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minnesota Concrete Council
Dedicated to Cast-in-Place Concrete

NON-DESTRUCTIVE TESTING – ADVANCED TECHNOLOGY AND A PRACTICAL REVIEW OF HOW TO USE IT

July22, 2021

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Outline

- Bridge Superstructure
  - Pre-stressed and Post-Tensioned Girders
  - Concrete Beams and Columns
  - Steel Girders
- Bridge Decks
  - Concrete
  - Asphalt Overlaid Concrete
  - White-Topping on Concrete
- Concrete Dams
  - Dam Integrity
  - Spillway Subgrade Support

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Standard Reference for Nondestructive Test Methods

ACI 228.2R-13 Report on Nondestructive Test Methods for Evaluation of Concrete in Structures

- Chapter 3 - Summary of Methods
  - 3.1 - Visual inspection
  - 3.2 - Stress-wave methods for structures
  - 3.3 - Low strain stress-wave methods for deep foundations
  - 3.4 - Nuclear methods
  - 3.5 - Magnetic and electrical methods
  - 3.6 - Methods for measuring transport properties
  - 3.7 - Infrared thermography
  - 3.8 - Radar
- Chapter 4 - Planning and Performing Nondestructive Testing Investigations

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Bridge Superstructure NDE Methods & Applications

- **Concrete & steel**
  - **Visual assessment** – Bridge Inspections often combined with NDE
- **Concrete**
  - **Impact Echo – Concrete** cracking, corrosion delamination damage, honeycomb, thickness, voided vs. grouted post-tensioning ducts
  - **Spectral Analysis of Surface Waves -** cracking, crack depths, void/honeycomb and velocity/modulus
  - **Ultrasonic Pulse Velocity/Tomography** – internal flaws imaging
  - **Ground Penetrating Radar –** steel mapping & corrosion potential
  - **Slab Impulse Response** - Integrity and approach slab void
  - Infrared Thermography – shallow delamination corrosion damage (not discussed today)
  - Galvanostatic Pulse **–** Rebar Corrosion Rates, Resistance and Half-Cell Potential (not discussed today)

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NDE Methods for QA of Epoxy Injection Crack Repairs

- **Pre-stressed concrete I-beam bridge girder over freeway was impacted by a large forklift carried by a truck**
- **Cracks and spalls were observed on the east side of the girder, but it did not fail**

NONDESTRUCTIVE EVALUATION (NDE) Methods for Quality Assurance of Epoxy Injection Crack Repairs, Promboon, Y., Olson, L., Lund, J., International Concrete Repair Bulletin, V. 15, No. 1, Jan./Feb., pp. 12-16)

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Concrete Repair Procedures for Truck Impacted Bridge Girder

- Chipped out loose and damaged concrete
- Pre-saturated the surface with water
- Used structural repair mortar to patch the spalling damage
- Used epoxy injection for filling cracks

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NDE Methods Used for QA of Epoxy Injection Repairs

Impact Echo (IE) over injected cracks

Ultrasonic Pulse Velocity (UPV) Direct testing front to back

Spectral Analysis of Surface Waves (SASW) across injected cracks

Nondestructive Quality Assurance of repairs per "**Guide for Verifying Field Performance of Epoxy Injection of Concrete Cracks**" International Concrete Repair Institute Technical Guideline No. 210.1R-2016

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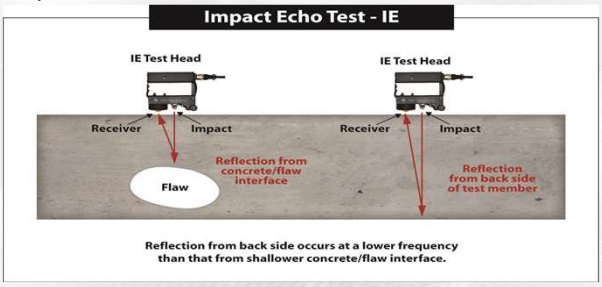
Impact Echo Method



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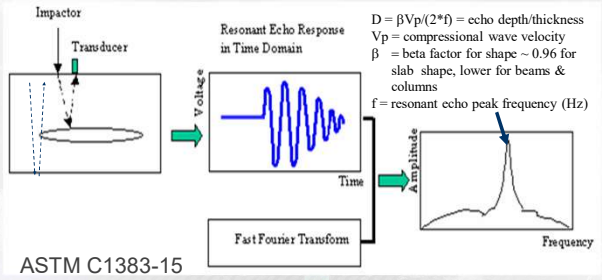
Impact Echo Data Analysis



D = βVp/(2*f) = echo depth/thickness
Vp = compressional wave velocity
β = beta factor for shape ~ 0.96 for slab shape, lower for beams & columns
f = resonant echo peak frequency (Hz)

ASTM C1383-15

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Impact Echo Gauge for 1 Sided Concrete Thickness & Flaws

Olson Instruments Concrete Thickness Gauge (CTG-2)

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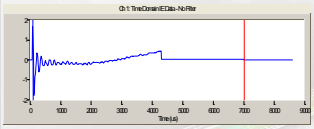
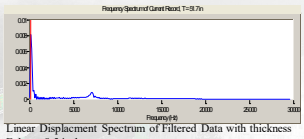
CTG-2 Impact Echo (IE) Signal Processing & Filtering

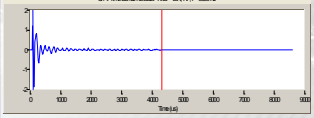
Raw Time Domain IE Displacement Transducer Data



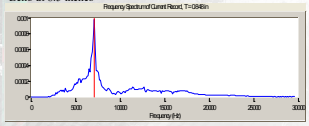
Linear Displacement Spectrum of Raw IE Data



Filtered IE Data (Highpass of 3,000 Hz)



Linear Displacement Spectrum of Filtered Data with thickness Echo at 8.5 inches



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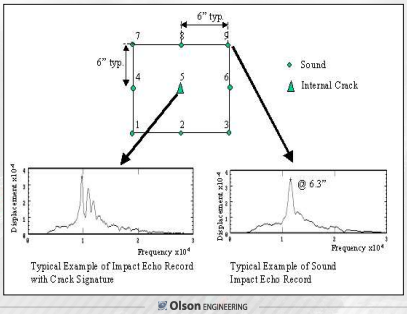
Impact Echo (IE) Results – Unfilled & Filled Cracks



Typical Example of Impact Echo Record with Crack Signature

Typical Example of Sound Impact Echo Record

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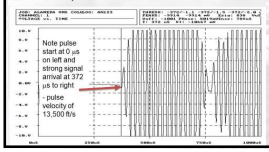
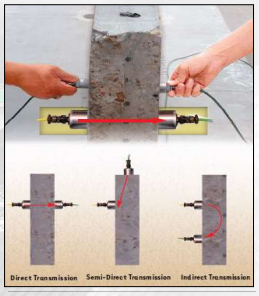
Ultrasonic Pulse Velocity (ASTM C597-16) & Sonic Pulse Velocity Test

- Using 2 transducers - source and receiver
- Calibrate on calibration bar
- Measure signal time and signal amplitude between the source and receiver (transmission test)
- Calculate concrete compressional wave velocity (Vp)
- SPV uses an impact source rather than 50 kHz piezoceramic transducers for testing thicker concrete over 5 to 8 ft
- Pulse Velocity = Vp = d/t = distance /travel time

UPV Example from Sound Concrete





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Concrete Velocity and Quality Relationship

General Concrete Condition	Ultrasonic Pulse Velocity ft/s (m/s)
Excellent	Above 15,000 (4,500)
Good	12,000-15,000 (3,600 – 4.500)
Questionable	10,000-12,000 (3,000 – 3,600)
Poor	7,000-10,000 (2,100 – 3,000)
Very Poor	Below 7,000 (2,100)

(After Leslie and Cheeseman, 1949)

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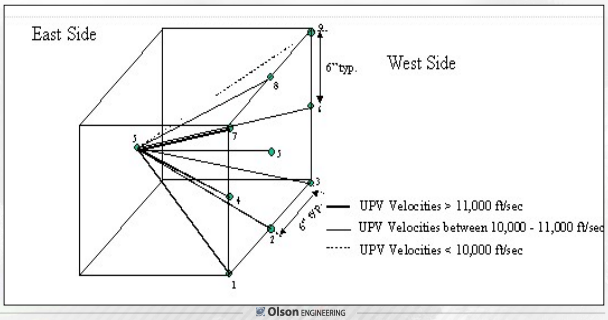
UPV Results through Epoxy Injected Web of Girder



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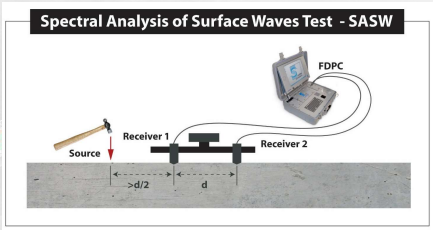
Spectral Analysis of Surface Waves Method (SASW)

- Acoustic method – measures the propagation speed of surface waves with various wavelengths
- Short wavelength waves sample shallow, longer wavelengths sample deeper
- Surface Wave Velocity = $V_R = f^*\lambda$ = frequency x wavelength
- Measures velocity profile versus depth into the structure
- Indicates modulus/ relative strength/ perpendicular crack depths



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NDE Data Acquisition Platforms and SASW Systems

Freedom Data PC - Windows 10 - Ruggedized

SASW-S Bar for 6 to 80 cm spacings with 2 displacement transducers and 2 small accelerometers for larger, variable spacings

NDE-360 Platform Touch Screen w/ Compact Flash

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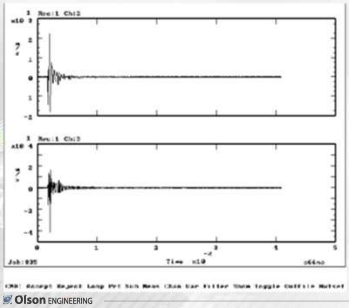
Example Time Domain Test Results SASW

Typical Time Domain Records for the Two Receivers used in SASW Testing, R1–R2 = 30 cm



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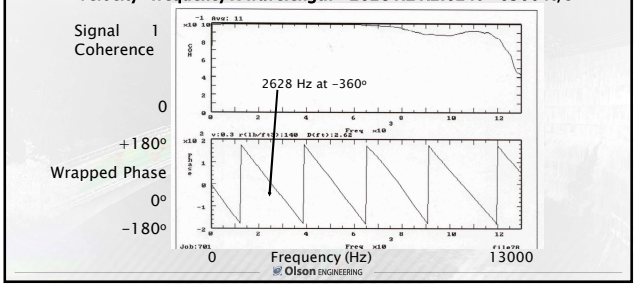
SASW Phase Plot from Sound Concrete Area

for 2.62ft SASW Bar spacing = 1 wavelength (–360° phase),
Velocity=frequency x wavelength= 2628 Hz x2.62 ft =6900 ft/s



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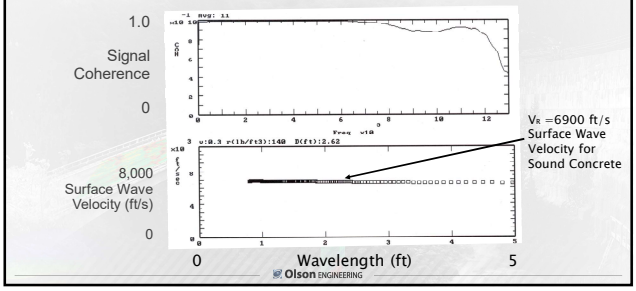
Surface (Rayleigh) Wave Velocity vs. Wavelength



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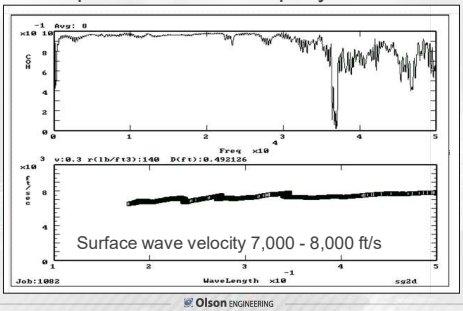
SASW Example Results from Epoxy Filled Crack



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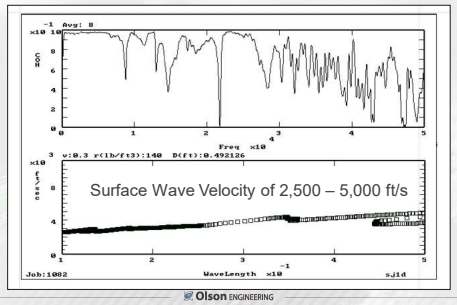
SASW Example Results of Unfilled Crack



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Fusion Overlay of NDE Scanning and Photogrammetric Image Results for Concrete Bridge Girders

- **Photogrammetry** - detailed mapping of concrete surface distress conditions
- **3-D Ground Penetrating Radar (GPR) -** detection/mapping of embedded reinforcing, PT Ducts and steel plates
- **Spectral Analyses of Surface Waves (SASW) –** cracking extent, perpendicular crack depths, void/honeycomb and velocity/modulus
- **Impact Echo Scanning (IES) -** cracking, corrosion delamination damage, honeycomb, thickness, voided vs. grouted post-tensioning ducts
- **Data fusion overlay -** NDE results overlaid on photogrammetric images

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Photogrammetry

Applications:

- Collecting baseline data
  - Thermal Cracking in Drilled Shaft
  - Current cracking, moisture, efflorescence, etc.
  - Current assets
- Monitor deformations over time
- Mapping surface degradations over time

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Photogrammetry Method

Procedures

- Capture Raw Photographic Digital Images with high resolution phone camera at a minimum – telephoto lens camera useful for larger structures
- Identify target features that occur in multiple photographs.
- Use angle changes in target features from photograph to photograph to determine the 3D structure of the object
- Project pixels from the photos onto the 3D structure and generate texture
- Agisoft Metashape software used for bridge image processing on Windows PC with fast processor/GPU
- High resolution (0.6 to 1 mm) images took 1-2 hours of processing
- Offers 100% coverage but large data files (1 GigaByte)

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Digital Photgrammetry Pro's and Con's

Advantages:

- Low-cost equipment – iPhone/Android or telephoto digital cameras
- Deterioration progress over time of surface concrete can be precisely compared
- Detailed permanent record of defects marked during inspection
- 1 GB high resolution images can be viewed with Windows 10 3-D viewer

Limitations:

- Only can collect data on objects in line-of-sight
- Multiple angles/photographs will likely be required for full coverage and identifiable features in overlapping photographs

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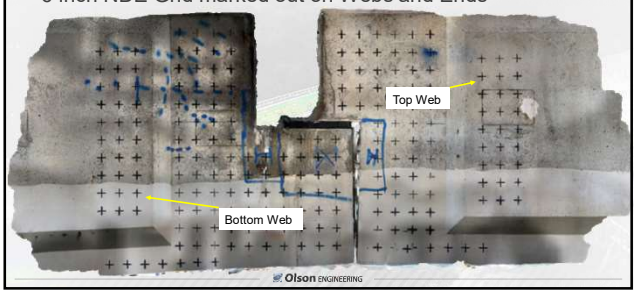
Digital Photogrammetry Example Data Bridge Girders with 6 inch NDE Grid marked out on Webs and Ends



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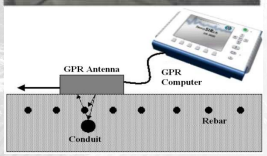
Physical Principle of GPR - ASTM D6087 - 08(2015)e1

- GPR antenna is in contact with test surface while moving and pulsing
- The electromagnetic pulses reflect back from embedded features
- Distance measured
- Data plotted as waterfall plots
- Measures responses caused by variations in electrical properties of the materials and metals are strong reflectors



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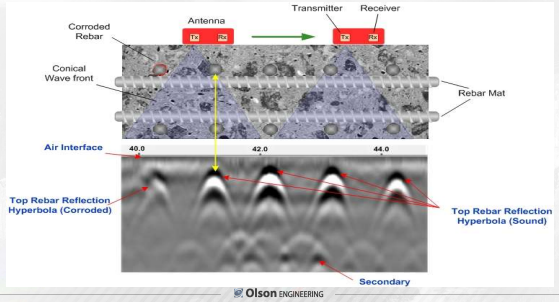
Physical GPR Principle (continued)



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GPR scanning with GSSI StructureScan Mini XT unit (2700 MHz Antenna. Note the 6 inch "+" grid marks to guide horizontal and vertical GPR scan lines on a 3 inch grid for 3D GPR data analyses

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2-D GPR Scan Data Analysis

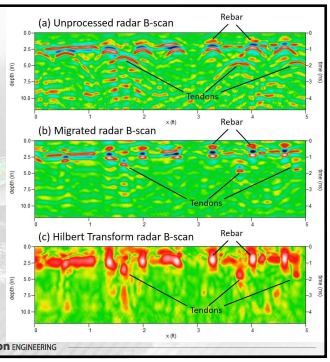
(a) the raw GPR data is shown with the hyperbola reflections from a 2D scan across the rebar and ducts;

(b) next the signals are migrated to collapse the hyperbola reflections from the rebar and tendon ducts to their locations

(c) the pulses are merged into a single pulse envelope via a Hilbert Transform

(d) the Hilbert Transformed data is then gridded in two directions and summed

(e) both rebar and PT Tendon Ducts are noted in the data



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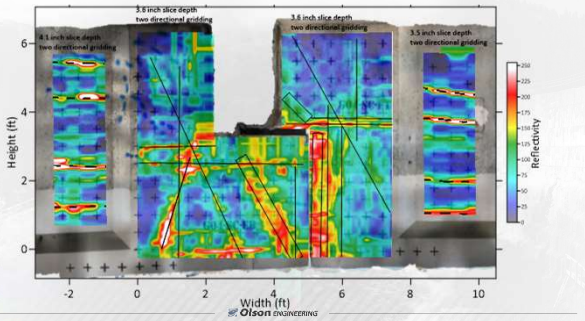
Data Fusion - 3D GPR Depth Slices for PT Ducts, Rebar and Embedded Plates



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Surface Waves testing across crack using an SASW bar with two displacement transducers spaced 1.31 ft apart with a 2-oz metal ball-peen hammer impactor for in-line impacts

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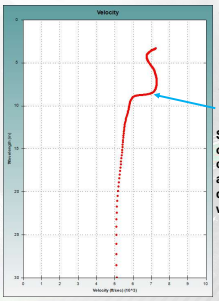
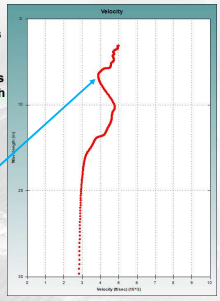
SASW Results for Sound and Cracked Concrete Girder Areas



The backside of the sound 7.5 inch thick web section is shown by the drop in surface wave velocity from ~7,000 ft/s from 4 to 8 inches to ~5,500 ft/s at a wavelength of 8 inches

SASW test across a crack on a girder end indicating a crack depth from surface to approximately 7-8 inch depth where the surface wave velocity increases



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Corrosion of Post-Tensioned (PT) Tendons in poorly grouted ducts

Sunshine Skyway Bridge in Tampa, FL

(Courtesy of Florida Department of Transportation)

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Impact Echo Scanner (IES) Features

- Rolling displacement transducer/ solenoid impactor scanner system that covers more testing area in less time with a test every 25 mm (1 inch)
- Generate 2-D and 3-D plots of Impact Echo results

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Test Girder for Bridge Research

NCHRP IDEA Research Contract No. 102

- Full scale Precast Bridge Girder
- 30m (100 ft) in length with 8 empty steel ducts (100 mm-4inches in diameter)
- Typical wall thickness of the web is 250 mm (10 inches)

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Grout Defect Simulation with Styrofoam Voids

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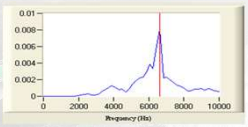
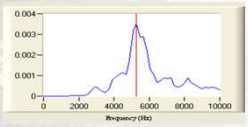
IES Data Interpretation

- Fully Grouted Duct
  - Frequency peak = 6445 Hz
  - Apparent Thickness = 11.17 inches (284 mm)
- Empty Duct
  - Frequency peak = 5274 Hz
  - Apparent Thickness = 13.65 inches (347 mm)
- 22% apparent thickness increase due to void





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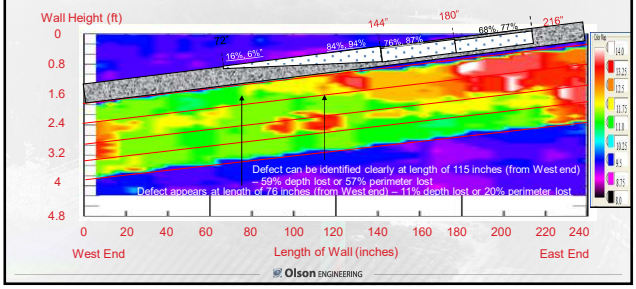
IE Surface Thickness Results



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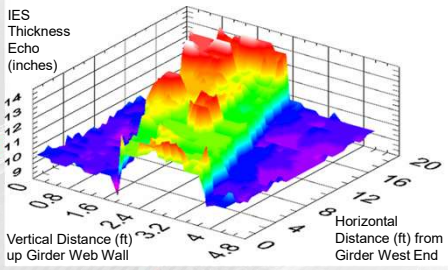
Skewed 3-D Plot to image sound vs. grouted PT ducts

- Three-dimensional surface plots are helpful with interpretation & visualization of defects



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Vertical Impact Echo Scanning (IES) on 6 inch lines

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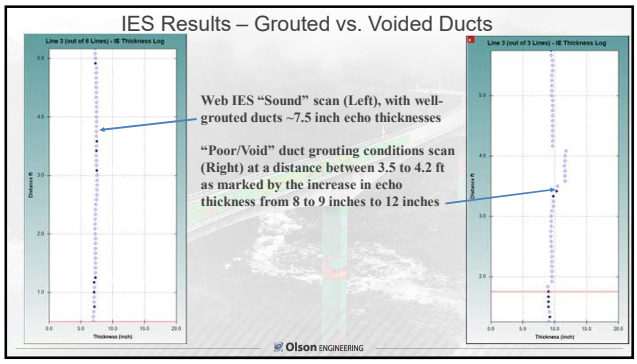
IES Results – Grouted vs. Voided Ducts
Web IES "Sound" scan (Left), with well-grouted ducts ~7.5 inch echo thicknesses
"Poor/Void" duct grouting conditions scan (Right) at a distance between 3.5 to 4.2 ft as marked by the increase in echo thickness from 8 to 9 inches to 12 inches
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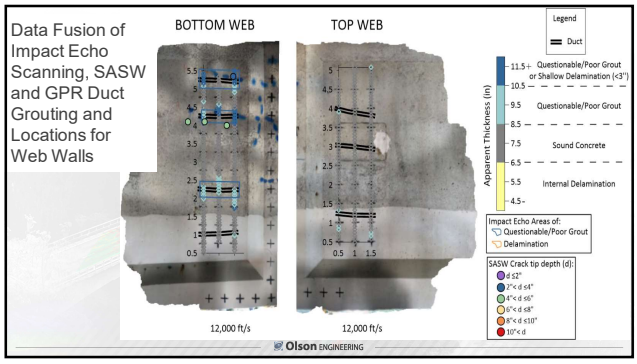
Data Fusion of Impact Echo Scanning, SASW and GPR Duct Grouting and Locations for Web Walls
BOTTOM WEB
TOP WEB
Legend
Duct
Apparent Thickness (in)
11.5+ Questionable/Poor Grout or Shallow Delamination (<3")
9.5 Questionable/Poor Grout
7.5 Sound Concrete
5.5 Internal Delamination
Impact Echo Areas of:
Questionable/Poor Grout
Delamination
SASW Crack tip depth (d):
d ≤2"
2"< d ≤4"
4"< d ≤6"
6"< d ≤8"
8"< d ≤10"
10"< d
12,000 ft/s
12,000 ft/s
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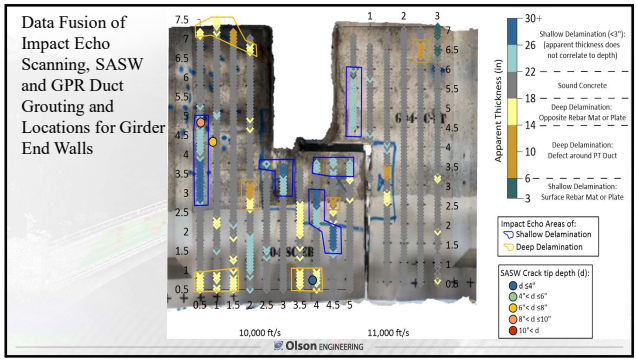
Data Fusion of Impact Echo Scanning, SASW and GPR Duct Grouting and Locations for Girder End Walls
Apparent Thickness (in)
30+
Shallow Delamination (<3"): (apparent thickness does not correlate to depth)
26
22
Sound Concrete
18
Deep Delamination: Opposite Rebar Mat or Plate
14
10
Deep Delamination: Defect around PT Duct
6
Shallow Delamination: Surface Rebar Mat or Plate
3
Impact Echo Areas of:
Shallow Delamination
Deep Delamination
SASW Crack tip depth (d):
d ≤4"
4"< d ≤6"
6"< d ≤8"
8"< d ≤10"
10"< d
10,000 ft/s
11,000 ft/s
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Summary of NDE and Data Fusion Capabilities

- **Photogrammetry** provides detailed imaging with depth of concrete surface conditions
- Use of **3-D Ground Penetrating Radar (GPR)** can image complex reinforcement, PT duct and embedment conditions
- **Spectral Analyses of Surface Waves (SASW)** provides data on depth of cracking and concrete integrity as well as one-sided velocity measurements
- **Impact Echo Scanning (IES)** identifies grouted vs. voided Post-Tensioning Duct conditions and delamination/cracking in concrete
- **Data Fusion** integrates Internal Concrete Conditions from NDE with Photogrammetric Surface Concrete Images for **clearer Structural Assessment**

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Ultrasonic Pulse Velocity (UPV) Investigation of Honeycomb/Void

50 kHz UPV transducers with 1 ft grid direct test patterns from North-South and East-West

UPV test data recorded for pulse velocity arrival time analyses on Freedom NDT PC

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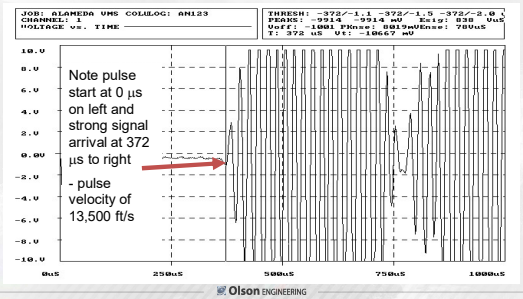
UPV Example from Sound Concrete



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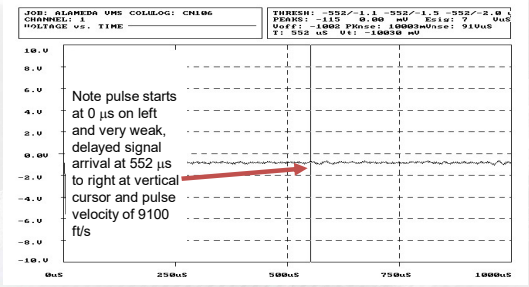
UPV Example from Concrete with Honeycomb



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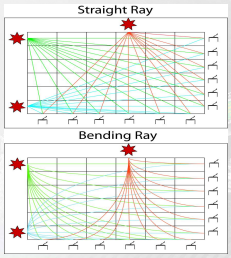
Velocity Tomography Ray Paths, Straight vs. Curved



Rays - Infinitesimally narrow path perpendicular to the spherically spreading seismic wave front.

- Straight Rays
  - "Travel" from Source Location to the Receiver Location in the most direct path.
- Curved Rays (AKA Bending Rays)
  - Seismic Waves and therefore their associated rays can bend within a volume if there are changes in the material properties (I.e. density)
  - These rays are initially estimated as Straight Rays and then iteratively perturbed until the residuals are minimized.
  - More appropriate for mediums containing strong velocity contrasts.

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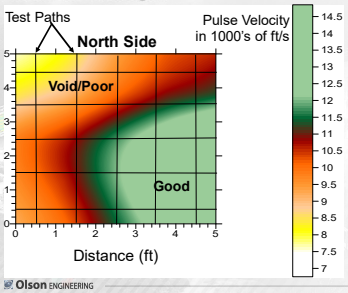
Ultrasonic Tomography of Internal Void/Honeycomb Conditions – Horizontal Cross-Section of Column at 5 ft height

- 2-D Velocity Tomogram of Column showing slow velocity zones indicative of internal poor quality concrete due to poor consolidation in a horizontal slice and good concrete
- UPV data from 5 N-S and 5 E-W tests on a 1 ft grid was used for this tomogram – angled rays and more tests produce more accurate images



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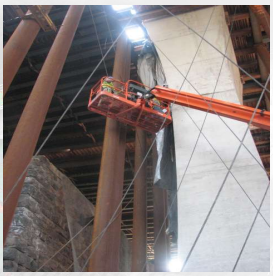
UPV Investigation of Concrete Bridge Pier Honeycomb/Void



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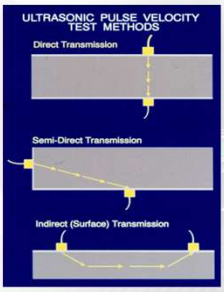
Images of Surface Honeycomb and UPV Grid Layout



Semi-Direct UPV Testing was performed on the corner of this column – note lithium grease spots for coupling of 50 kHz transducers to concrete

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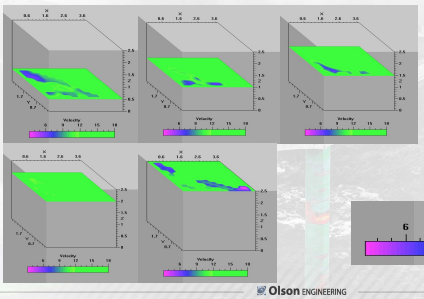
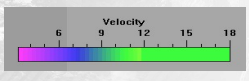
2-D Tomography Slices of Honeycomb/Void Areas



Distances: ft
Velocities:1000's of ft/s

used to guide epoxy injection repairs to fill small honeycomb/void areas



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UPV Tomography Advantages and Disadvantages

- Requires extensive training and experience for analysis, but field data collection less complicated
- Image internal flaws in 2-D and now 3-D fashion with angled and direct tests
- A picture is worth a thousand words sometimes and velocity tomograms provide an image of internal void, cracking and honeycomb
- Requires a lot of 2-sided UPV testing and more detailed analysis to obtain clear images

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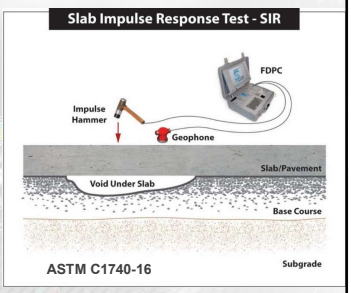
Slab Impulse Response Method

- Olson Instruments Freedom Data PC (or NDE 360) with Slab IR system (SIR-1)
- 3-lb instrumented hammer impacts and geophone records slab response time domain data
  - Wilcoxson velocity transducer used when slab slopes more than 10% – Also used for tunnel liners to test at any angle
- Measures mobility (velocity/force vs. frequency) and flexibility (displacement/force vs. frequency) which is inverse of stiffness
- High mobilities and flexibilities correspond to flawed structural concrete and subgrade void below slabs-on-grade



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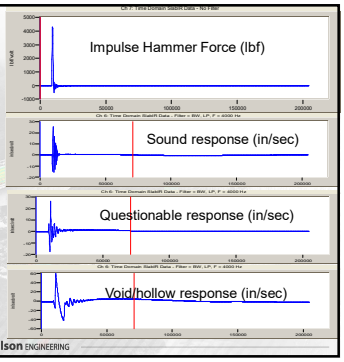
SIR Example Time Domain Data

Impulse hammer force & Sound, Questionable and Void/Hollow velocity transducer responses for support conditions of steel-lined concrete pipe conduit



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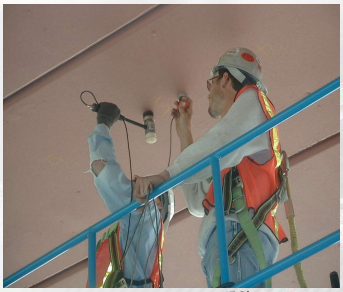
SIR on pre-stressed box girder for void/integrity



SIR on underside of pre-stressed box girder bridge showing 3 lb impulse hammer and geophone

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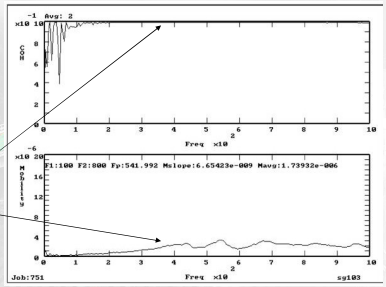
SIR Example Frequency Domain Mobility Data

SIR record on a prestressed concrete box girder of a freight rail bridge with 6.7 inch normal thickness from IE

Note the good coherence near 1.0 in the top plot and low mobility and flat slope indicative of the 6.7 inch thick slab of a box girder



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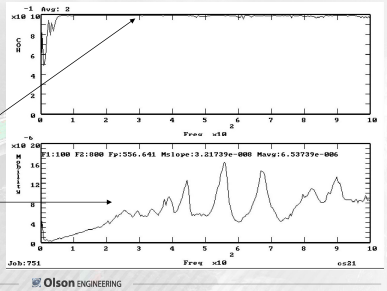
SIR Example Data

SIR record on a prestressed concrete box girder of a freight rail bridge with 2.6 inch normal thickness from IE

Note good coherence of 1.0 but irregular and higher mobility and steeper slope indicative of the much greater flexibility of the thin slab



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Bridge Deck Condition Assessment Methods

- **Visual assessment and Sounding** – visual inspections guide NDE method selection
- **Impact Echo Scanning -** delamination mapping on bare and epoxy coated Concrete Decks
- **Spectral Analysis of Surface Waves Scanning** for delamination mapping on Asphalt Overlaid Decks
- **Ground Penetrating Radar Scanning** for top steel depth and delamination damage potential
- Infrared Thermal Images for top steel delamination (not discussed)
- Galvanostatic Pulse for rebar corrosion – half-cell potential, concrete resistance and corrosion rate (not discussed)
- **Destructive Coring laboratory tests, NDE results confirmation & Service Life**

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Sonic Surface Scanner (S^3) – Decks, Pavements &Slabs

- **Impact Echo – IE Scanning of Bare Concrete** finds Top and Bottom Delaminations and Other damagem (**NCHRP IDEA Contract No. 134 Research)**
- **Spectral Analysis of Surface Waves – SASW of Asphalt Overlaid Concrete Decks** provided the best results of detecting both Top and Bottom Delaminations as well as Debonding of Asphalt Pavement Lifts
- Evaluate general concrete and asphalt quality, cracking damage and slab/deck/pavement thicknesses and elastic modulus for strength estimation (calibrated with cores)

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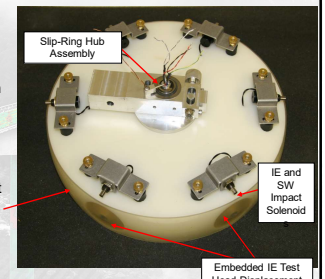
S^3-IE Sensor Wheel

- 6 displacement transducers
- 6 solenoid impactors timed to impact concrete as SSS is rolled at 1-1.5 mph
- Impacts spaced 150 mm (6 inches) apart along a scan line (around the wheel circumference)
- The thin urethane tire serves as a dust cover, protects piezoceramic transducers and improves coupling



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S^3-IE scanning to check for Void/Honeycomb in new Bridge Decks

Total size of both decks was approximately 180 x 11 m (600 ft x 36 ft) – 42,000 Impact Echo tests in for a test every 0.05 m^2 (0.5 ft^2) – Test ~10,000 ft^2 / hr at 1 ft spacing

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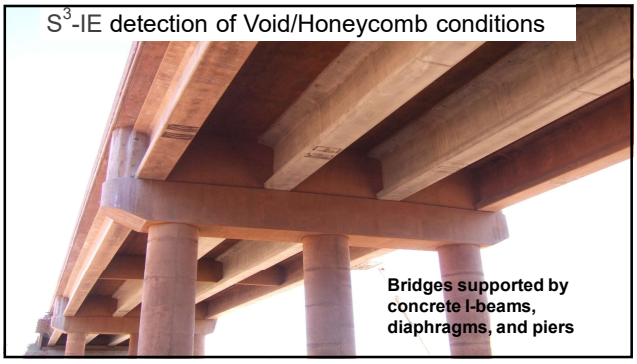
S^3-IE detection of Void/Honeycomb conditions



Bridges supported by concrete I-beams, diaphragms, and piers

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S^3-IE detection of Void/Honeycomb conditions

Tests on Grid Lines at 0.3 m (1 ft) spacing across width of decks with early wagon cart

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S^3-IE detection of Void/Honeycomb conditions

rough concrete tested well

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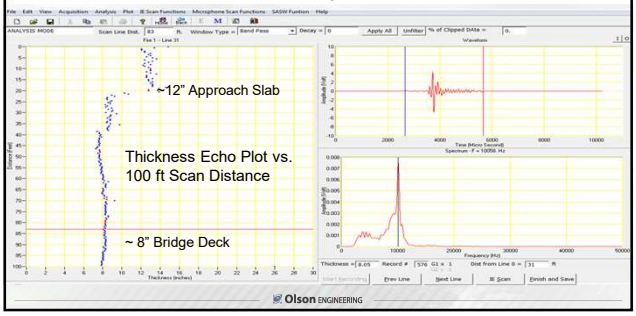
S^3-IE detection of Void/Honeycomb conditions



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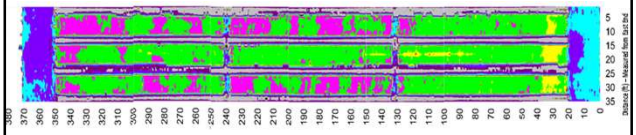
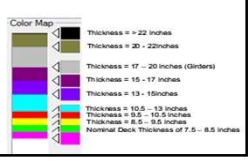
S^3-IE Thickness Results



Length measured from South End of Approach Slab (ft)

Thickness changes such as the approach slabs, piers, diaphragms, and girders can all be observed in the IE thickness data.

Green = nominal thickness
Pink = thin
Blue, maroon, grey = thick



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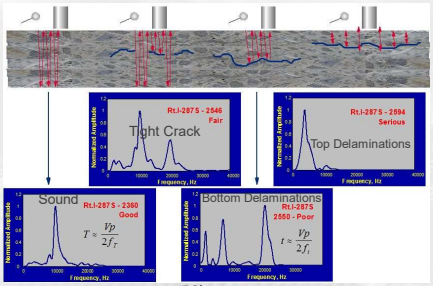
Impact Echo Results on Bridge Deck from Point Testing



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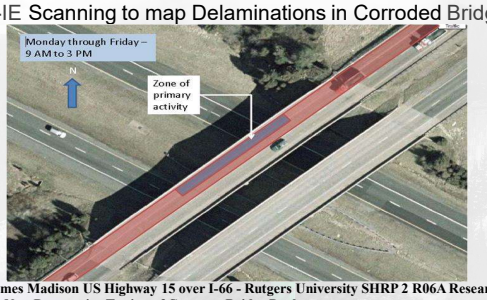
S^3-IE Scanning to map Delaminations in Corroded Bridge Deck



James Madison US Highway 15 over I-66 - Rutgers University SHRP 2 R06A Research on Non-Destructive Testing of Concrete Bridge Decks

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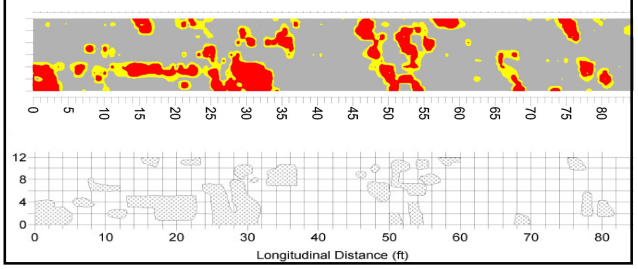
Top Delamination Test Results from Olson S^3-IE Scanning (red and yellow in top plot) and Rutgers Univ. Chain Dragging (bottom plot)



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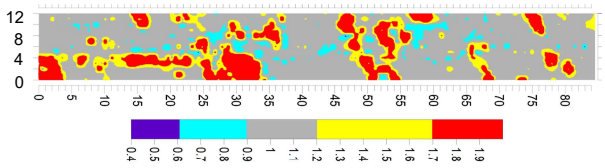
S^3-IE Normalized Thickness Echo Plot of Corroded Delaminated Bridge Deck



Areas with probable top delaminations = 14% (red)
Areas with probable incipient top delaminations = 13% (yellow)
Areas with probable bottom delaminations (or thin section) = 5.7% (light blue)
Sound concrete areas = 67.3% (gray)

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Ground Penetrating Radar (GPR) Deck Scanning with a 2 GHz Bi-Polar Antenna

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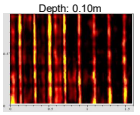
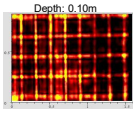
Bi-Polar vs Mono-Polar Antenna

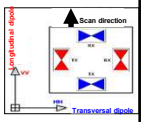


The mono-polar antenna can read the shallow targets (rebars), but is not able to reveal the lower structures



Instead, the FULL-Pbi-polar antenna is able to identify both targets (shallow and deep) in just one scan.

The **SPECIAL BI-POLAR (VV and HH) or FULL-POLAR (VV, HH, VH and HV)** high-frequency (2 GHz) antenna combinations along with the **Pad Survey Guide (PSG)** permit joint orthogonally polarized scans to be acquired in a single pass, detecting shallow and deep structures and halving acquisition time compared to standard methods.



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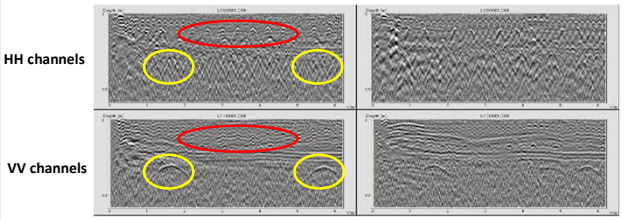
Benefits from double polarization

- Hyperbolas produced by shallower rebars can be detected in HH data only
- Hyperbolas produced by deeper objects/rebars can be detected in VV data only



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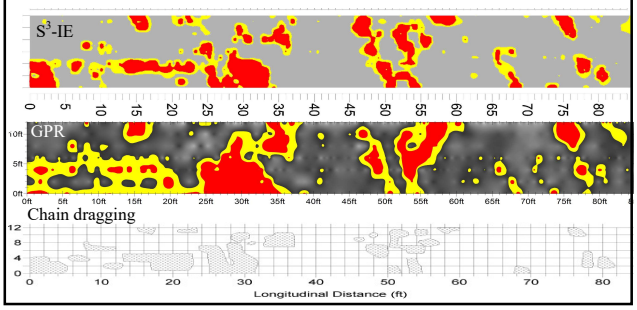
Comparison of S^3-IE, GPR, and Chain Dragging Methods to Detect Top Deck Steel Delaminations



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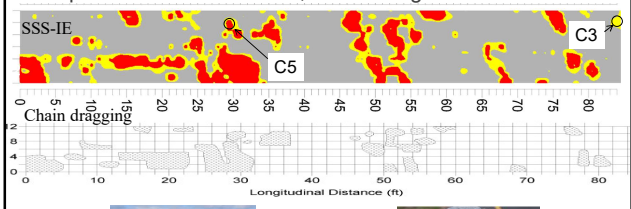
Comparisons Between S^3-IE, Chain Drag and Cores



C5 – delamination at 2.5 inches

C3 – delamination at 3.5 inches

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S^3-IE Scanning - 2 miles of Interstate Bridge Deck+GPS

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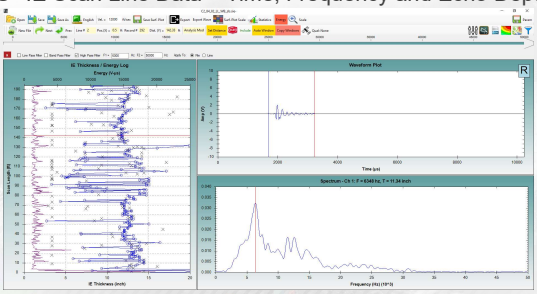
S^3-IE Scan Line Data – Time, Frequency and Echo Depths



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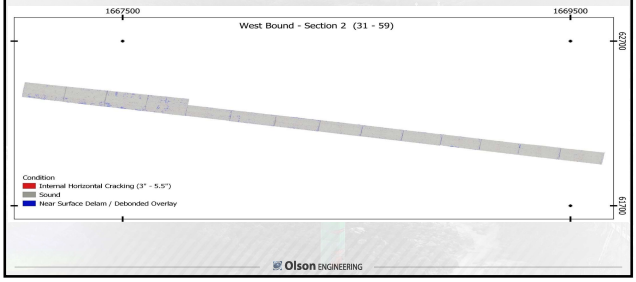
S^3-IE Deck Delamination, Cracking & Sound Deck Results



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S^3-IE Delamination, Cracking and Sound Deck Results for 200 ft Section overlaid on Google Earth View

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S^3-IE Tabular Summary of Deck Conditions & Repair Quantities

Test Area Between Joints	Total Area Tested (ft^2)	Sound Area (ft^2)	Sound %	Near-Surface Delamination Area (ft^2)	Near-Surface Delamination Area %	Internal Horizontal Cracking 3" - 5.5" dp (ft^2)	Internal Horizontal Cracking 3" - 5.5" dp %	Test Area Between Joints	Estimated Near Surface Repair Volume (yd^3)	Estimated Internal Cracking Repair Volume (yd^3)
33 - 31	17,144	15,877	92.6	1,078	6.3	189	1.1	33 - 31	10.0	2.9
35 -33	17,751	16,458	92.7	1,119	6.3	173	1.0	35 -33	10.4	2.7
37 - 35	18,341	16,435	89.6	1,707	9.3	199	1.1	37 - 35	15.8	3.1
39 - 37	18,780	16,814	89.5	1,686	9.0	279	1.5	39 - 37	15.6	4.3
41 - 39	13,364	12,357	92.5	777	5.8	230	1.7	41 - 39	7.2	3.6
43 - 41	13,726	12,818	93.4	775	5.6	133	1.0	43 - 41	7.2	2.1
45 - 43	13,596	12,532	92.2	800	5.9	264	1.9	45 - 43	7.4	4.1
47 - 45	13,186	12,471	94.6	564	4.3	151	1.1	47 - 45	5.2	2.3
49 - 47	12,560	11,899	94.7	562	4.5	100	0.8	49 - 47	5.2	1.5
51 - 49	11,966	11,417	95.4	452	3.8	97	0.8	51 - 49	4.2	1.5
53 - 51	11,838	11,128	94.0	557	4.7	152	1.3	53 - 51	5.2	2.4
55 - 53	12,277	11,825	96.3	331	2.7	121	1.0	55 - 53	3.1	1.9
57 - 55	12,954	12,460	96.2	389	3.0	106	0.8	57 - 55	3.6	1.6
59 - 57	14,027	13,479	96.1	378	2.7	171	1.2	59 - 57	3.5	2.6

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SHRP 2 R06(D) HMAC Delamination of Asphalt Pavement Lifts Research by National Center for Asphalt Technologies at Auburn University Surface Waves mapped debonds - Sonic Surface Scanner (S^3-IE-SASW)

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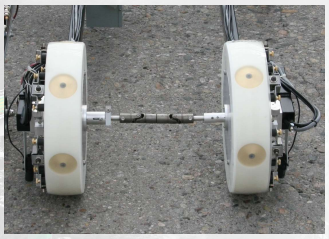
S^3-IE-SASW Sensor Wheel Setup

- Use 2 identical sensor/impactor wheels
- Only one wheel with the impactor turned on and displacement transducers lined up for left wheel IE test and SASW test between wheels
- The spacing between the transducers is typically 6 to 9 inches for asphalt overlaid decks
- Can rotate the wheels 30 degree out of phase to perform IE testing on both wheels simultaneously



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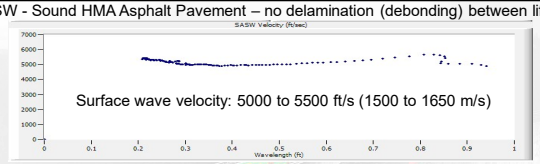
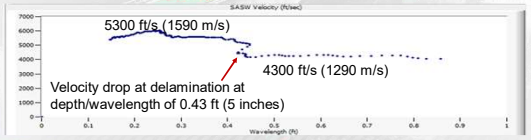
SASW - Sound HMA Asphalt Pavement – no delamination (debonding) between lifts



SASW - Asphalt Pavement with Thin paper delamination at 0.43 ft (5 inches or 12.5 cm)



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S^3-IE-SASW Scanner for Debonded Asphalt Pavement Summary

- Spectral Analysis of Surface Waves (SASW) provided the best results of detecting asphalt pavement delaminations
- Dispersion curve plots of Surface Wave Velocity vs. Wavelength show velocity decreases at debonded asphalt lift depths
- Led to applied research demonstration for Colorado DOT on Asphalt Overlaid Concrete Deck Delamination Evaluations

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Technologies for Assessment of Asphalt Overlaid Decks

- Sounding – hard to hear through the asphalt
- Infrared Thermography – hard to apply the heat source to the concrete layer through the asphalt plus debonding of asphalt/concrete interface and sensitive to the first 2-3 inches
- Impact Echo Scanning – asphalt absorbs the energy (unless colder and concrete-like) and it can be debonded
- Ground Penetrating Radar
  - Complicated by de-icing salts and moisture that is often present at asphalt/concrete interface
- Spectral Analyses of Surface Waves detected delaminations of asphalt pavement lifts in SHRP 2 R06D National Center for Asphalt Technology study at Auburn University and extended to Asphalt Overlaid Decks

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S^3-IE-SASW Scanner Internal R&D demo for Colorado DOT

- Structure E-17-IN: I-270 westbound bridge over Dahlia Street (asphalt covered concrete deck with water-proofing membrane)
- Structure E-17-IE: I-270 eastbound bridge over South Platte River (asphalt covered concrete deck without water-proofing membrane)

Internal Research Project on 2 Asphalt Overlaid Decks with the Colorado DOT

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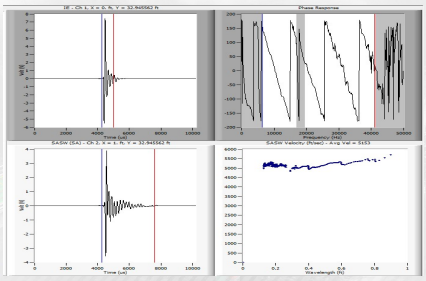
Bonded Asphalt on Sound Concrete



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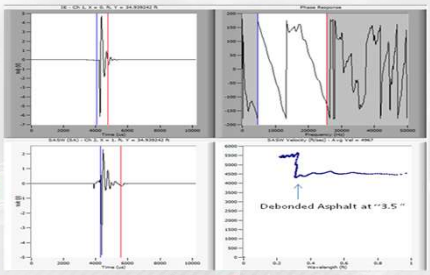
Sound Concrete with Asphalt Debonding



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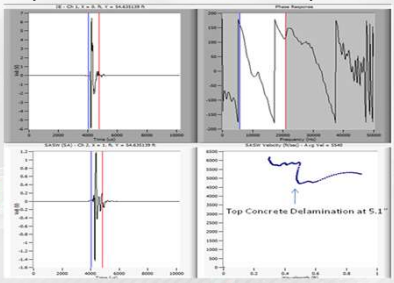
Bonded Asphalt on Concrete with Top Delamination



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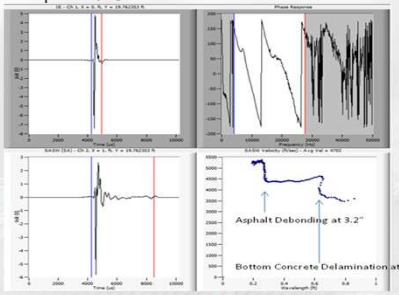
Debonded Asphalt / Concrete with Bottom Delamination



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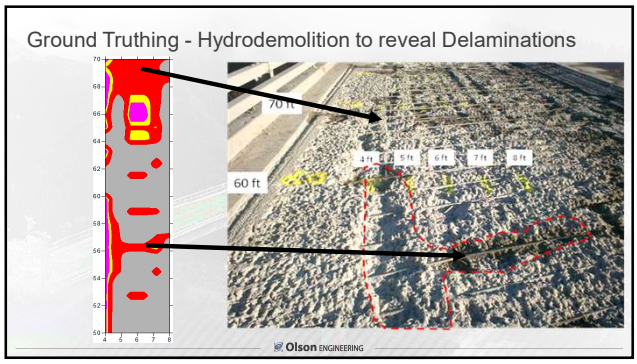
Ground Truthing - Hydrodemolition to reveal Delaminations
70 ft
60 ft
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S3-IE Scanning for Detection of Debonding
4 inch thick White Topping Overlay of Concrete Deck
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S3- IE on white-topped deck
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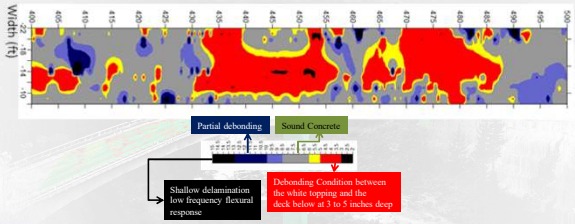
S^3-IE Test Results from the Texas Deck



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Sonic Surface Scanner S^3-IE Summary

- Impact Echo Scanning had the most resolution of Top Delaminations on concrete bridge decks better than GPR and chain-dragging
- IE identified bottom delaminations as well as profiling deck thickness echoes (where sound above)
- GPR method is not sensitive to bottom delaminations and better at mapping damage potential in vehicle speed surveys – not as precise as Impact Echo for project level surveys
- Spectral Analysis of Surface Waves (SASW) for mapping out delaminations of asphalt overlaid concrete bridge decks and asphalt pavement lift debonding
- IE Scanning mapped out debonded white-topped concrete deck

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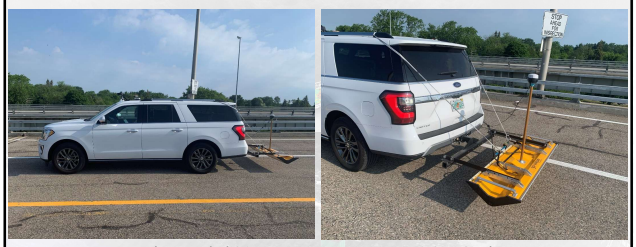
3-D Radar Scanning of Asphalt Overlaid Bridge Deck at 25 mph to map Asphalt Thickness and Top Deck Steel Delaminations



Air-Coupled 21 GPR Antenna Array at 0.2 to 3 GigaHertz

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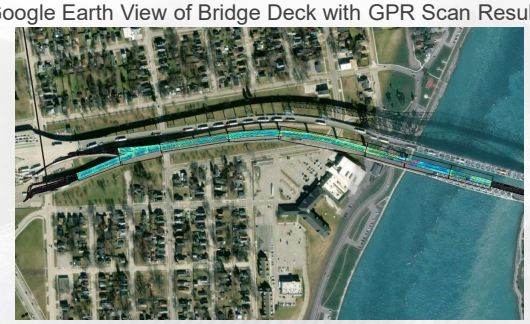
Google Earth View of Bridge Deck with GPR Scan Results



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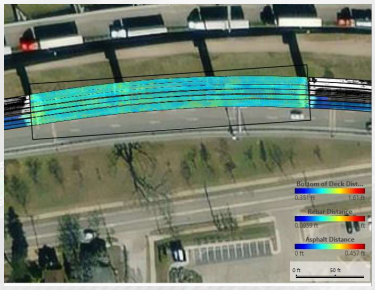
3D Radar Results for Deck, Rebar and Asphalt Depths



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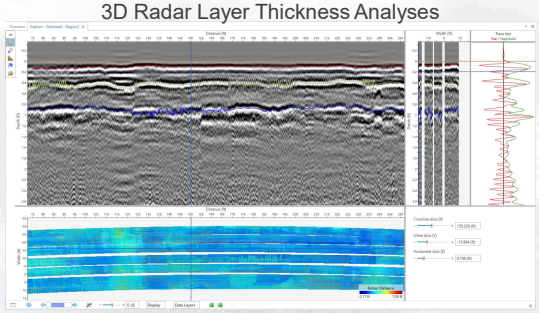
3D Radar Layer Thickness Analyses



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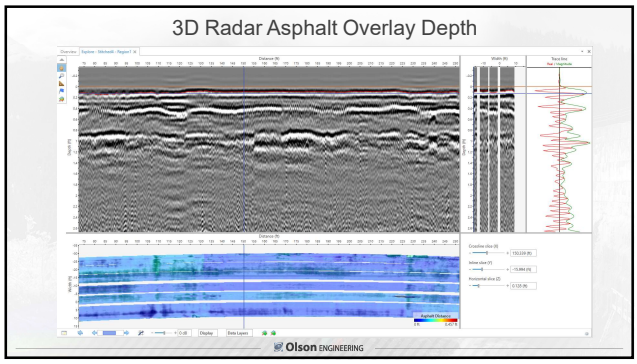
3D Radar Asphalt Overlay Depth
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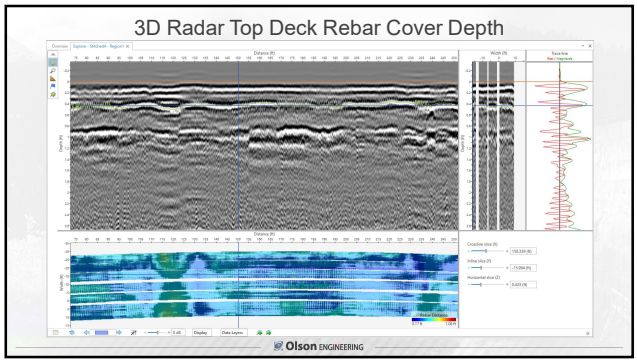
3D Radar Top Deck Rebar Cover Depth
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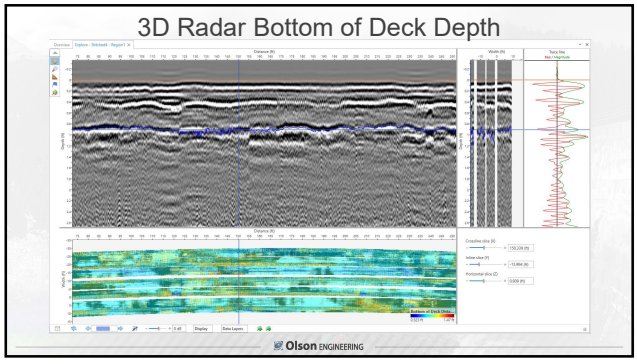
3D Radar Bottom of Deck Depth
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Thank You
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