Nondestructive Tunnel Liner Evaluation

Using Ground Penetrating Radar, Infrared Thermography and High Resolution Imaging

Anthony Alongi, President – Penetradar Corporation

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Evaluation of Tunnel Liners Presents a Challenging Problem

- Tunnels are in the constant presence of moisture, and over time can experience:
  - Deterioration of liner & corrosion of reinforcement,
  - Voids behind liner & water flow thru liner

- Evaluation & maintenance is difficult due to:
  - Limited access & high usage,
  - Accessible from one side only
  - Presence of tile face masking underlying problems
  - Difficulties in physical access to conduct inspections

- Manual and destructive methods exist, but are difficult, labor intensive, require closures and are expensive

What is needed is a better, more cost effective non-destructive method
Tunnel Evaluation
Using GPR - IRT - HRI Technology

SHRP2 R06G Proposed NDT Solution

• Ground Penetrating Radar
• Infrared Thermography, and
• High Resolution Video Imaging
• IRIS GPR
• IRT Systems
• HRI Systems
• Vehicle Inspection Systems
• R&D – SHRP, NASA, NVESD
Technical Services
SHRP2 R06G Focused on Existing NDT Technologies Previously Used in Other Applications

- Infrared Thermography
- Ground Penetrating Radar
- High Resolution Imaging
High-Speed Infrared Thermography

- **Infrared Camera**
  - 640 x 480 resolution
  - 0.1 degree C resolution
  - 30 Hz scan rate
  - Radiometric data

- **Data Collected in a Continuous Swath**

- **Results are converted from forward-view to plan-view.**

IRT bridge deck evaluation shown below. Delaminations shown as “red” areas.
High-Speed Ground Penetrating Radar

- **GPR**
  - Non-contacting antennas (500MHz to 2.5GHz)
  - 100 Hz scan rate (or greater)
  - 4 Antenna array

- Data Collected as Individual Scans

- Results are assembled into a plan-view map.

GPR bridge deck evaluation. Probable areas of delamination shown as green-yellow-red
High Resolution Imaging

- High Resolution Video Camera
  - 4k optical resolution (3840 x 2160 pixel = 8.3M pixel)
  - 120Hz scan rate

- High speed image recording (50MPH)
  - Collected in forward-view
  - Converted to plan-view (top-view)
Advantages of GPR and IRT for Evaluation of Tunnels

- Non-Destructive
- Non-Contacting
- Fast (10-15MPH) Inspection Speed
- Not affected by Surface Material (or Presence of Tile) - GPR
USES OF NDT IN TUNNEL EVALUATION

• Liner Thickness & Depth of Reinforcement
• Delamination of the Concrete Liner
• Voids Between the Liner and Base
• Water Flow Through and Behind the Liner
• Detection of Cracks
Tunnel Liner Evaluation

Theory

- GPR Layer Thickness
- GPR Void Detection
- GPR Detection of Moisture Within and Behind Liner
- GPR Detection of Deterioration of Concrete Liner
- IRT Detection of Concrete Cracks & Water Flow
Tunnel Liner Evaluation

GPR - Generation of Radar Waveforms

Transmitted Signal

Surface Echo
Concrete-Base Echo
Asphalt-Concrete Echo

Emitted Signal

Air $\varepsilon_0 = 1$
Asphalt $\varepsilon_1 = 6$
Concrete $\varepsilon_2 = 8$
Base Material $\varepsilon_3 = 10$
GPR Measurement of Layer Thickness ($X$) Based on Transit Time of Radar Wave ($T$) and Radar Wave Velocity ($V$)

\[ X = V \times T \]
Tunnel Liner Evaluation - GPR

- GPR Detection of Voids Behind Tunnel Liner Based on Polarity of Signal from Back of the Liner
- Could be Air or Water-Filled
MOISTURE DETECTION

GPR Detection of Moisture in Liner or Base by Measuring the Reflection Coefficient ($\rho$) or Dielectric Constant ($\varepsilon$) of Material
GPR Detection of Deteriorated Concrete is Based on Measurement of Signal Attenuation in the Material.
Tunnel Liner Evaluation - IRT

CONCRETE DETERIORATION, CRACKS AND WATER FLOW

• IRT DETECTS CRACKS AND WATER FLOW BASED ON TEMPERATURE DIFFERENTIAL
INSPECTION METHOD

- **GPR** - Longitudinal Scans are made in all Clock Positions Along Length of Tunnel – 3 Ft apart

- **IRT & HRI** – Longitudinal Scans are made along the length of the tunnel. Left & Right Wall & Ceiling

- **Speed** 10-15MPH
Tunnel Liner Evaluation

GPR Data Collection

GPR System used for Inspection of Roadway Tunnels

- Penetradar GPR Shown in Liberty Tunnel, Pittsburgh, PA
Tunnel Liner Evaluation

GPR Data Collection

GPR System used for Inspection of Roadway Tunnels

- Penetrador’s GPR Shown in Liberty Tunnel in Pittsburgh, PA

45 second video [click image to start/stop]
Tunnel Liner Evaluation

GPR Data Collection

Hyrail GPR System used for Inspection of Rail Tunnels

- Penetradar’s GPR System Shown in DART Tunnel
Tunnel Liner Evaluation

NON-DESTRUCTIVE INSPECTION OF LIBERTY AND ARMSTRONG TUNNELS
NON-DESTRUCTIVE INSPECTION OF LIBERTY AND ARMSTRONG TUNNELS (September 22 – 25, 2015)

Methods used:
- Ground Penetrating Radar
- Infrared Thermography
- High Resolution Imaging

Objectives:
**GPR**
- Detect Delamination/Deterioration – shallow delamination
- Voids & Areas of High Moisture Behind Liner
- Areas of Moisture in Liner

**IRT**
- Areas of Water Flow & Surface Moisture
- Cracks
- Debonded Tiles

**HRI**
- Visual documentation
- Used for comparison with GPR and IRT
Liberty Tunnel NDT Inspection

- GPR, IRT and HRI
  - Approx. 177,000 sq. ft. inspected in one evening (over 1 mile length)
- Shallow delamination of liner
  - Detected with GPR in 4.1% of area inspected, overall
  - In test area GPR detected 11.9% and sounding detected 7.2%
  - In test area GPR detected 73.2% of delaminations that were detected with sounding
  - In test area GPR detected 90.2% of sound areas that were detected with sounding
- Water-filled voids and moisture behind liner
  - Was detected with GPR in 13.2% of area, overall
- Air-filled voids behind liner
  - Was detected with GPR in 6.5% of area, overall
- IRT did not produce usable information
Armstrong Tunnel NDT Inspection

➢ GPR, IRT and HRI
  - Approx. 57,000 square feet of wall area inspected in one evening

➢ Deterioration of concrete liner
  - Measurement of GPR signal attenuation per ASTM D6087-03
  - Medium or high signal attenuation detected in 14.4% of wall area
  - Low signal attenuation detected in 10.9% of wall area

➢ Moisture in concrete liner
  - Was detected with GPR by measurement of dielectric constant
  - High moisture (10+%) detected in 14.1% of wall area
  - Medium moisture (2% - 10%) detected in 73.4% of wall area
  - Low moisture (<2%) detected in 12.5% of wall area
Tunnel Liner Evaluation

NDT TUNNEL LINING CONDITION ASSESSMENT

Visual Plan-View Map
Scale: 1 Inch = 10 feet

IRT Plan-View Map

GPR Attenuation Plan-View Map

GPR Dielectric Constant Plan-View Map

Armstrong Tunnel
High Resolution Image
IRT Thermal Image
GPR Attenuation
GPR Dielectric Constant

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Armstrong Tunnel GPR Attenuation Distribution

- West Wall Attenuation: 25.0% Total
- East Wall Attenuation: 25.5% Total
- East Wall contained higher levels of attenuation
  - Suggest east wall to be in generally worse physical condition
Armstrong Tunnel Dielectric Constant ($\varepsilon_r$) Distribution

➢ West Wall Average $\varepsilon_r$: 9.6 (≈ 4% moisture content)
➢ East Wall Average $\varepsilon_r$: 12.2 (≈ 8% moisture content)
➢ East Wall was calculated to have almost twice the moisture content as the West Wall.
Armstrong Tunnel Infrared Temperature Distribution

➢ West Wall Average Temperature: 78.1° F
➢ East Wall Average Temperature: 77.2° F

➢ Difference in temperature could be due to:
  ➢ Construction of tunnel and area behind each wall
  ➢ Result of higher moisture content conducting heat
Conclusions and Recommendations

- Methods defined by SHRP2 R06G for tunnel evaluation were shown to be feasible in practice
  - Equipment specifications have been identified
  - Procedures have been developed & demonstrated
  - Methods of analysis of data have been suggested
- Additional Field Testing with Additional Ground Truth
  - with emphasis on determining reliability of NDT relative to various types of defects and identification of appropriate method of data analysis
- Each Tunnel to be Evaluated Based on its Specific Design
  - Need to better define the technique and analysis methods to achieve optimal results based on design, age and general condition
- Development of Standards – ASTM & AASHTO
Tunnel Evaluation
Using GPR - IRT - HRI Technology

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**PENETRADAR CORPORATION**
2509 Niagara Falls Boulevard
Niagara Falls, New York
14304, U.S.A.
Tel: (716) 731-4369
Fax: (716) 731-5040
Web Site: [www.pemetrador.com](http://www.penetradar.com)