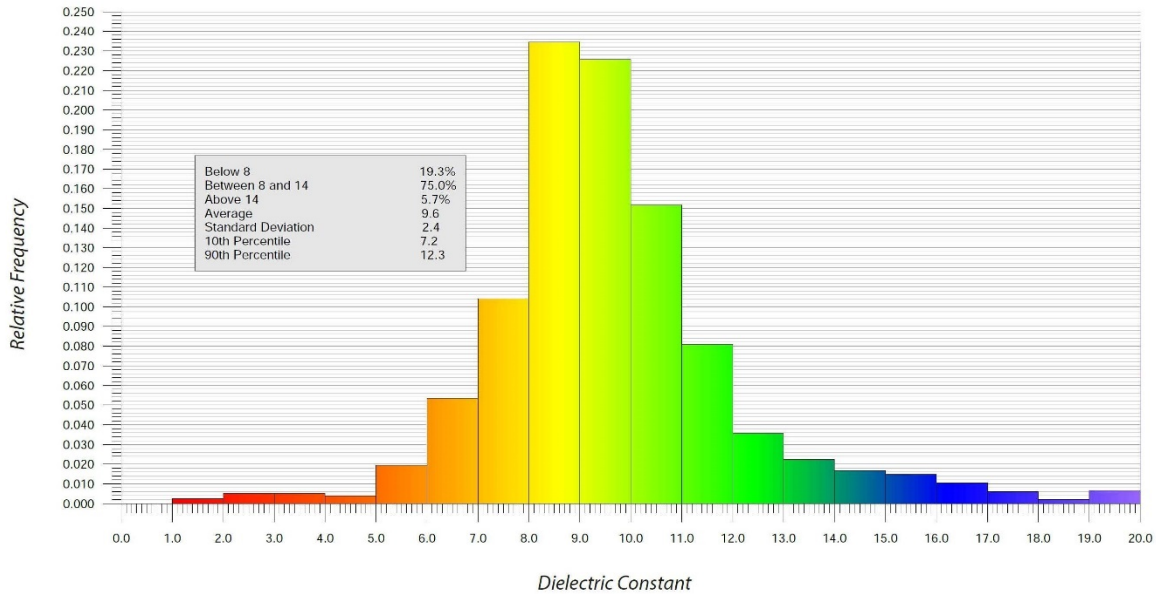


Figure 9: Armstrong Tunnel West Wall - Histogram showing Dielectric Constant

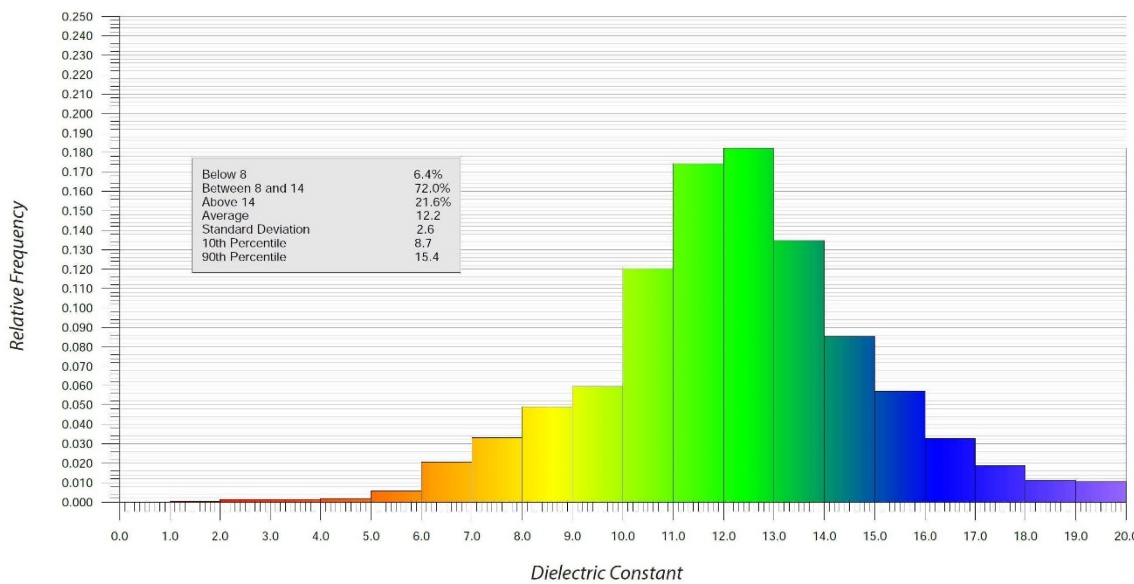


Figure 10: Armstrong Tunnel East Wall - Histogram showing Dielectric Constant

A comparison of dielectric constant for the west and east walls revealed a greater number of higher dielectric measurements in the east wall, suggesting a higher overall moisture content in the east wall. In addition, with an average dielectric of 9.6, the west wall was estimated to have 4% moisture content, whereas the east wall, with an average dielectric of 12.2 was determined to have a moisture content of approximately 8%. Based on this observation, it was estimated that the east wall has almost twice the moisture content as the west wall.

The table below summarizes the GPR results for signal attenuation and dielectric content at Armstrong Tunnel.

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

Table 2: Summary of GPR Detections for Armstrong Tunnel

In regards to the IRT scanning at Armstrong Tunnel, results were optimized using a number of image enhancements to improve the thermal sensitivity and detection of defects. In addition to aspect correction and conversion to a plan-view, coherent image integration (stacking of image data) and analysis of numerical renderings of image data were also performed. While these methods did achieve some measure of improvement in data quality, they did not add to the overall detection rate for defects. Penetradar indicated that this was not unexpected, since it was their belief that both tunnels were in reasonably good condition.

The Armstrong Tunnel infrared mappings revealed few distinct detections of thermal variation. However, visual distress was clearly observed in some of those areas, in the form of discolored tile, exposed concrete areas or visible evidence of moisture on the tunnel liner. Temperature measurement distributions for the west and east wall showed temperatures plotted over 1 °F increments. The west wall and east wall temperature distribution plots generally follow a normal (Gaussian) distribution, except with a slight skewing toward the low temperature end. The main observation from the thermal data was the difference in the mean or average temperature difference between the east and west wall. The mean temperature was 78.1 °F for the west wall and 77.2 °F for the east wall, which is a difference of almost 1 °F. This difference could be due to the construction of the tunnel and the fact that the west wall borders an open air southbound tunnel whereas the east wall does not. However, it could also be the result of higher moisture content in the concrete, which would serve as a better conductor of heat into the wall. This would further confirm the results obtained by GPR scanning, which identified greater moisture content (based on measured dielectric constant) and higher attenuation levels in the east wall.

Figures 11 and 12 below show the distribution of the temperature values for the east wall and west wall at Armstrong Tunnel:

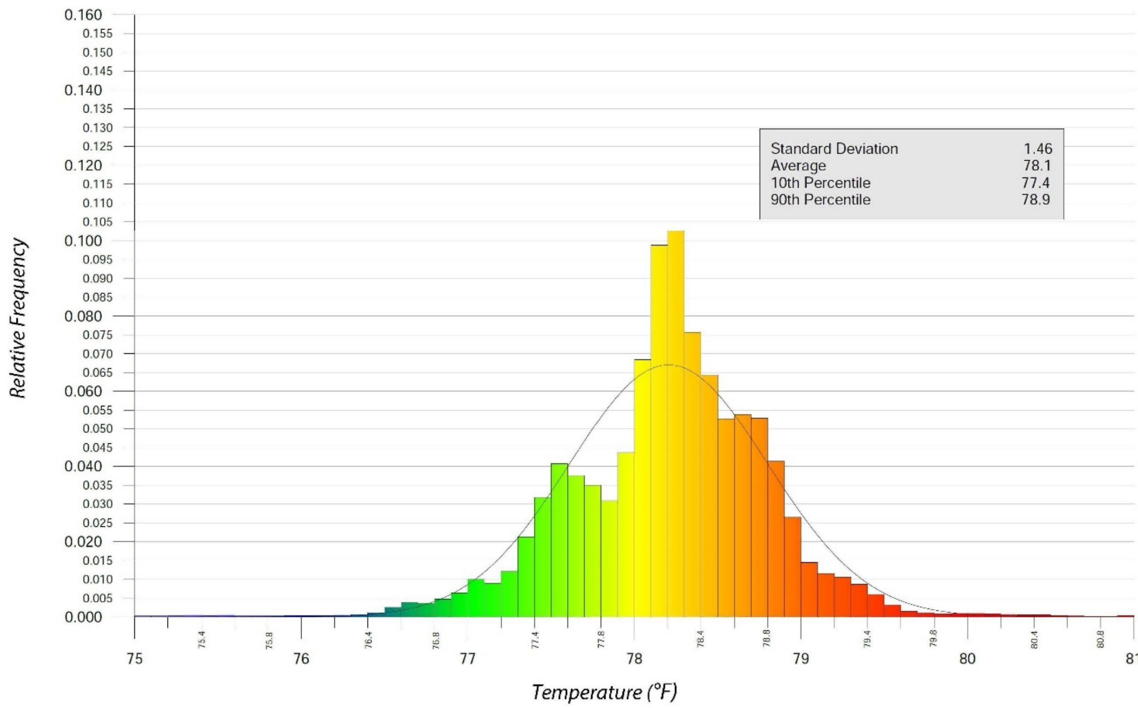


Figure 11: Armstrong Tunnel West Wall - Histogram showing Thermal Distribution

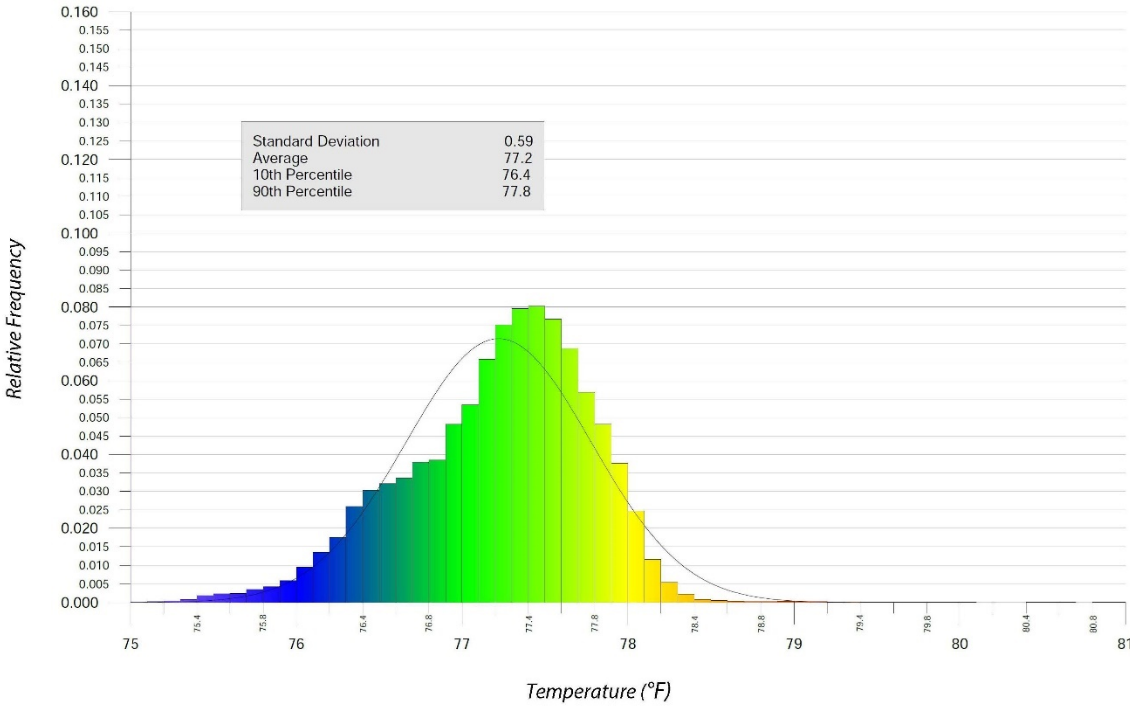


Figure 12: Armstrong Tunnel East Wall - Histogram showing Thermal Distribution

SPACETEC MOBILE SCANNING RESULTS

SPACTEC's three-channel scanner (TS3) was used for this project. This advanced scanning technology is capable of obtaining thermal data (IRT), profile data (3-D survey), and visual data in one simultaneous scan using a recording angle of 360 degrees. The scanner was assembled on a vehicle that traveled at a rate of 1.12 mph to achieve a resolution of 10,000 pixels per scan. Vehicle speeds greater than the recommended rate would cause pixels to stretch on the scanned images, thereby compromising the scanning resolution. The stationing that was used for the SPACETEC scanning was correlated to the stationing established by Mackin using the measuring wheel and paint marking on the east wall traffic barrier. This was done to reference the location of anomalies with consistency.

Photo 10: SPACTEC scanner on vehicle

Photo 11: Data processing equipment

Photo 12: SPACETEC scanning in Liberty Tunnel

Temperature differences (minimum of 1-degree F) on the surface of the tunnel were detectable and displayed on thermal images. Using the combined laser image and thermal image, deficiencies such as concrete spalls, efflorescence, delaminated and debonded areas, cracks as small as 0.3mm wide, and water infiltration can be detected on the tunnel liner surface. The profile data can also be used to measure clearance problems and analyzing the tunnel surface with respect to defects related to spalling, bulges, changes in shape, etc. that are significant to monitoring changes over time or over subsequent inspections. The data obtained from previous scans can be superimposed with current findings to facilitate a comparison.

The results of the SPACETEC scanning were presented in graphical format for the test section and are presented in Appendix E. The data from the initial results provided by AID is discussed below. As an example, the visual and thermal images recorded at the test section from Station 3+350 to 3+450 of the east wall at Liberty Tunnel are shown below in unfolded plan view:

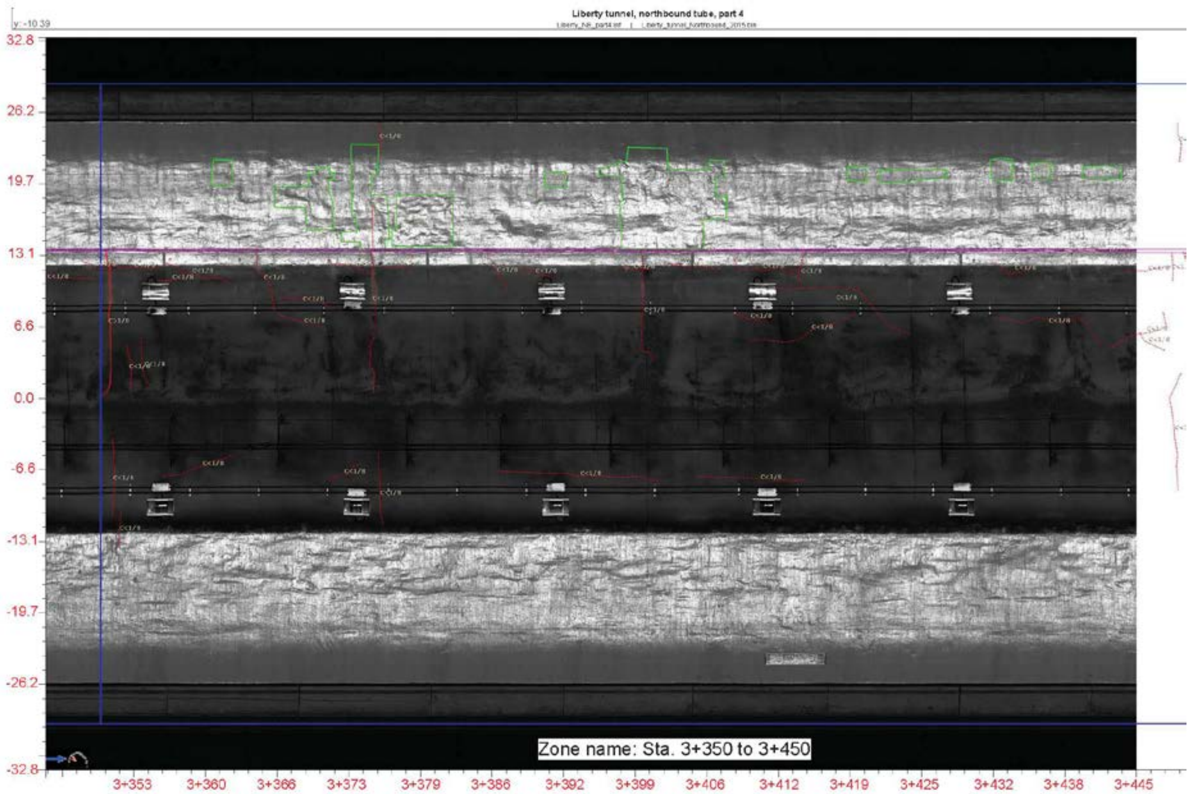


Figure 13: SPACETEC Visual Data Scan, Station 3+350 to 3+450 Liberty Tunnel

The apex of the tunnel arch is indicated as "0.0" on image, and the east wall is shown on the upper section of the data image between 13.0 and 26.0. Previous concrete repair locations detected by the scanning are delineated by green lines and cracks are delineated by red lines. The difference in shading between the walls (lighter shaded zones) and the ceiling (darker shaded zones) is due to the walls having a white, protective paint coating. No spalls were present at this section of the wall. The white boxes at the ceiling region are an indication of the luminaire heads detected by the scan.

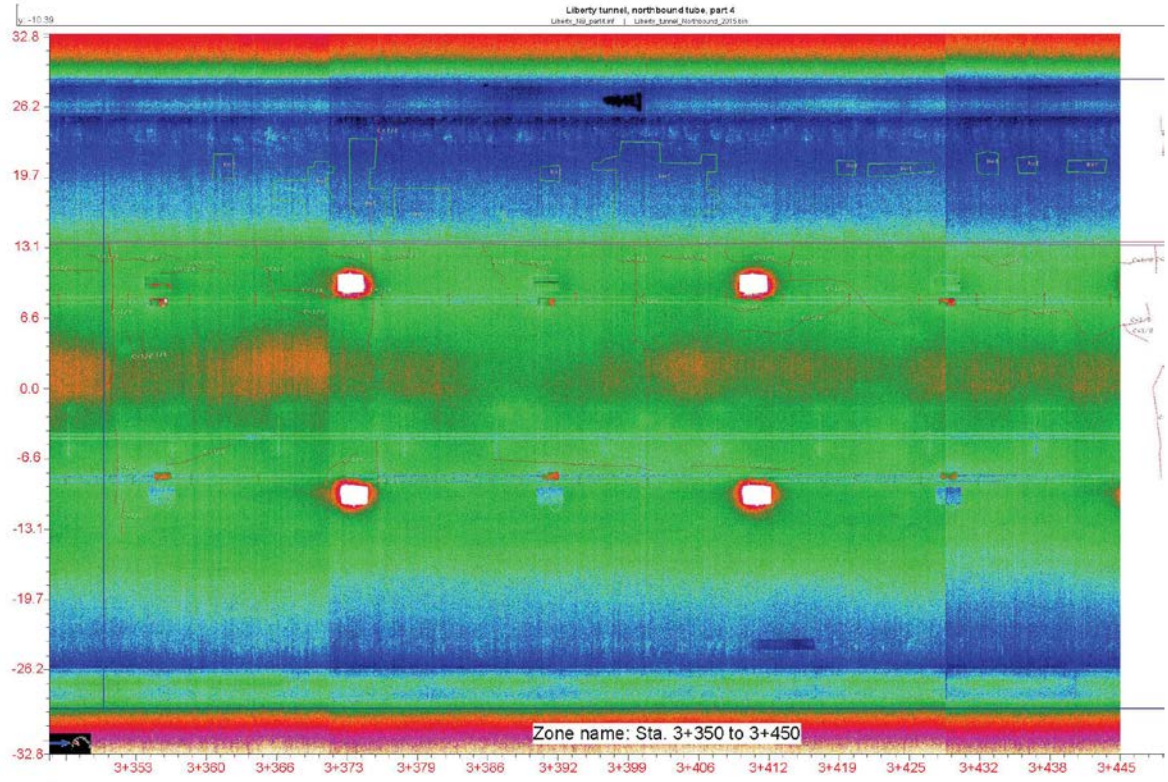


Figure 14: SPACETEC Thermal Scan, Station 3+350 to 3+450 Liberty Tunnel

The thermal image above indicates cracks (red lines) and delineates previous repair locations with green lines, which have been superimposed from the video scanning at Station 3+350 to 3+450. The IRT scan was not effective at detecting defects, such as delaminations, because the temperature variation between the tunnel surface and air temperature was relatively uniform. This was attributed to the length of the Liberty Tunnel and the location the test section within the tunnel. The luminaire heads are indicated as white spots on the thermal image, which produce a warm heat signature compared to the concrete surface. Based on conversations with AID, the red shaded area along the arch apex is an indication that the ceiling is warmer than the walls and is not an indication of a warm anomaly. In addition, the blue shaded areas at the walls are not indication of deterioration or moisture intrusion. These general thermal variations between the ceiling and the walls were likely attributed to different concrete thicknesses at the walls and ceiling, and also from the protective paint coating on the walls. AID indicated that when a thermal analysis is conducted and this color pattern is observed, different thermal analyses are conducted for the walls and ceiling.

The defect quantities that were identified at the test section from Station 3+300 to 3+500 of the east wall at Liberty Tunnel were also presented in tabular form and are included in Appendix E. The defect quantities from the initial report prepared by AID for the test section is discussed below. The quantities for patch/repair areas at the wall and edge chipping at the traffic safety barrier for the test section were tabulated in 100-foot segments and were shown graphically with bar charts:

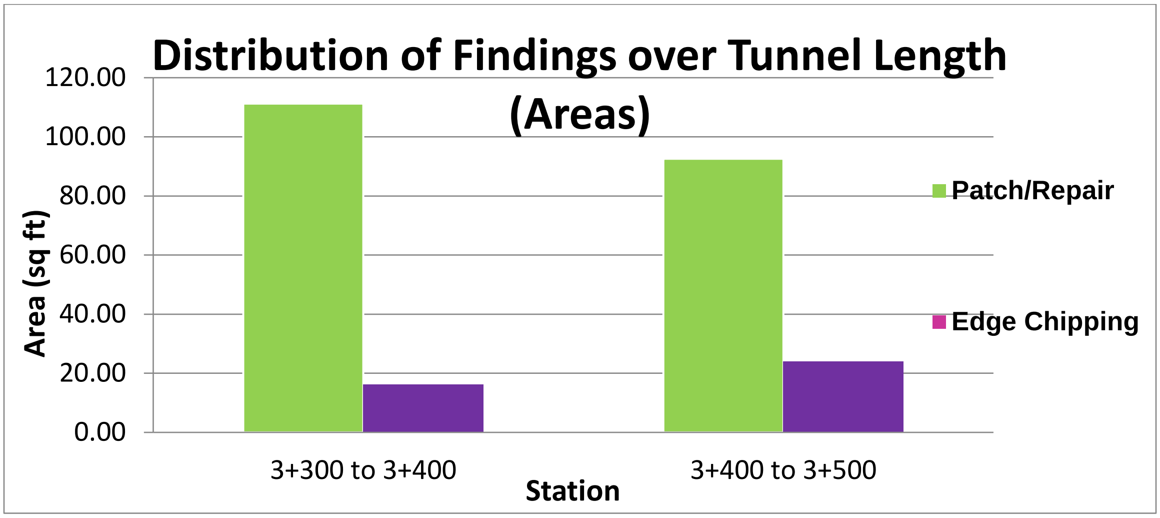


Figure 15: Total Quantity (SF) of Patch/Repair Areas and Safety Barrier Edge Chipping

The total area of previous concrete patch/repair areas at the test section detected from the laser scanning was 203.79 SF, and the total area of edge chipping/spalling at the safety barrier was 40.14 SF. Since the barrier edge chipping/spalling was not considered to be significant to the project, Mackin requested AID to remove this deterioration from the complete reports for Liberty and Armstrong Tunnels. Nonetheless, the data above is shown to illustrate concrete spalling can be detected by the SPACETEC scanning. In addition, Mackin was not able to compare the total area of patch/repair areas detected from scanning to the recent rehabilitation drawings S-29344 since no repairs or quantities were shown at this section of the of tunnel.

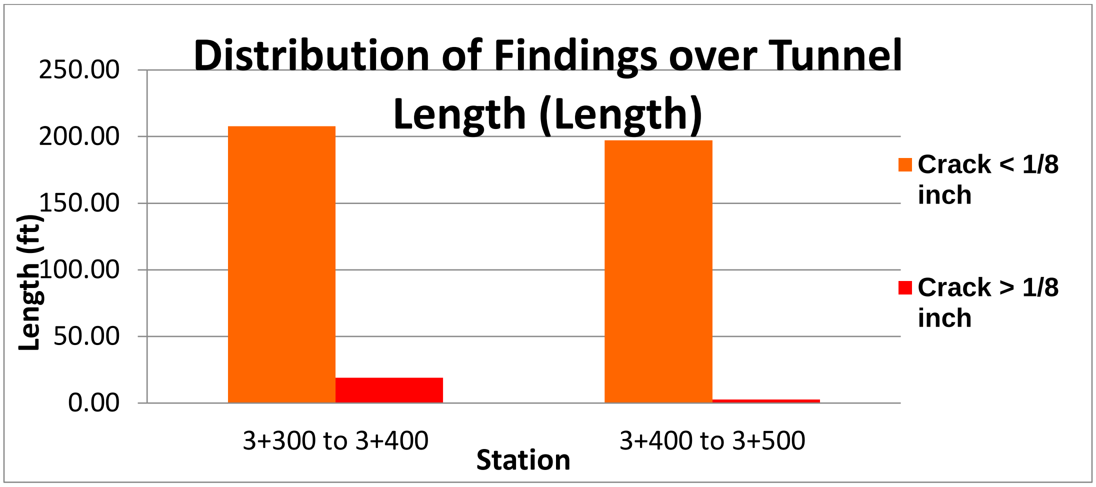


Figure 16: Total Quantity (LF) of Concrete Cracks

The concrete cracks (tabulated above) were quantified for the ceiling and east wall from Station 3+300 to 3+500 and were separated for cracks greater than and less than 1/8”. The total quantity of cracks greater than 1/8” was 21.66 ft and the total quantity of cracks less than 1/8” was 405.09 ft. As result, the majority of cracking noted at this section of the tunnel was considered minor hairline cracking.

The complete results and tabulated defects for the entire Liberty Tunnel are included in Appendix F. Figures 17 through 20 below show the tabulated results for cracks, cold anomalies, and refurbished (patch/repair) areas for the entire northbound Liberty Tunnel bore. Other tabulated results, such as defect counts, crack area, and honeycombing were included but are not shown below.

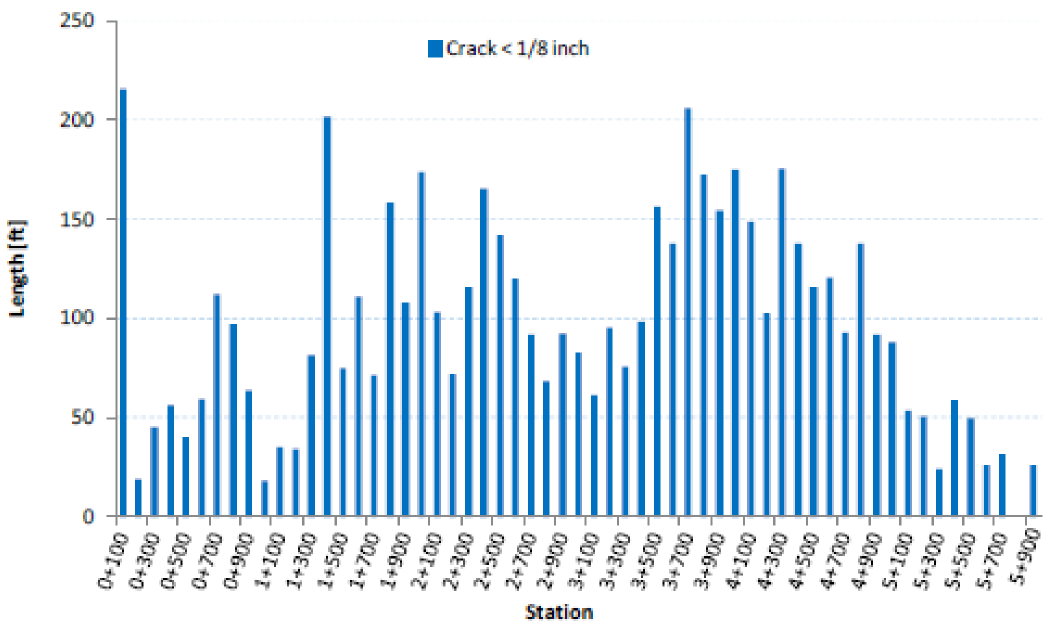


Figure 17: Total Distribution of Cracks less than 1/8” for Liberty Tunnel

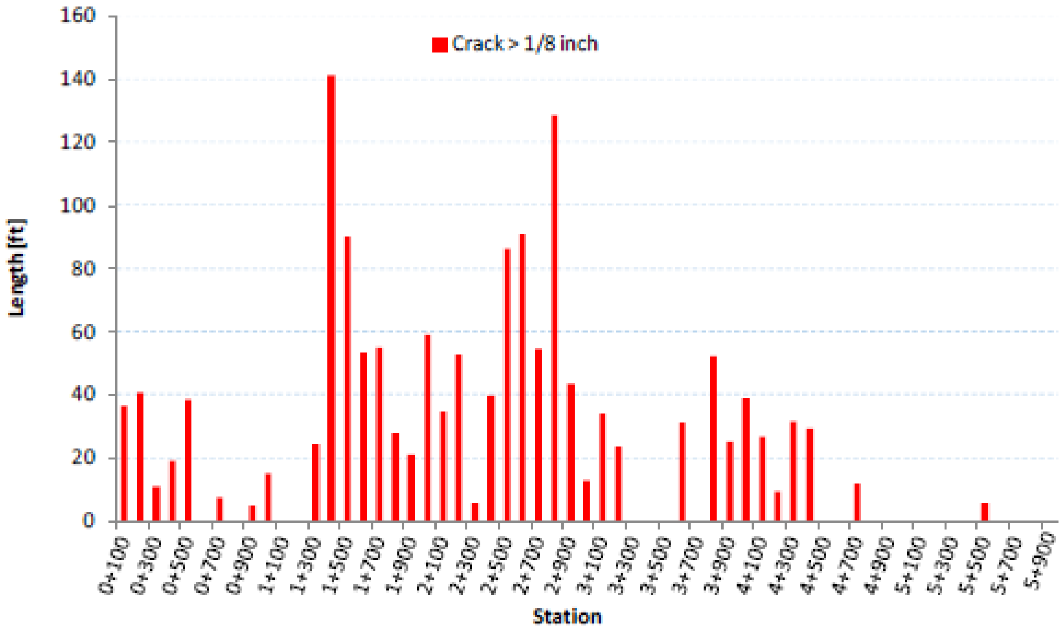


Figure 18: Total Distribution of Cracks greater than 1/8” for Liberty Tunnel

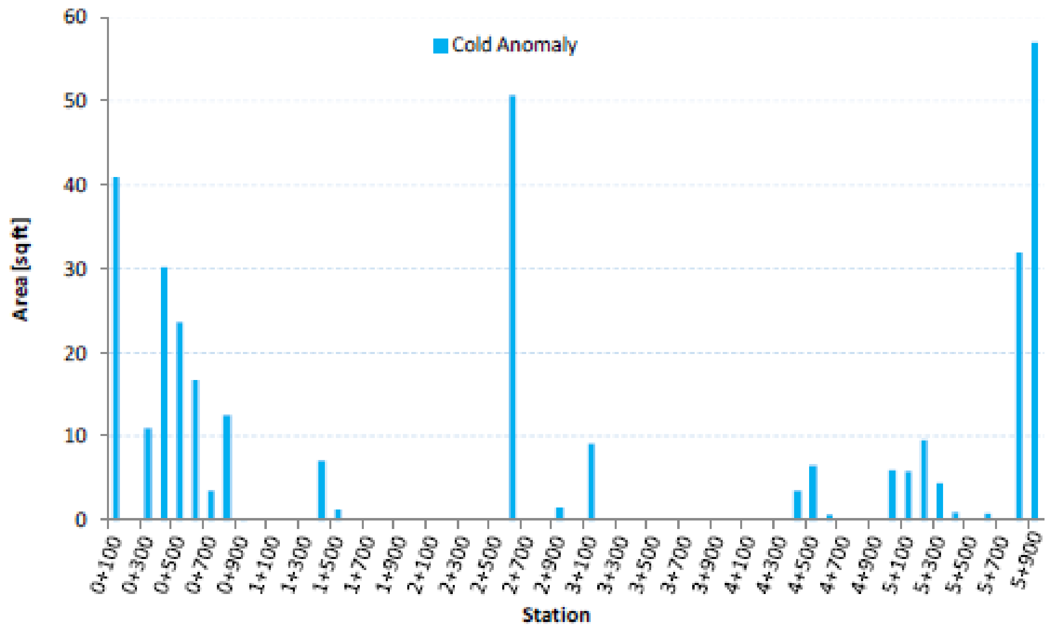


Figure 19: Distribution of Cold Anomalies for Liberty Tunnel

In review of the cold anomaly results (shown in the above figure) that were detected from the IRT scan, it can be seen that a larger area of defects (moisture related or delaminations) were identified near the portals. These results were expected due to air temperature having a greater effect on the tunnel surface temperature near the portals and also because moisture intrusion was visually observed near the portals.

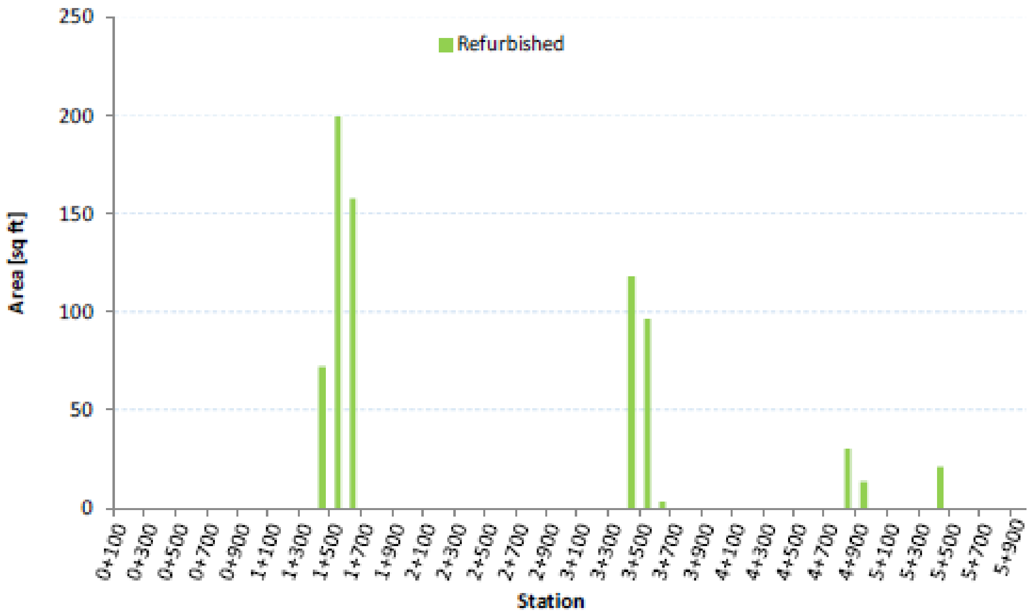


Figure 20: Distribution of Refurbished (Patched/Repair) Areas for Liberty Tunnel

In review of the patched/repair areas detected from the visual scanning (shown above), the distribution is random and isolated. The repaired areas were determined to be in sound condition since no debonding was detected from the thermal scans. Previous repair areas were also determined to be in good condition from the 2014 Mackin inspection and the hammer sounding that was performed at the test section. However, in comparison to the rehabilitation drawings S-29344, a much greater quantity of repair areas was observed on the drawings than was detected by the visual scan. One possible reason for this difference is the visual appearance of repaired areas and non-repaired areas is similar, which makes the distinction difficult.

For Armstrong Tunnels, the complete results are presented in Appendix G. The SPACETEC scanning successfully detected cracks, warm and cold anomalies, and missing or debonded tiles. However, the distinction between true anomalies and the general shading resulting from overall surface temperature is somewhat difficult. The figures below show typical visual and thermal scans at Station 2+00 to 2+50 in Armstrong Tunnel. On the visual image scan, cracks are delineated by red lines and cold anomalies are delineated by blue lines. On the thermal image, cold anomalies are blue shaded areas and cracks have been superimposed from the visual scan.

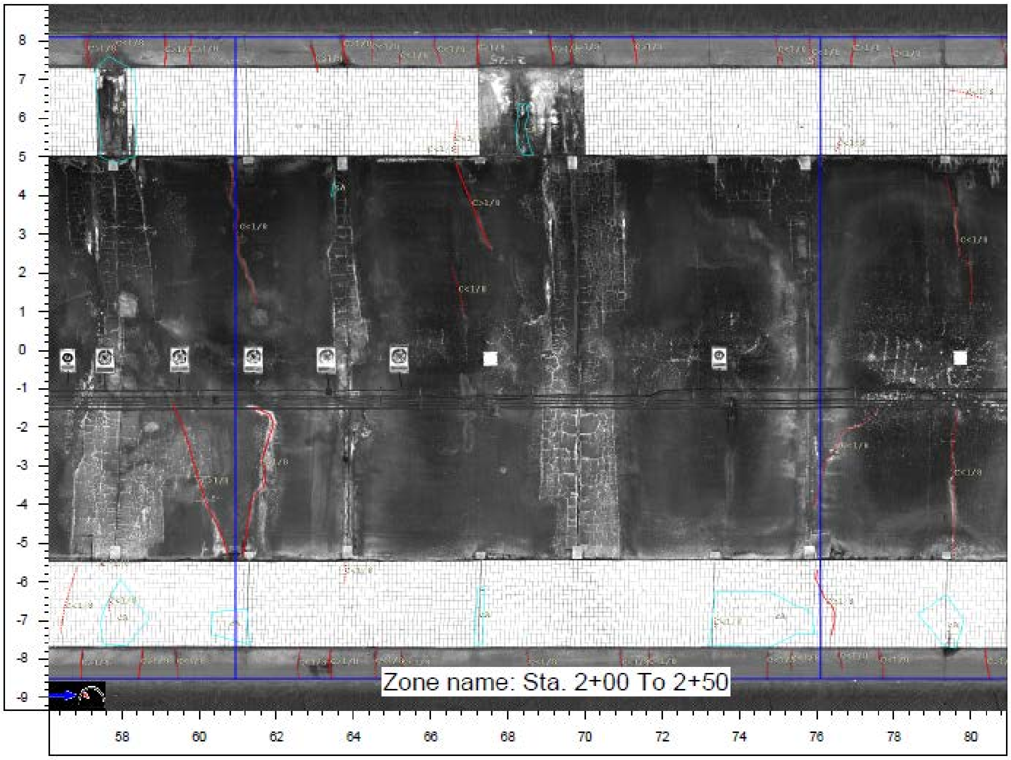


Figure 21: Visual scan, Armstrong Tunnel Station 2+00 to 2+50

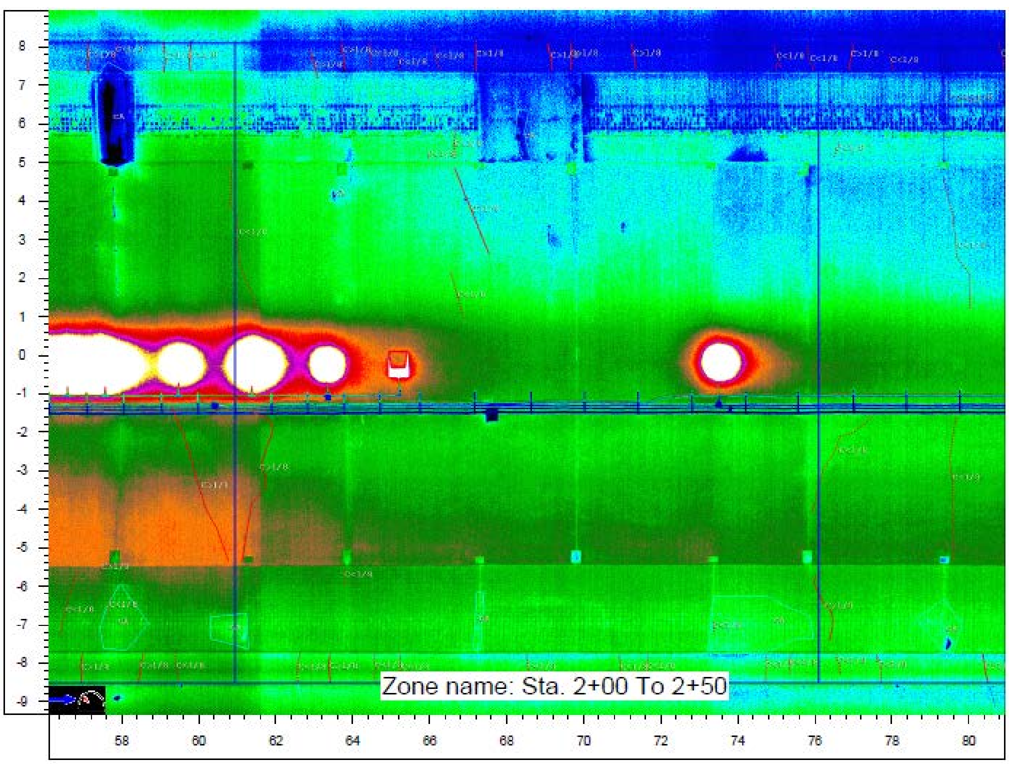


Figure 22: Thermal scan, Armstrong Tunnel Station 2+00 to 2+50

Figures 23 through 27 below show the tabulated results for cracks, cold anomalies, warm anomalies, and missing/debonded tile areas for the entire northbound Armstrong Tunnel bore. Other tabulated results, such as defect counts, efflorescence, cracked patches, and ceiling damage were included but are not shown below.

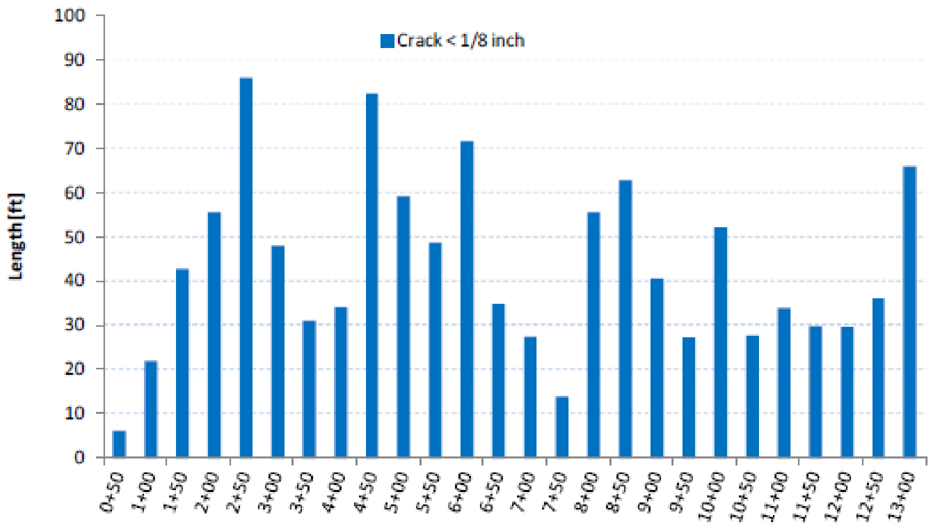


Figure 23: Distribution of Cracks Less Than 1/8", Armstrong Tunnel

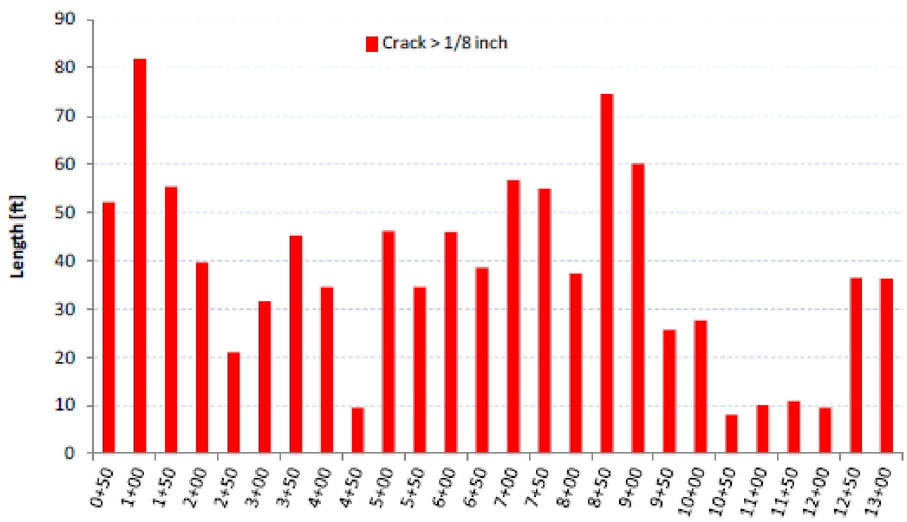


Figure 24: Distribution of Cracks Greater Than 1/8", Armstrong Tunnel

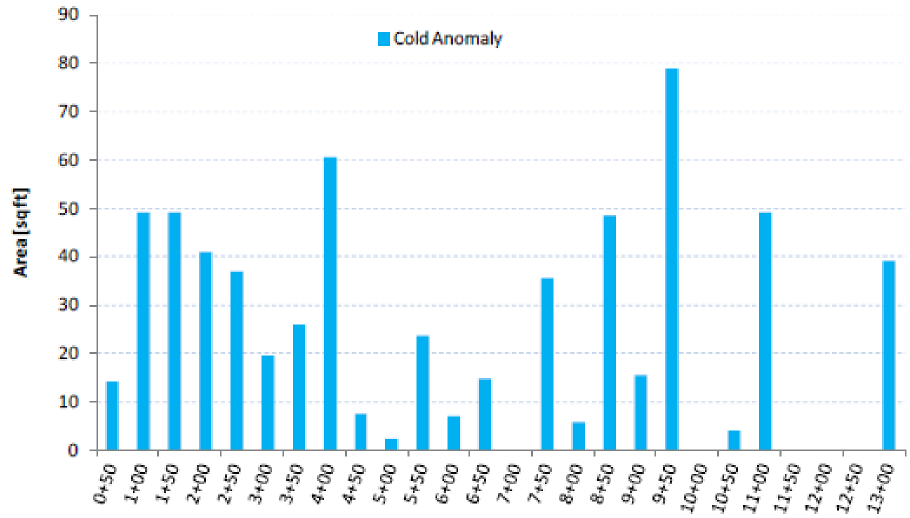


Figure 25: Distribution of Cold Anomalies, Armstrong Tunnel

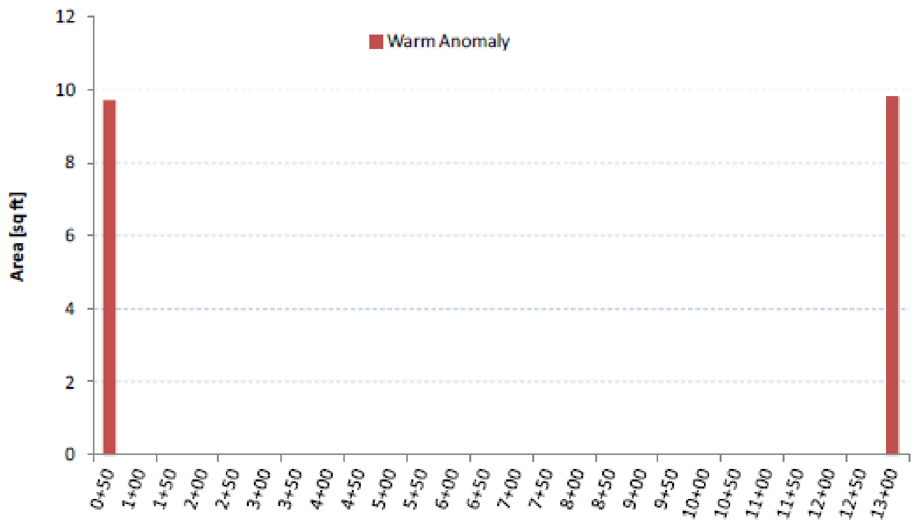


Figure 26: Distribution of Warm Anomalies, Armstrong Tunnel

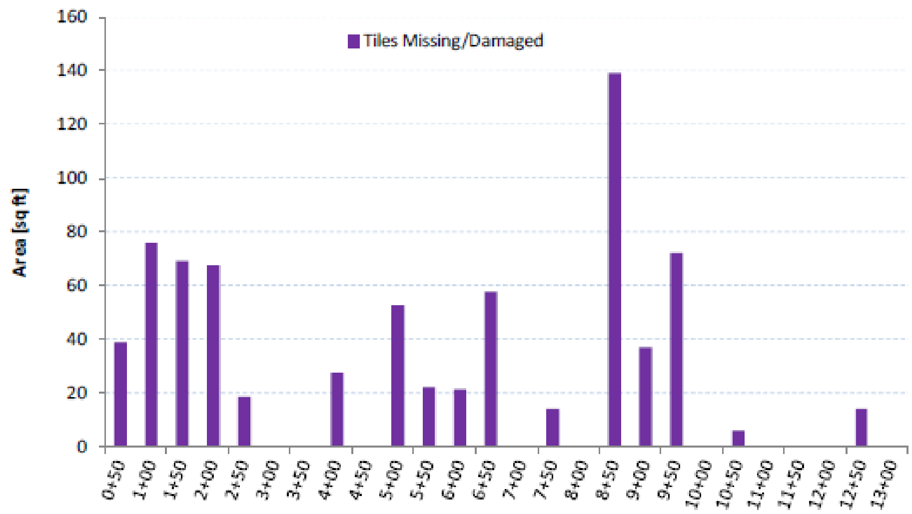


Figure 27: Distribution of Missing/Damaged Tiles, Armstrong Tunnel

In review of the figures above, it can be seen that small and large cracks are evenly distributed and are present throughout the length of the tunnel. Cold anomalies, which were likely due to concrete delaminations and/or moisture intrusion, were distributed throughout the tunnel but varied in terms of square foot quantity among the tunnel stations. Warm anomalies were only present at the south and north ends of tunnels; however, the cause of the heat source is unknown. In addition, missing and/or debonded tiles were present but varied throughout the tunnel (see Figure 27 above).

AID HAND-HELD NDT RESULTS (LIBERTY TUNNEL TEST SECTION)

Following the SPACETEC mobile scanning and initial reporting by AID for the test section, field verification testing was conducted on the test area of Liberty Tunnel using a Portable Seismic Property Analyzer (PSPA). The complete PSPA test results are included in Appendix F of this report. It should be noted that no PSPA testing was performed on the Armstrong Tunnel lining.

The PSPA is a hand-held device consisting of two ultrasonic transducers and an impact source that is operated from a laptop computer that measures the signals from the transducers, which are further subjected to processing and spectral analysis. From this data, the Ultrasonic Surface Wave (USW) method can be used to determine the seismic modulus from the measured surface wave velocity. The PSPA is also used to conduct Impact Echo (IE) testing. For the IE test, the impact source of the PSPA applies mechanical energy to the concrete surface; the incident waves and echoes, which are the waves reflected back from the boundaries of the slab and the heterogeneities with the concrete, are recorded by the receiver of the PSPA. The data analysis includes the transformation of the record into the frequency domain and inspection of the resulting spectrum.

The objective of the ultrasonic/seismic testing with the PSPA was to measure the seismic modulus of elasticity (USW method) of the concrete lining, conduct Impact Echo (IE) analysis, and identify areas exhibiting debonding/ delamination. The testing was performed using a grid system. A total of twenty-one (21) stations with a spacing of 10' were used over the 200-foot test section, and nine (9) PSPA test points were selected over the height of the wall between the safety barrier and the tunnel lighting system. From ground level, test points were selected at heights of 44", 59", 74", 89, 104", 122", 140", 158", and 176". As a result, 189 test points were evaluated with the PSPA. In addition, for every test point, up to three (3) repetitions with the PSPA were performed to measure the variation in the seismic modulus in the vicinity of the test point.

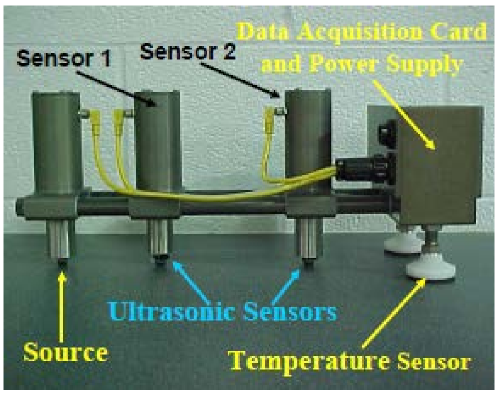


Photo 13: PSPA Device Overview


Photo 14: Layout of PSPA Test Points


Photo 15: PSPA Testing from Lift Vehicle

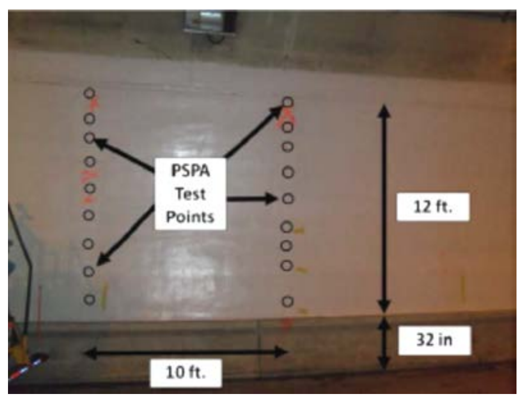


Photo 16: Typical Test Point Locations

Overall, AID concluded that there was good correlation between the seismic modulus obtained from the PSPA testing and the areas showing debonding or delamination. Areas of severe debonding were also clearly identified with the IE analysis. However, areas having average or above average modulus, either presented frequencies associated with the resonant frequency of the concrete lining or some indication of delamination. Nevertheless, a good correlation from Impact Echo results was also obtained.

The figure below shows the tabulated seismic modulus data obtained from the PSPA evaluation at the test section.

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%*
	3+370	3+380	3+390	3+400	3+410	3+420	3+430
176	4083	3830	4030	3220	3855	2987	3525
158	4207	3405	3765	3360	3650	3795	3740
140	3850	4063	4345	3565	3760	3307	3160
122	3585	3965	3960	3770	3975	3457	3625
104	4085	3835	2430	3780	3810	3545	3655
89	4100	4355	1660	3685	4075	3440	3420
74	2080	4045	4295	3925	4355	4070	3880
59	3483	4105	4540	2895	4495	4233	4405
44	3803	3570	4645	1910	4580	4455	4340
Average	*3697*	*3908*	*3741*	*3346*	*4062*	*3699*	*3750*
Stdev	*655*	*288*	*1019*	*627*	*339*	*476*	*407*
COV, %	*18%*	*7%*	*27%*	*19%*	*8%*	*13%*	*11%*
	3+440	3+450	3+460	3+470	3+480	3+490	3+500
176	3725	2858	3915	4405	4230	1743	3970
158	3827	3480	3825	4043	3525	4190	4495
140	3615	3830	3960	3410	4280	2703	4120
122	3553	2054	1915	3730	4045	4080	2498
104	3317	2730	4170	3850	4015	4015	3980
89	1630	4125	3487	4315	4095	3235	1548
74	4140	3830	4160	4425	4310	3403	3993
59	4255	4035	4265	3935	3975	3303	4360
44	4290	4230	3480	4250	4350	3557	4445
Average	*3595*	*3464*	*3686*	*4040*	*4092*	*3359*	*3712*
Stdev	*808*	*751*	*721*	*343*	*253*	*770*	*1007*
COV, %	*22%*	*22%*	*20%*	*8%*	*6%*	*23%*	*27%*

Figure 28: Summary of Seismic Modulus Results from Station 3+300 to 3+500

The measured modulus (ksi) at each test point, the average modulus (ksi), standard deviation (ksi) and covariance (%) for each station are shown. Based on this information, the individual modulus for all test points varied from 1,400 to 4,920 ksi. Based on visual observations and correlation with hammer soundings, test points with a modulus lower than 2,750 ksi were suspected of being delaminated/debonded. The average modulus at each station ranged from 2,744 to 4,092 ksi. The standard deviation and covariance over all stations varied from 253 to 1,229 ksi and from 6% to 35%, respectively. The higher variations in the standard deviation and covariance values at a particular station indicates the concrete exhibits areas of sound and unsound concrete over the height of the wall.

The seismic modulus results from the PSPA testing were also shown in the form of a colored contour map, which is shown in Figure 29 below. The color scale shows that blue and green colors are associated with higher modulus values and orange and red colors with lower modulus values. As previously indicated, test points with a modulus lower than 2,750 ksi (orange and red colors) are were suspected of being delaminated/ debonded. From this figure, it can be observed that the area around Stations 3+350 and 3+360 has the biggest concentration of concrete debonding/delamination. This correlates well with the tabulated seismic modulus data above, where the covariance at Station 3+350 was high (35%) and the average modulus at Station 3+360 was relatively low (2,744 ksi).

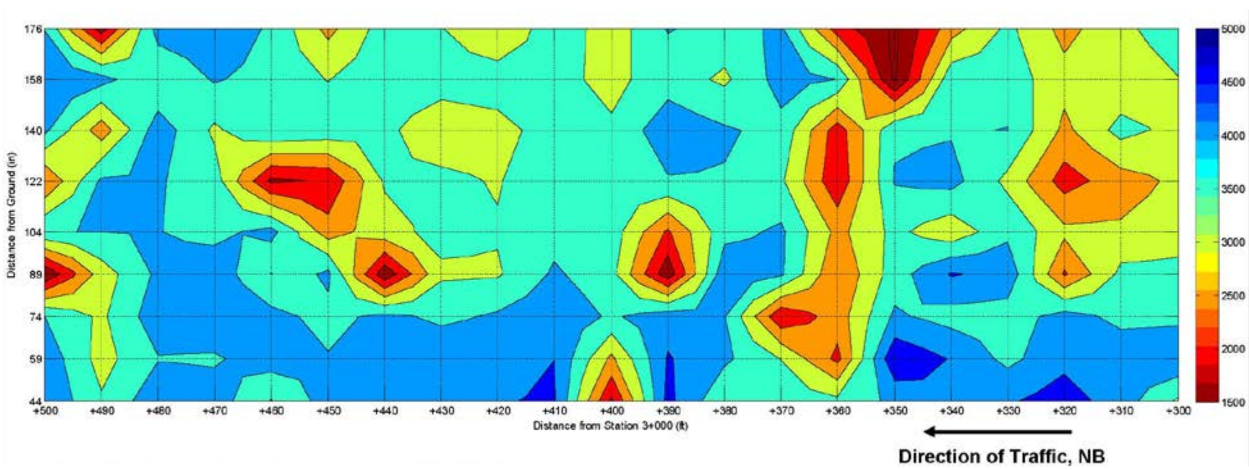


Figure 29: Colored Map Showing Seismic Modulus Results from PSPA Testing

If the compressive strength was able to be obtained from the concrete cores that were extracted, additional correlation between the compressive strength and seismic modulus could have been evaluated. In general, a larger seismic modulus corresponds to larger concrete strengths.

The IE results were also summarized in tabular format, which is shown below. The complete IE results are included in the AID report for the Liberty Tunnel in Appendix F. A numerical value (ranging from 1 to 4) was assigned to all points tested with the PSPA: a ‘1’ corresponded to a severely debonded location, a ‘2’ was associated with a moderate debonded/delamination location, a ‘3’ was assigned to a slightly debonded/delaminated location, and a ‘4’ represented an intact/sound location.

Distance from Ground, in	Station and Debonding Condition.						
	3+300	3+310	3+320	3+330	3+340	3+350	3+360
176	3	3	3	1	3	1	1
158	2	2	3	4	3	1	3
140	1	2	2	4	2	3	1
122	2	3	2	3	4	3	2
104	2	4	2	4	4	2	3
89	3	3	4	2	4	2	1
74	4	4	3	3	3	3	2
59	3	4	3	3	3	4	1
44	2	3	3	2	3	3	1
	3+370	3+380	3+390	3+400	3+410	3+420	3+430
176	1	2	2	3	2	3	4
158	4	3	3	4	3	4	4
140	2	2	3	2	2	3	3
122	3	4	2	2	3	3	2
104	4	3	2	2	2	2	4
89	3	4	1	4	4	4	4
74	4	2	4	4	4	3	4
59	3	3	3	3	4	3	2
44	3	3	3	1	3	4	2
	3+440	3+450	3+460	3+470	3+480	3+490	3+500
176	3	1	2	2	3	1	3
158	4	3	4	4	3	3	3
140	2	2	3	3	2	4	2
122	4	3	1	3	3	3	4
104	2	2	3	2	2	2	2
89	1	3	4	4	4	3	1
74	3	2	3	4	3	1	3
59	2	3	4	2	3	2	3
44	3	4	3	3	3	3	4

Figure 30: Summary of Impact Echo Results from Station 3+300 to 3+500

Similar to the seismic modulus results, a color contour map was developed for the IE results, which is shown below in Figure 31. The blue/green colors are associated with intact/sound locations and orange/red colors with debonded/delaminated locations. A good correlation was observed between the IE results and the seismic modulus results determined from the USW method.

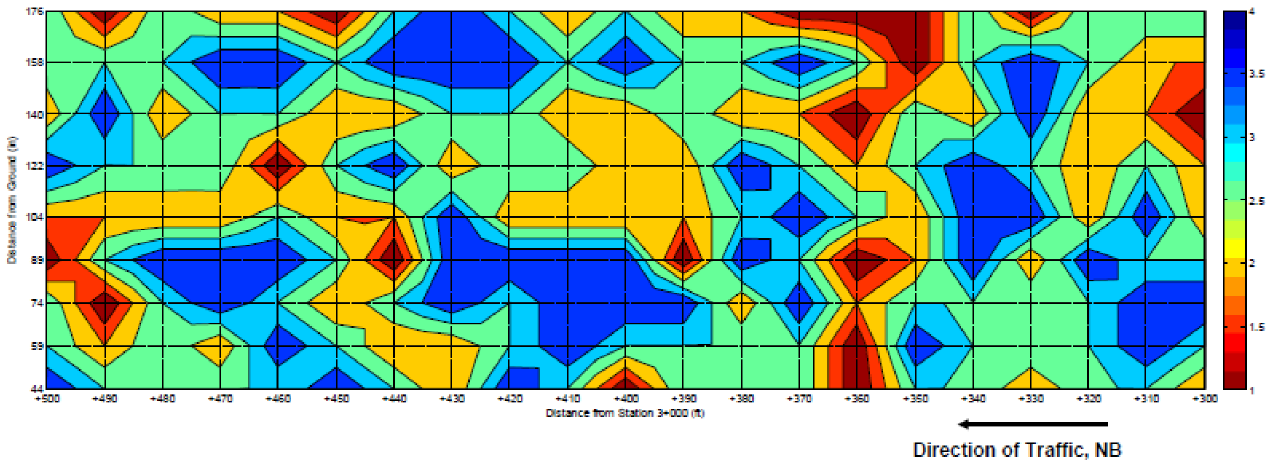


Figure 31: Colored Map Showing Impact Echo Results from PSPA Testing

PHYSICAL INSPECTION RESULTS

In conjunction with the hand-held NDT testing that was performed on November, 5, 2015, Mackin performed a physical inspection of the east wall test section of the Liberty Tunnel using an inspection hammer and delamination wheel. No physical inspection or concrete coring was performed on Armstrong Tunnel. The inspection sketches that were prepared during the Mackin 2014 routine inspection were updated for changes in existing deterioration and to identify any new deterioration.

Photo 17: Overview of Test Section

Photo 18: Hammer Sounding Inspection

Photo 19: Delamination Wheel

Figures 32 and 33 below show the results of the hammer sounding inspection. The delaminated areas that were identified correlated reasonably well with the 2014 inspection findings with only minor differences noted. These differences were attributed to different inspectors performing the soundings and the ability to accurately locate and size deteriorated areas with precision and consistency using the station markings. The delamination wheel (a rotary percussion tool) was also utilized to evaluate its ability to detect unsound and debonded areas. The delamination tool was effective at indicating delaminated areas, except for locations that were very shallow or only slightly unsound. Background noise from lift vehicles and from electric generators used for concrete coring operations also made it difficult to detect audible differences. In addition, the distance between the inspector and wheel made it difficult to accurately delineate unsound areas with marking keel that were not within arms-reach.

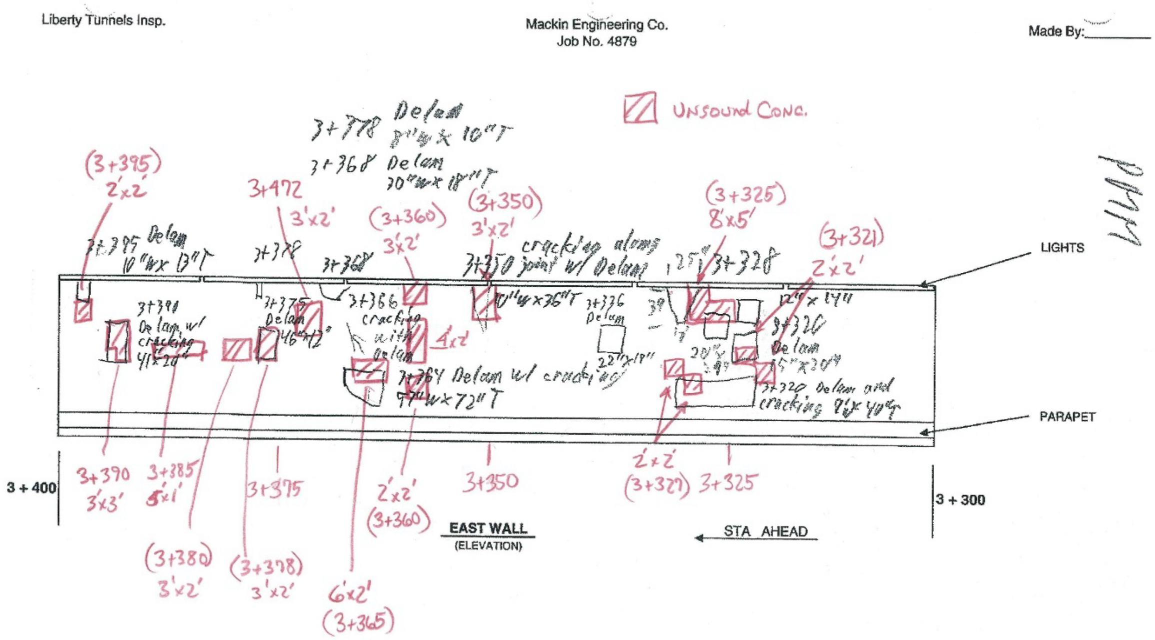


Figure 32: Mackin Hammer Soundings, Station 3+300 to 3+400

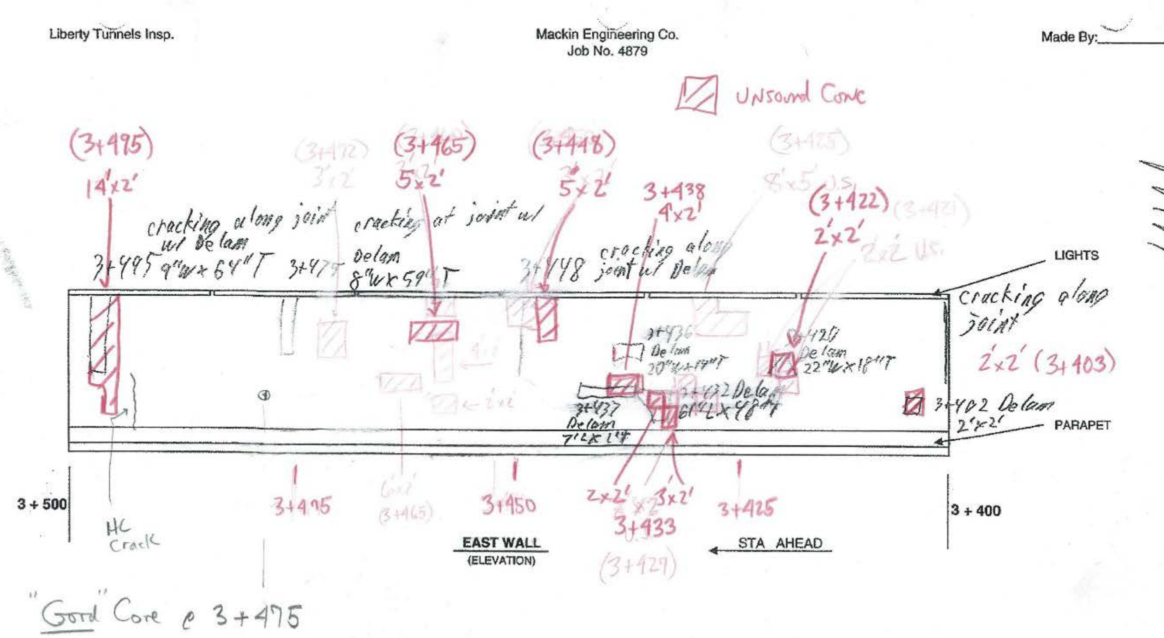


Figure 33: Mackin Hammer Soundings, Station 3+400 to 3+500

Concrete cores were also taken as part of the physical inspection tasks. Core #1 was taken from a sound concrete area (Station 3+475) and was completely intact when extracted, which indicated no delamination was present. Core #2 was taken from an unsound concrete area (Station 3+321). The top 3/8” separated from the core when it was extracted, which indicated shallow delamination was present. Both concrete cores were subjected to petrographic analysis. Compressive strength testing could not be performed because the core diameter was too small (2.70” O.D.). Chloride ion content was also requested for each core; however, this information was not included in the lab test results.

Photo 20: Concrete Coring, Station 3+321

Photo 21: Extracted Core, Station 3+321

Photo 22: Concrete Coring, Station 3+475

Photo 23: Extracted Core, Station 3+475

The petrographic analysis at Core #1 (Station 3+475) revealed that the core consisted of three layers: layer 1 that was comprised of thin white coating on top of a layer of mortar and fine aggregate that varied from 3/16” and 11/32”, layer 2 that was comprised of a slightly thicker white coating and layer of mortar with narrow-graded gravel coarse aggregate and gravel sand fine aggregate with a total thickness of 5/8” to 1 ½”, and layer 3 that consisted of oversized gravel coarse aggregate and gravel sand fine aggregate with a total thickness of 9 ¾” to 10 ½”. The third layer was identified as the original concrete. The petrographic analysis rated the overall condition of layer 1 as “good”, the overall condition of layer 2 as “fair”, and the overall condition of layer 3 as “fair”. The original concrete was rated as “fair” due to the highly variable paste quality, the lack of entrained air, and indications that excess water was present when the paste was plastic. The chloride ion content for Core #1 was not included in the test results. The complete concrete core lab test results are provided in Appendix H.

Similarly for Core #2 at Station 3+321, the sample consisted of three layers: layer 1 consisted of thin white coating on top of a layer of mortar and fine aggregate that varied from 7/16” and 1/2”, layer 2 that was comprised of a slightly thicker white coating and layer of mortar with narrow-graded gravel coarse aggregate and gravel sand fine aggregate with a total thickness of 13/16” to 25/32”, and layer 3 that consisted of oversized gravel coarse aggregate and gravel sand fine aggregate with a total thickness of 7 5/8” to 8 1/4”. The third layer was identified as the original concrete. In addition, the lab observed that the first layer had separated from the rest of the sample at the top white coating for layer 2, which was consistent with how the core was extracted from the field. The petrographic analysis rated the overall condition of layer 1 as “very good”, the overall condition of layer 2 as “fair”, and the overall condition of layer 3 as “fair”. The original concrete was rated as “fair” due to the highly variable paste quality, the lack of entrained air, and indications that excess water was present when the paste was plastic. The chloride ion content for Core #2 was not included in the test results. The complete concrete core lab test results are provided in Appendix H.

COMPARISON OF NDT RESULTS AND PHYSICAL INSPECTION RESULTS AT THE LIBERTY TUNNEL TEST SECTION

The data obtained from the high-speed mobile scans and the hand-held NDT was compared to the physical inspection findings and concrete core testing results. The comparison included only the test section at the east wall of the Liberty Tunnel and did not include Armstrong Tunnels. The comparisons have been made to determine how accurately the NDT methods can detect anomalies in order to evaluate their usefulness for assessing tunnel conditions.

The first comparison relates the mobile scanning results from Penetradar Corporation to physical inspection results. The GPR results were compared to the hammer soundings from the 2014 Mackin inspection findings at the test section, which were provided to Penetradar shortly after completing the mobile scanning (see Figures 34 through 37 below).

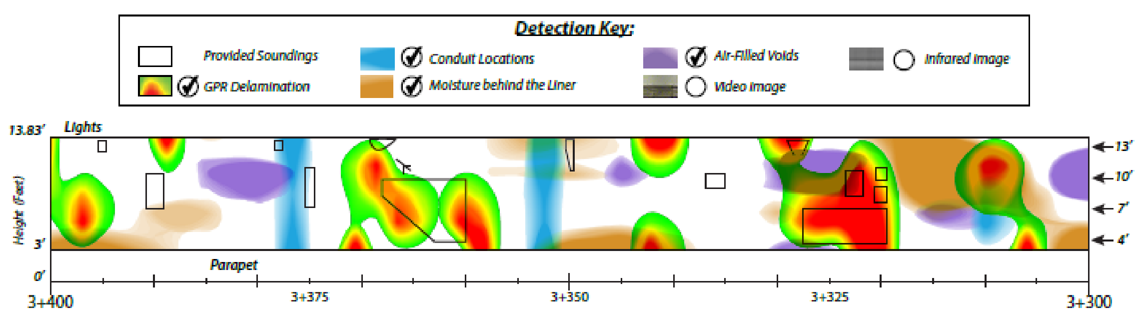


Figure 34: GPR Detections for Liberty Tunnel east wall, Station 3+300 to 3+400

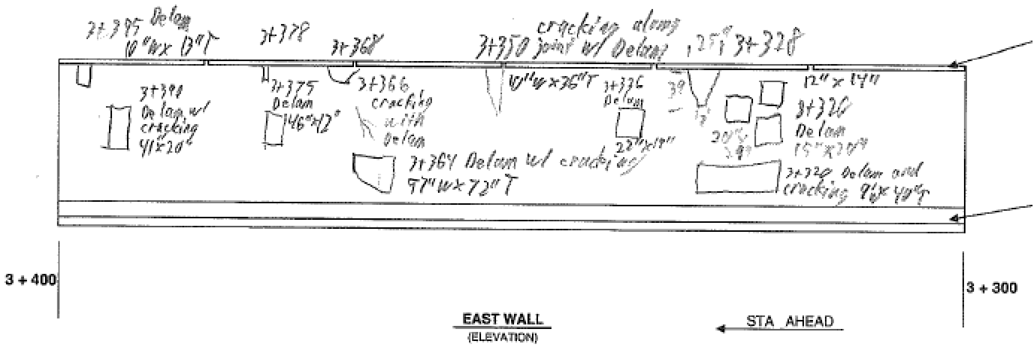


Figure 35: 2014 Inspection Results for Liberty Tunnel east wall, Station 3+300 to 3+400

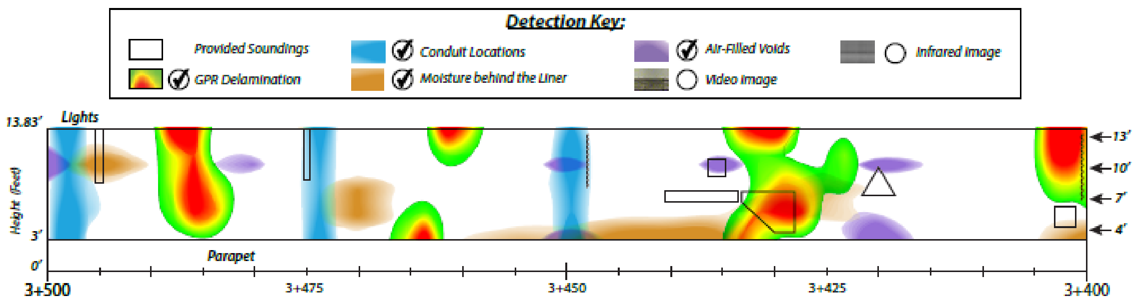


Figure 36: GPR Detections for Liberty Tunnel east wall, Station 3+400 to 3+500

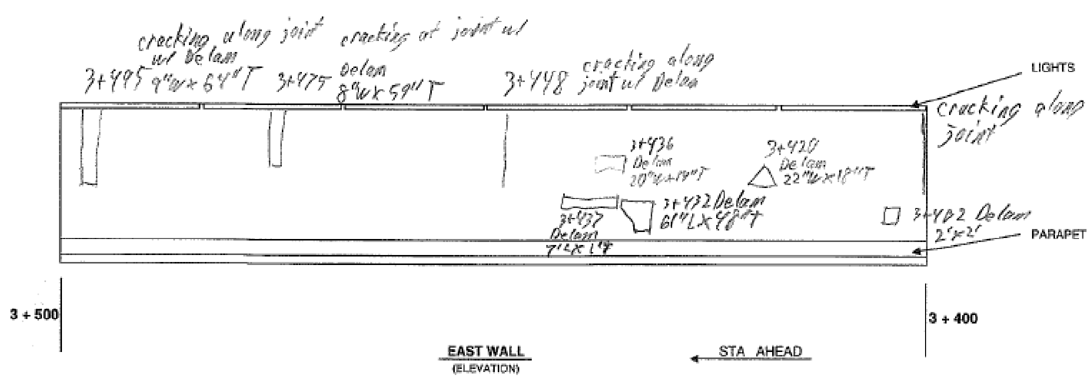


Figure 37: 2014 Inspection Results for Liberty Tunnel east wall, Station 3+400 to 3+500

The GPR detection of unsound areas correlated reasonable well with the 2014 inspection findings. The GPR method found 11.9% (257 SF) of the test area wall to be delaminated while the sounding inspection identified 7.2% (156 SF). In addition, it was found that the GPR delamination detections accounted for 73.2% of the sounding delamination locations, and GPR detected 90.2% of the sound areas of concrete. GPR also identified what would be considered high levels of moisture (or water-filled voids) in 10.2% of the test area and air voids in 6.2% of the test area. The voids and moisture typically were found at the interface between the concrete liner and underlying subbase material. GPR also detected what was believed to be electrical conduit embedded in several locations within the concrete. Table 3 below provides a summary of the results from the GPR data in the test area.

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

Table 3: Summary of GPR Detections at Liberty Tunnel Test Section.

In relating the GPR data to the condition of the concrete cores that were extracted, Core #1 was taken 3 feet above the safety barrier at Station 3+475, which coincided with a sound concrete location on the GPR data. The GPR data also indicated that moisture behind liner was detected near this area (within 10'). The petrographic analysis for Core #1 showed that the paste quality in the original concrete was highly variable and ranged from low water content to very high water content. In conjunction with other observations in the concrete composition, the petrographic analysis concluded there was excess water present in the paste of the plastic concrete when it was placed, and that this excess water tried to move outward towards the outer face of the plastic concrete. The detailed examination also showed that the original concrete had very little entrained air in it. These observations indicate that the GPR data and petrographic analysis are generally consistent. Figure 38 below shows the GPR mapping from Penetradar's final report for Station 3+400 to 3+500 with the location of Core #1 plotted on the image. In comparing Figure 38 below and Figure 36 above, differences were noted in the GPR mappings, but this was believed to be the result of Penetradar refining the GPR analysis between the initial and final results.

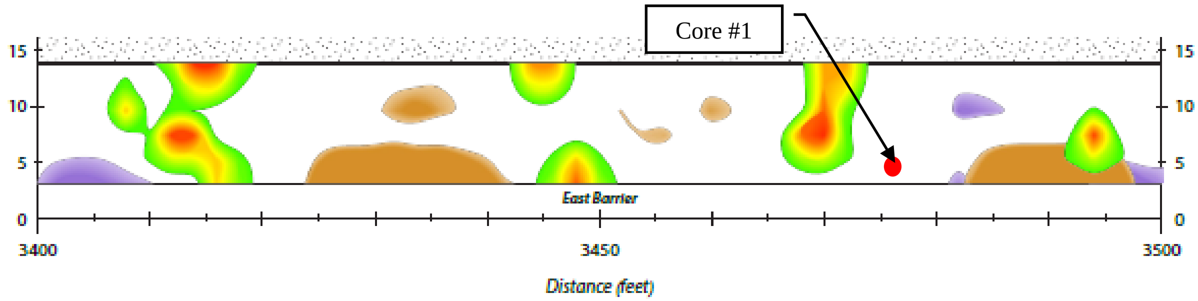


Figure 38: Core #1 location on GPR mapping, Station 3+400 to 3+500

Similarly, Core #2 was taken 4 feet above the safety barrier at Station 3+321, which coincided with an unsound concrete location on the GPR data. The GPR data also indicated that moisture behind liner was detected near this area. The petrographic analysis for Core #2 showed that the paste quality in the original concrete was highly variable and ranged from low water content to very high water content. In conjunction with other observations in the concrete composition, the petrographic analysis concluded there was excess water present in the paste of the plastic concrete when it was placed, and that this excess water tried to move outward towards the outer face of the plastic concrete. The detailed examination also showed that the original concrete had very little entrained air in it. In addition, the top 3/8" that had separated from the core upon extraction was supported by the findings of the petrographic analysis, and it appears this debonding was detected as an area of GPR delamination. These observations indicate that the GPR data and petrographic analysis are generally consistent. Figure 39 below shows the GPR mapping from Penetradar's final report for Station 3+300 to 3+400 with the location of Core #2 plotted on the image. In comparing Figure 39 below and Figure 34 above, differences were noted in the GPR mappings, but this was believed to be the result of Penetradar refining the GPR analysis between the initial and final results.

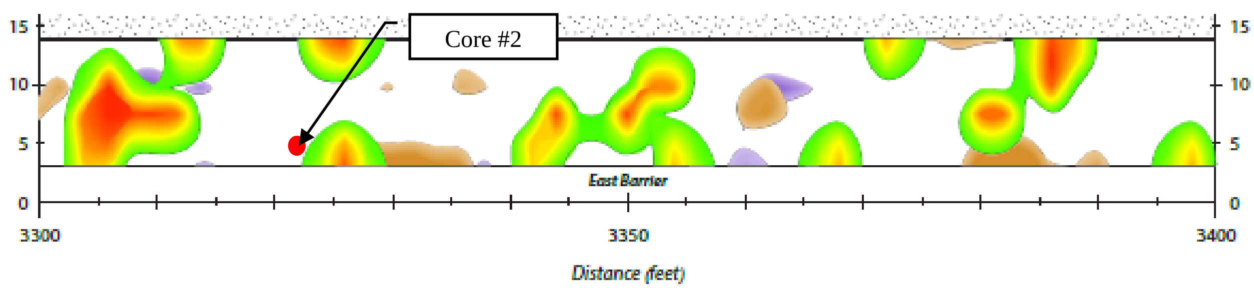


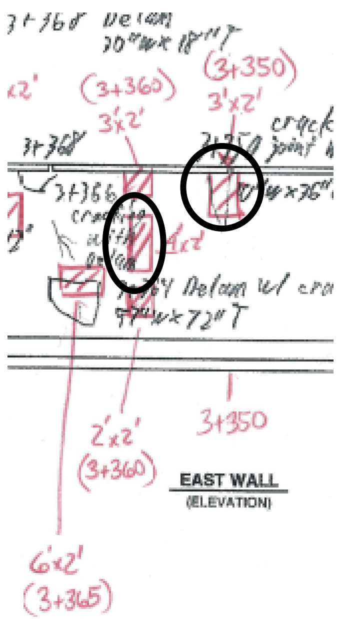
Figure 39: Core #2 location on GPR mapping, Station 3+300 to 3+400

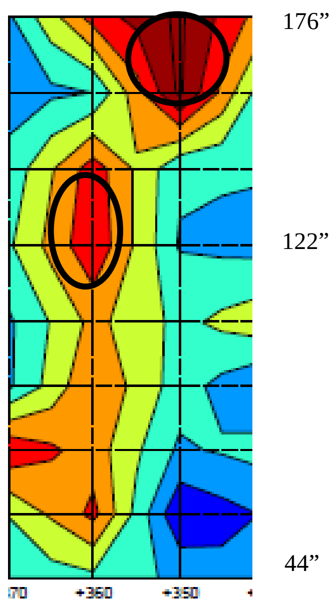
The IRT scanning performed by Penetradar Corporation did not provide usable results with regard to delamination detection at the test section as no temperature differential was identified with the infrared camera. In addition, no major cracking or water flow was detected with IRT, which did correlate with visual observations.

The second evaluation compares the SPACETEC mobile scanning results to the physical inspection findings. In review of the visual image scanning from Station 3+300 to

3+500, little to no cracking was present at the east wall. Based on the physical inspection results, several delaminated areas were noted as having associated cracking. As a result, it does not appear that the laser scanning identified existing cracks or the existing cracks were very fine and were not able to be delineated on the scanned images resulting from the data processing. In regards to the IRT scanning performed by SPACETEC, no delaminated areas or areas exhibiting moisture intrusion were identified from the IRT data at the test section. This was the result of insufficient temperature variation between the tunnel surface and the ambient air temperature. As a result, the delaminated areas identified from the physical inspection could not be confirmed from the thermographic data.

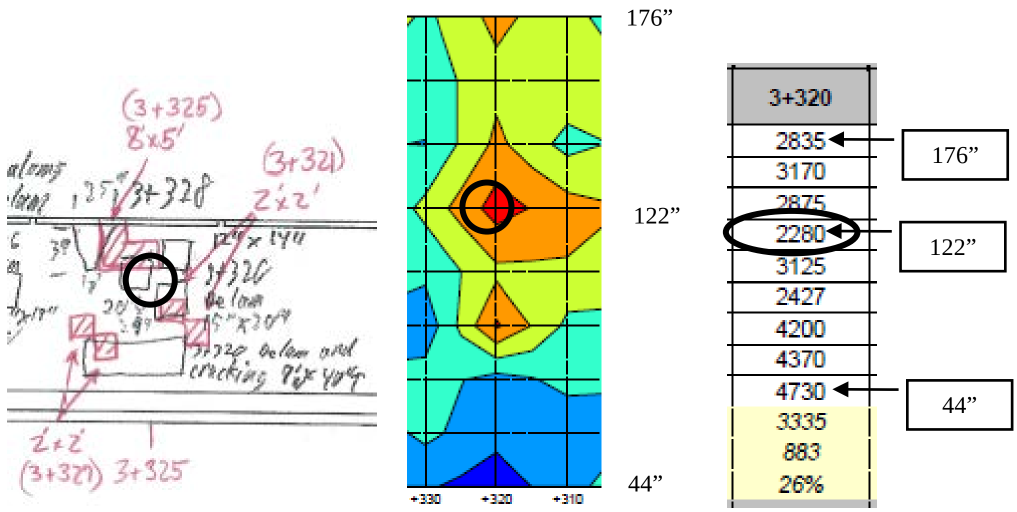
The third comparison relates the hand-held PSPA testing to the physical inspection results. The seismic modulus table and the contour map summarizing the PSPA results were compared to the updated hammer sounding sketches from the physical inspection. The figures below show the hammer sounding results, contour map, and seismic modulus results from the PSPA testing between Station 3+350 and 3+360.





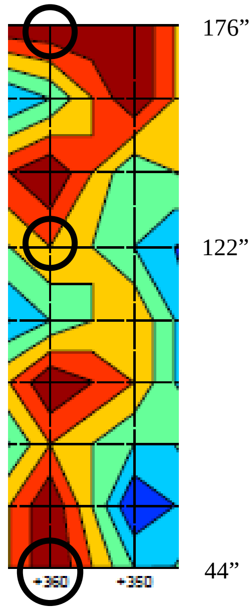
3+350	3+360	
1410	2247	176"
1400	3993	
3925	2240	
4040	2103	122"
3640	2850	
3755	2525	
4080	2745	
4920	2370	
4125	3620	44"
3477	*2744*	
1229	*656*	
35%	*24%*	

Near the top of the wall at Station 3+350, the hammer soundings reveal a 3'x2' area of delamination. On the contour map, this area corresponded to burgundy and red colors, and the seismic modulus resulting from the PSPA testing ranged from 1400 ksi at 158" (13'-2") to 1410 ksi at 176" (14'-8") from ground level. It can also be noted that the seismic modulus from the PSPA testing improves further down the wall at Station 3+350, which is evidenced by the green and blue areas on the color map; no delaminations were noted from the hammer soundings at this region. Similarly, at Station 3+360, the seismic modulus was slightly lower but relatively uniform along the height of the wall, which is evidenced by the orange and red color distribution on the map, and the hammer soundings revealed several unsound areas over the height of the wall. Another example of the relationship between the physical inspection results and the seismic modulus results is shown below in the area of Station 3+320.



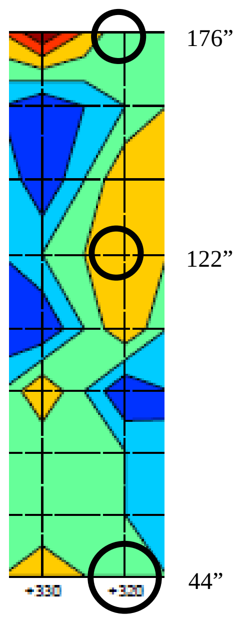
In the figures above, the hammer soundings revealed several unsound areas between Station 3+322 and 3+327 that is evidenced by the orange and yellow color distribution on the contour map. The seismic modulus from the PSPA testing at Station 3+320 ranged from 2280 ksi to 4730 ksi. In general, some variation between the PSPA results and hammer soundings can be expected due to the inspector’s estimation of the location of the deterioration vertically and horizontally on the wall according to the station markings. The PSPA testing exhibits better quality control in terms of locating deterioration because of the grid system that is used to conduct the testing. As a result, some judgment is required to establish a test grid that can provide satisfactory results.

Similar results were observed in review of the IE data from the PSPA testing. Using the figures below, the IE contour map at the top of the wall (158” to 176” from ground level) between Station 3+350 and 3+360 showed a distribution of red and burgundy colors, which corresponded to a value of ‘1’ (severely debonded) from the IE analysis. These results correlated with the seismic modulus results. Near the bottom of the wall at Station 3+360, some difference was observed with burgundy/red colors from the IE testing and the orange/yellow color from the seismic modulus results. Aside from this location, the IE results and seismic modulus results correlated well when comparing the color contour maps.



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”

At Station 3+322 to 3+327, the contour map and numerical values from the IE analysis (shown below) indicates the concrete condition typically varies from moderate to slightly debonded/delaminated. These results corresponded with the seismic modulus results.



3+320	
3	176”
3	
2	
2	122”
2	
4	
3	
3	
3	44”

In the figures below, the concrete core locations have been plotted on the seismic modulus contour map that was developed from the PSPA testing. Core #1 was taken at sound concrete location at Station 3+475 at a point 3 feet above the safety barrier (68” from ground level). Core #2 was taken at an unsound concrete location at Station 3+321 at a point 4 feet above the safety barrier (80” from ground level).

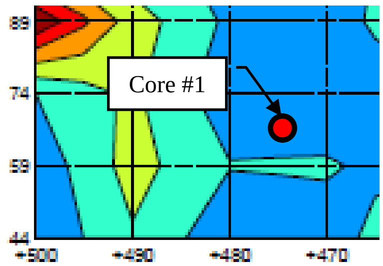


Figure 40: Core #1, Sta. 3+475

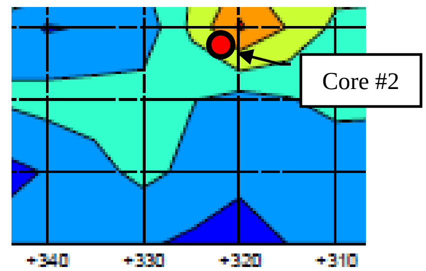


Figure 41: Core #2, Sta. 3+321

The seismic modulus at Station 3+475 at a location 68" from ground level was estimated to be 4000 ksi from the PSPA results, which corresponds to the blue region (sound concrete) of the color map. The seismic modulus at Station 3+321 at a location 80" from ground level was estimated to be 3490 ksi (using linear interpolation at Station 3+320), which corresponds to the orange/yellow region of the color map. The interpolated value suggests the concrete is in good condition; however, when Core #2 was extracted, the top 3/8" of concrete separated from the main core sample. As a result, it seems this area of concrete is between a sound and unsound condition, and that the concrete deeper the top 3/8" is in good condition. Similar results were observed when reviewing the IE data from the PSPA testing at Stations 3+475 and 3+321.

COST EVALUATION

The cost estimates prepared by Penetradar and AID were dependent on several factors, such as tunnel dimensions and geometry, type of testing required, MPT requirements, data-processing and reporting format, project location, etc. Therefore, it was important to clearly define the project requirements during the NDT proposal solicitation.

The Penetradar estimate was based on the combined length of the Liberty and Armstrong Tunnels (7,218 feet); unit costs (cost per LF) were provided per scan and for the entire tunnel. Data Collection and Analysis & Report were presented as separate costs. During the proposal phase, Penetradar estimated that 8 passes for Liberty Tunnel and 12 passes for Armstrong Tunnel would be required to complete the GPR scanning. For the IRT scanning and video recording, Penetradar estimated that 3 passes would be required for each tunnel. Mobilization costs were relatively small, which was facilitated by the close proximity of the tunnels (approximately 1 mile apart).

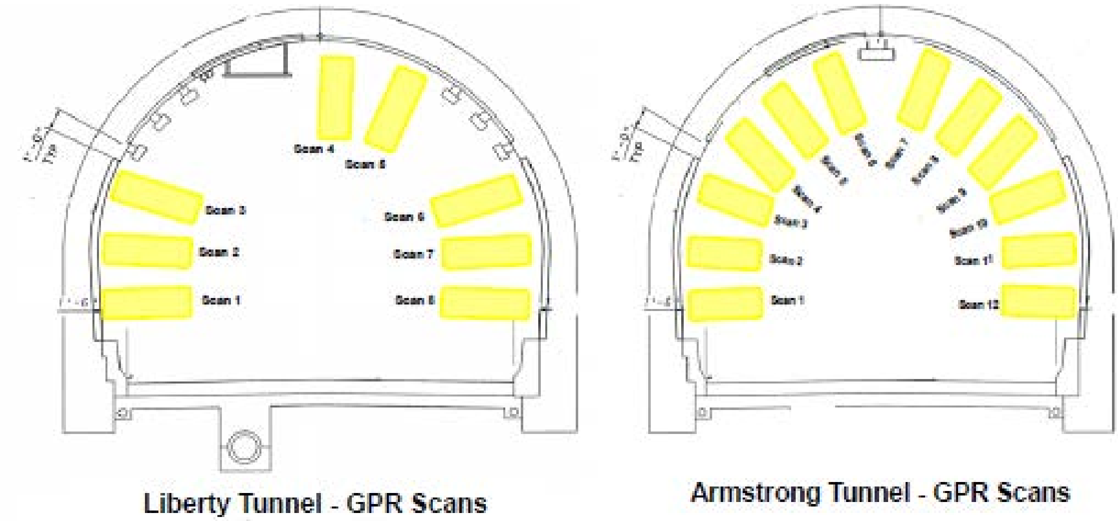


Figure 42 – Proposed GPR Scan Locations for Liberty and Armstrong Tunnel

COST		LF	Cost/LF	Total Cost
Item 1.	**GROUND PENETRATING RADAR (GPR)**			
	(A) DATA COLLECTION - One Scan	7218	$3.24	$23,386
	(B) ANALYSIS & REPORT - One Scan	7218	$1.82	$13,137
	Total Cost			**$36,523**
	(A) DATA COLLECTION - Entire Tunnel	63024	$0.48	$30,252
	(B) ANALYSIS & REPORT - Entire Tunnel	63024	$0.417	$26,281
	Total Cost			**$56,533**
Item 2.	**INFRARED THERMOGRAPHY (IRT)**			
	(A) DATA COLLECTION - One Scan	7218	$1.48	$10,717
	(B) ANALYSIS & REPORT - One Scan	7218	$1.82	$13,138
	Total Cost			**$23,855**
	(A) DATA COLLECTION - Entire Tunnel	21654	$0.55	$11,905
	(B) ANALYSIS & REPORT - Entire Tunnel	21654	$1.213	$26,275
	Total Cost			**$38,180**
Item 3.	**VIDEO IMAGE RECORDING**			
	(A) DATA COLLECTION - One Scan	7218	0	0
	(B) ANALYSIS & REPORT - One Scan	7218	$1.82	$13,138
	Total Cost			**$13,138**
	(A) DATA COLLECTION - Entire Tunnel	21654	0	0
	(B) ANALYSIS & REPORT - Entire Tunnel	21654	$1.213	$26,275
	Total Cost			**$26,275**
Item 4.	**MOBILIZATION** (cost each mobilization)			
	Total Cost		$2,805	**$2,805**

Figure 43 – Penetradar Cost Table

Based on the cost table in Figure 43, the total cost of GPR data collection, analysis, and reporting for Liberty and Armstrong Tunnel was $56,533 with a unit cost of $0.897/LF. The total cost of IRT data collection, analysis, and reporting for both tunnels was $38,180 with a unit cost of $1.763/LF. For video recording, the total cost was $26,275 for both tunnels with a unit cost of $1.213/LF. The mobilization cost for both tunnels was $2,805. As a result, Penetradar's total cost to perform GPR, IRT, and video image recording for the project was $123,793. It can be noted that unit costs decrease as the total length of scanning increased.

The total cost for AID to the complete mobile scanning, which used SPACETEC technology, and prepare the report for Liberty and Armstrong Tunnels was $79,412. Based on a combined tunnel length of 7,800 feet and utilizing one (1) pass in each tunnel, this resulted in a unit cost of $10.18/LF. AID also included contingent costs for additional scanning resulting from changes in work scope, etc. at a cost of $6,800 per night, and a stand-by cost of $3,000 per day resulting from potential schedule delays.

For the hand-held NDT verification testing, AID estimated a total cost of $14,384, which included mobilization, travel, testing, analysis, and reporting. The estimate was based on 50-100 anticipated test locations, which resulted in a unit cost of $143 to $286 per test location (Note: AID actually performed testing at 189 locations; however, the total cost did not change).

Other costs for the project included MPT (changeable messages boards, traffic control, etc.), lift vehicles, equipment trucks, and tool trucks for concrete coring. The MPT and inspection support was provided by Mackin's inspection services contractor, Sofis Company. For Liberty Tunnel, the unit cost for MPT was $4,100 per day (which included message boards and traffic control for lane and tunnel closure), and the equipment truck was $500 per day. This resulted in a total inspection support cost was $18,400 for the four (4) nights of scanning from September 21 through 24. Inspection services costs for the verification testing that was performed on November 5, 2015 consisted of MPT ($4,100 per day), an equipment truck ($500 per day), a 45-foot reach bucket truck ($375 per day), and a tool truck for concrete coring operations ($850 per day). This resulted in a total inspection support cost of $5,825. The lift truck provided by PennDOT District 11-0 and the lab testing that was performed by PennDOT on the two (2) concrete cores were provided at no cost to the project. MPT and inspection support costs were not available for Armstrong Tunnel.

To compare the cost of the mobile scanning and hand-held NDT testing to a routine NBIS inspection of the Liberty Tunnel using traditional inspection methods, the following information is provided. The engineering cost to inspect the Liberty Tunnel as a cost per unit of work is $37,744 (includes Mackin and subconsultant costs for inspection and report). This cost is based on the average of two inspections, one of which includes the air shafts, fire passages, and the tunnel bore while the other includes only the tunnel bore inspection. Typical inspection support costs for the tunnel bore only includes MPT and traffic control for lane/tunnel closure, JLG man-lifts, and equipment trucks, resulting in a total cost of $6,800 per day. As a result, the total cost to conduct a routine inspection of the northbound Liberty Tunnel bore is $51,344 and is completed in 2 nights.

For comparison, using Penetradar's unit costs and length of 5,900 feet (for Liberty Tunnel), including inspection services, the total cost (including data collection and reporting) is estimated to be:

GPR: $0.897/LF x 5,900 ft x 8 passes = $42,338
IRT: $1.763/LF x 5,900 ft x 3 passes = $31,205
Video: $1.213/LF x 5,900 ft x 3 passes = $21,470
Inspection support: $4,600/day x 3 days = $13,800
Total = $108,813

Using the same information for SPACETEC, the total cost is estimated to be:

IRT/3-D scan/Video: $10.18/LF x 5,900 ft x 1 pass = $60,062
Inspection support: $4,600 x 1 day = $4,600
Total = $64,662

For PSPA testing, the cost would vary based on the condition of the tunnel and the number of test locations anticipated. Assuming 500 test points would be required over the full tunnel length and using a reduced unit cost of $130 per point, the total cost is estimated to be:

IE/USW: $130/point x 500 points = $65,000
Inspection support (incld. man-lift): $5,500 x 2 days = $11,000
Total = $76,000

As indicated previously, project costs are dependent on the scope of work and inspection support requirements. When comparing inspection techniques for Liberty Tunnel, Penetradar's costs were approximately two times greater and SPACTEC was approximately 1.25 times greater than traditional inspection methods. PSPA testing was not compared since this method was only performed on a limited area of the tunnel.

As an example of a practical application of utilizing NDT would be to perform GPR mobile scanning in conjunction with hand-held PSPA testing at 500 points. Based on the unit prices used above for Liberty Tunnel, this results in a total estimated cost of $133,000 ($43k GPR + $25k Inspection Services + $65k). By comparison, this is roughly 2.5 times greater than a normal routine inspection of (1) tunnel bore ($51k). Another example would be use GPR mobile scanning in conjunction with a physical inspection. In this case, the total estimate cost would be $94,000 ($43k GPR + $25k Inspection Services + $37 Inspection). This is two times greater than a normal inspection, which could improve further under the assumption that the physical inspection effort could be reduced if it used to compliment the GPR inspection.

The NDT evaluation (either mobile scanning or point-by-point testing) could be reduced to specific regions or deteriorated areas of the tunnel; however, unit costs for testing are typically higher for smaller quantities. NDT testing could also be performed using single lane closures in-lieu of complete tunnel closure; however, mobile scanning could take longer due to alternating lane closures. In addition, MPT costs for single lane closures could be greater due traffic control requirements, maintaining traffic flow, extending traffic patterns through the tunnel, etc.

Conclusions

The Liberty and Armstrong Tunnels were investigated under the FHWA Implementation Program for the SHRP2 R06G Project, which focused on High-Speed Nondestructive Testing Methods for Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings. The Liberty and Armstrong Tunnels were evaluated using GPR, IRT, 3-D Laser Scanning, and Video Image Recording using high-speed mobile applications. Further hand-held NDT testing was performed on a small test section at the east wall of the Liberty Tunnel using a Portable Seismic Property Analyzer (PSPA). The mobile and hand-held NDT data was compared to traditional physical inspection findings in order to validate the NDT methods used and evaluate the effectiveness of detecting defects in the tunnel lining.

The following conclusions can be made as a result of the NDT testing that was performed:

<u>NDT Mobile Scanning</u>

- The mobile scanning performed by Penetradar Corporation was effective at detecting tunnel lining defects, such as delamination, moisture, and voids. The combination of utilizing GPR, IRT, and image recording allowed for deterioration to be identified at the surface, within the liner, and behind the liner. However, it did not appear that surface-opening cracks were identified or located.
- Liberty Tunnel was recently rehabilitated with hydro-demolition and synthetic fiber reinforced shotcrete repairs. Penetradar did not observe any significant difference in material property between repaired and non-repaired areas. There was no change in reflectivity or dielectric observed, which lead to the conclusion that the material used for repair was electrically similar to the original surrounding material and would not be detected, as expected. It should be noted that this is not true in all cases and should be investigated on a case-by-case basis.
- GPR results correlated reasonably well with the hammer soundings at the Liberty Tunnel test section.
- At Liberty Tunnel, shallow delaminations (1”+/-) were difficult to detect with GPR. The decorrelation method used by Penetradar Corporation improved the detection of shallow delaminations at Liberty Tunnel.
- For Armstrong Tunnel, GPR detections were based on measuring signal attenuation and dielectric content (moisture content).
- GPR technology cannot be used to detect deterioration in tunnels with steel liners or steel fiber reinforced concrete repairs. The ability of using GPR to detect defects at wire mesh fabric reinforced concrete repairs should be discussed with the vendor.

- The IRT scanning performed by Penetradar and SPACETEC did not produce usable results in Liberty Tunnel at the test section due to uniform temperature at this location in the tunnel. As a result, IRT scanning does not appear to be effective for very long tunnels or tunnels that do not exhibit large amounts of deterioration unless a temperature difference between the liner and ambient air can be induced (note: IRT testing is effective at locating moisture intrusion, even without an induced temperature differential).
- SPACETEC was effective at detecting cold anomalies (tile debonding, water intrusion, etc.) in Armstrong Tunnel using IRT. Penetradar's infrared mappings revealed few distinct detections of thermal variation; however, visual distress was clearly in some of those areas in the form of discolored tile, exposed concrete areas, or visible evidence of moisture on the tunnel liner.
- The thermal image resolution used by SPACETEC could be improved for better interpretation of results. Some discussion with AID was required to clarify "true" versus "false" indications, which was anticipated.
- IRT scanning only provides the indication of an anomaly. Additional inspection (visual, physical) is required to determine the type and/or cause of the anomaly.
- Mobile scanning is repeatable and relatively fast. Liberty Tunnel GPR scanning was completed in 2 nights and Armstrong GPR scanning was completed in 1 night; Penetradar and SPACETEC completed IRT/video scanning for both tunnels in 1 night.
- Mobile scanning was performed on the northbound Armstrong and Liberty Tunnel bores only. Additional inspection is required for the airshafts, fire passages, portal facades, etc.
- The mobile scanning by SPACTEC was able to produce a detailed summary of visible crack locations, widths, and densities. These are results that could be fed directly into a year to year evaluation of tunnel liner changes as part of an asset management program.
- Data processing and reporting for the mobile scanning that was performed by Penetradar and SPACETEC was time consuming (2-3 months for SPACETEC; 7-8 months for Penetradar).

<u>Hand-held PSPA Testing</u>

- The Portable Seismic Property Analyzer (PSPA) results correlated well with the hammer soundings at the test section. In addition, the IE and USW results from the PSPA testing correlated well.
- PSPA testing is time consuming. Testing was performed at approximately 200 locations over an area of approximately 2200 SF, which took about 5 hours to complete. Conversely, hammer soundings performed over the same area were completed in 1 hour.

- PSPA testing did not provide an indication of the depth of delamination. Additional NDT testing, such as GPR, or physical testing, such as hammer drills or additional coring would be required to determine the delamination depth.
- PSPA testing is useful for evaluating concrete deterioration limited areas of a tunnel.

Physical Inspection

- The delaminated areas that were identified from the hammer soundings at the Liberty Tunnel test section correlated reasonably well with the Mackin 2014 inspection findings. Only minor differences were noted, which were attributed to different inspectors performing the soundings, and the ability of the inspector to accurately locate and size deteriorated areas with precision and consistency using the station markings.
- The delamination wheel used for detecting delaminations at the test section was fast and repeatable. However, shallow delaminations and areas that were slightly unsound were difficult to detect. In addition, accurate documentation of unsound areas was difficult.
- The petrographic analysis revealed that the core at Station 3+475 consisted of three layers, and rated the overall condition of layer 1 as “good”, the overall condition of layer 2 as “fair”, and the overall condition of layer 3 (original concrete) as “fair”. Similarly, for the core at Station 3+321, the sample consisted of three layers. The petrographic analysis rated the overall condition of layer 1 as “very good”, the overall condition of layer 2 as “fair”, and the overall condition of layer 3 (original concrete) as “fair”.
- The chloride ion content of each core was not included in the lab test results, and it is not known why this information was not provided. In addition, compressive strength testing could not be performed on the extracted cores because the sample diameter was less than the minimum diameter required for testing.

Cost

- The cost of completing GPR/IRT/Video scanning for Liberty using Penetradar Corporation was approximately two times greater than performing a traditional physical inspection.
- IRT/3-D Survey/Video scanning performed by SPACETEC was approximately twenty-five percent (25%) more than a traditional inspection.
- PSPA is testing is not cost effective for evaluating large concrete surface areas.

General

- No NDT testing was performed on the air shafts, fire passages, or portal facades. It appears that traditional inspection techniques would be the most practical method to assess these tunnel components.
- None of the individual NDT methods are 100% effective at identifying deterioration. Each method has limitations that need to be considered. However, GPR appears to provide the most useful results for detecting tunnel liner defects.
- NDT mobile scanning can be a useful asset management tool. However, it seems it is more effective to use one or two NDT methods (e.g. GPR or IRT) to compliment inspections performed by traditional means.
- NDT mobile scanning methods can provide useful information for major tunnel rehabilitation projects.
- NDT testing should be performed at additional tunnels to improve methods, procedures, data processing, etc. While useful observations were obtained from Liberty and Armstrong Tunnels, a larger sampling of tunnels is needed to further evaluate tunnels of different construction and levels of deterioration.

Recommendations

The following recommendations should be considered when evaluating NDT methods to assess tunnel lining conditions:

- Ensure compatibility of tunnel construction and NDT method(s) used (e.g. GPR will not work with steel tunnel liners or steel fiber reinforced concrete, repairs, etc.).
- Allow for sufficient time to solicit vendors for NDT testing (minimum 2 months prior to testing). In addition, provide a detailed Scope of Work for accurate cost estimates and to ensure project requirements are met.
- Proper planning, coordination, and scheduling are critical to successful utilization of NDT for detecting tunnel defects.
- Evaluate MPT requirements (single lane closure, tunnel closure, detours, etc.) prior to NDT testing.
- Consideration of temperature variation (time of year, climate, length of the tunnel, condition of the tunnel) is critical to obtaining good IRT results.
- Existing tunnel conditions should be considered when evaluating which type(s) of NDT methods will be used for detecting specific types of defects.
- As an additional measure to validate NDT results, inspection personnel can utilize the NDT reports during field inspections to verify and confirm deterioration detected from the NDT methods.

- The ability of NDT methods to collect tunnel condition data should be evaluated against the requirements of the new National Tunnel Inspection Standards (NTIS), the Specifications for the National Tunnel Inventory (SNTI), and the Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual. The inventory data collection and element-level data collection requirements could be completed using NDT mobile scanning methods.
- Consideration of the time required for NDT data processing and report preparation is significant to the project schedule (up to 8 months were needed for complete GPR results for this project).
- Concrete core sample removal and testing are recommended for correlating NDT results.
- NDT mobile scanning should be performed on additional tunnels to obtain a larger sampling tunnels evaluated by NDT.
- Additional tunnels should be inspected with NDT methods to encourage competition amongst vendors and to gain popularity. This could result in cost and time savings in regard to data collection and data processing.
- NDT mobile scanning on Liberty and Armstrong Tunnel should be performed in the future to determine how well NDT methods can detect changes in conditions and to evaluate time/cost savings resulting from repeated inspections. This would facilitate to decision to incorporate NDT methods into a regular inspection program.
- NDT application to tunnels is relatively new. Additional work should focus on understanding the strengths and limitations of the methods as well as development of standards. The full potential and ultimate success of using NDT for tunnels will only be realized through continued development and use.
- Other NDT methods, such as photogrammetry in combination with IRT (Tonon USA) or 3-D Radar (Chemring Group), should also be considered for evaluating tunnel conditions. These results could be compared to other NDT service providers (i.e. Penetradar, SPACETEC, etc.).

APPENDICES

- Appendix A: Penetradar Corporation Proposal
- Appendix B: AID Proposal
- Appendix C: Penetradar Initial Report on Liberty Test Section
- Appendix D: Penetradar Final Report for Liberty and Armstrong Tunnels
- Appendix E: AID Initial Report on Liberty Test Section
- Appendix F: AID Liberty Tunnel Final Report
- Appendix G: AID Armstrong Tunnel Final Report
- Appendix H: Concrete Core Lab Test Results
- Appendix I: Liberty Tunnel Rehabilitation Drawings S-29344