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2024
FALL CONVENTION

DENVER, COLORADO | OCTOBER 22-25, 2024

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Nondestructive Evaluation (NDE) for Concrete Honeycomb/Void Detection and Imaging and Repair QA

Larry D. Olson, PE

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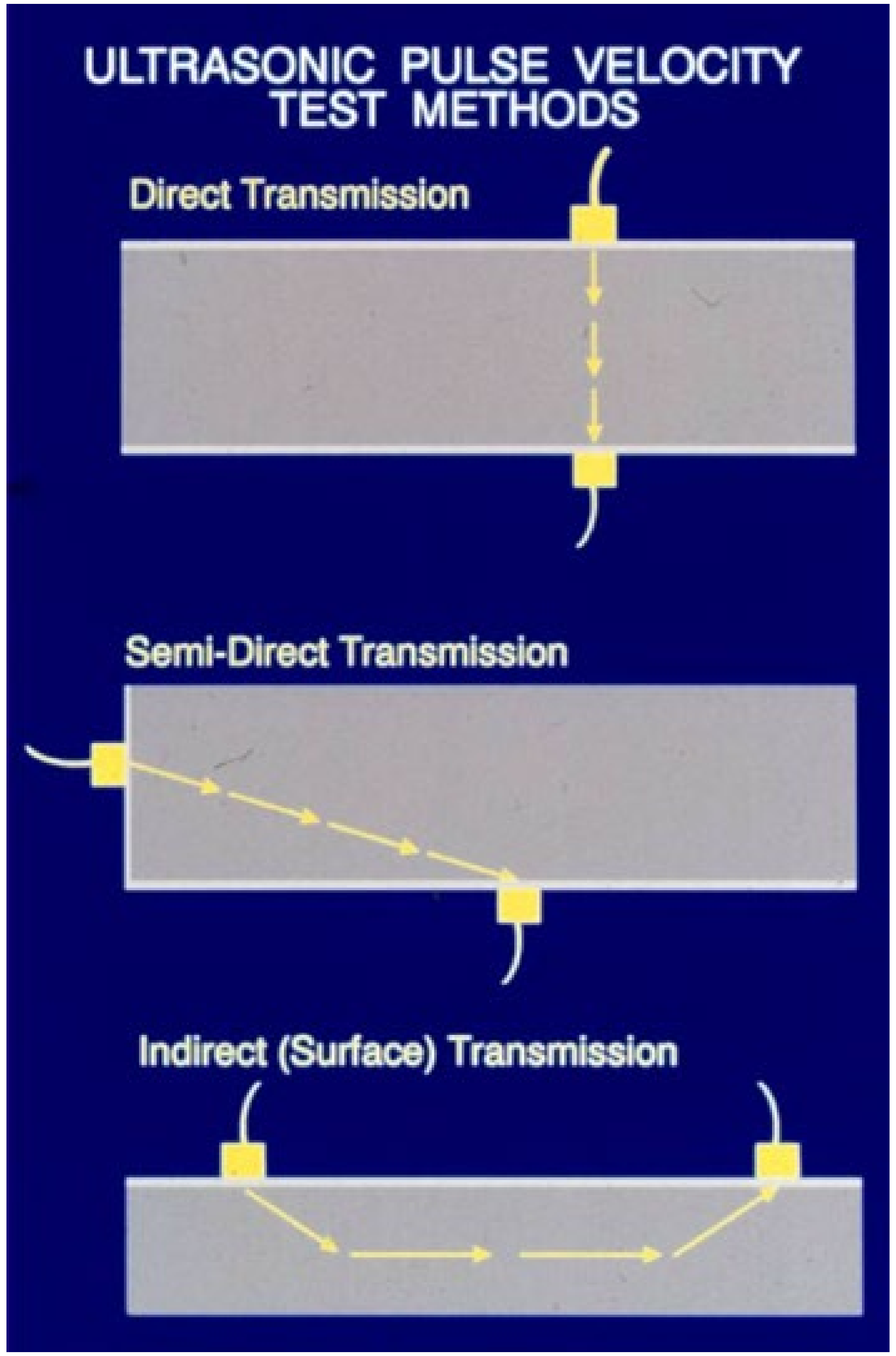
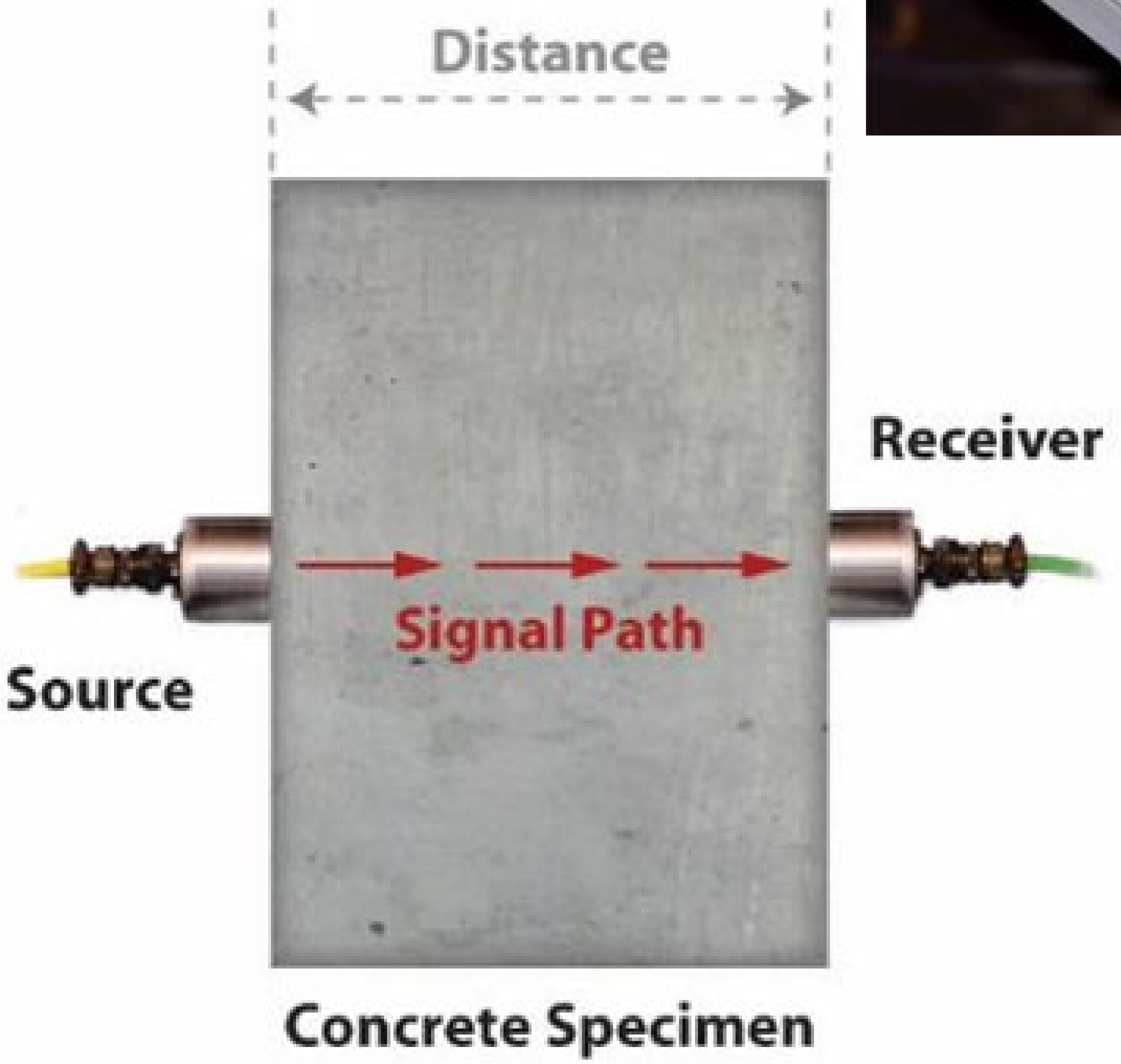
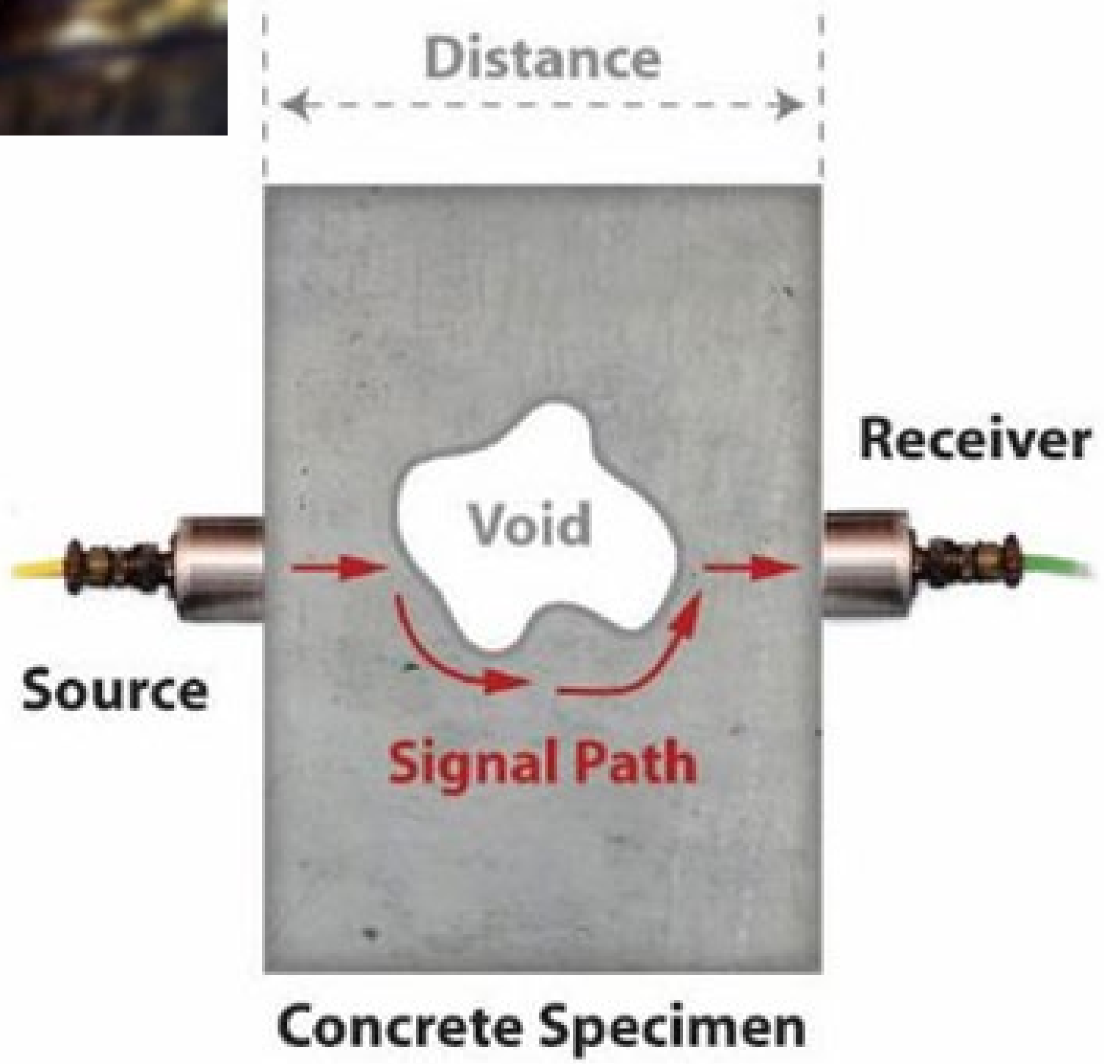
NDE Methods can detect/image honeycomb/void/cracks - 5% loss of density due to honeycomb reduces strength by 25 to 30% per PCA study

- **Ultrasonic Pulse Velocity/Tomography of this Building Transfer Beam**
- **Impact Echo Scanning of PT Ducts**
- **Spectral Analyses of Surface Waves**
- **Ultrasonic Pulse Echo Shear Wave Tomography**
- **supporting Ground Penetrating Radar**

Ultrasonic Pulse Velocity (UPV - ASTM C597)







Concrete Ultrasonic Pulse Velocity (P-wave) and Quality Relationship

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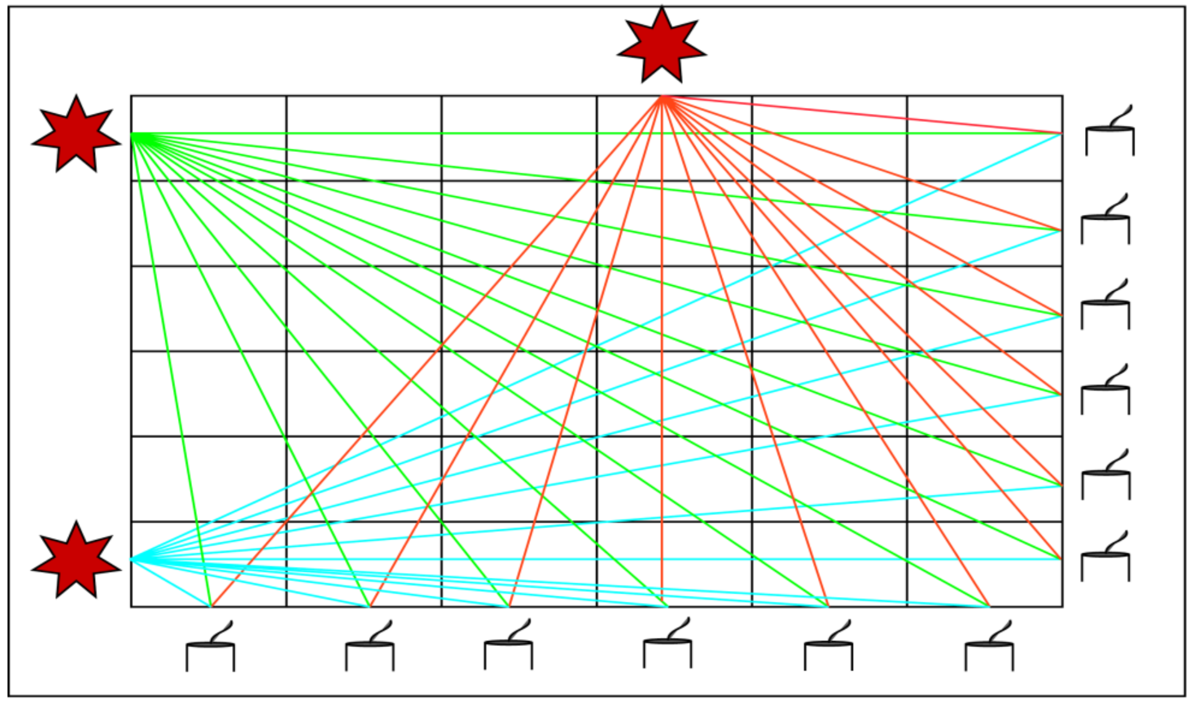
General Concrete Quality	Ultrasonic Pulse Velocity ft/s (m/s)
Excellent	Above 15,000 (4,500)
Good	12,000-15,000 (3,600 – 4.500)
Questionable	10,000-12,000 (3,000 – 3,600)
Poor	7,000-10,000 (2,100 – 3,000)
Very Poor	Below 7,000 (2,100)

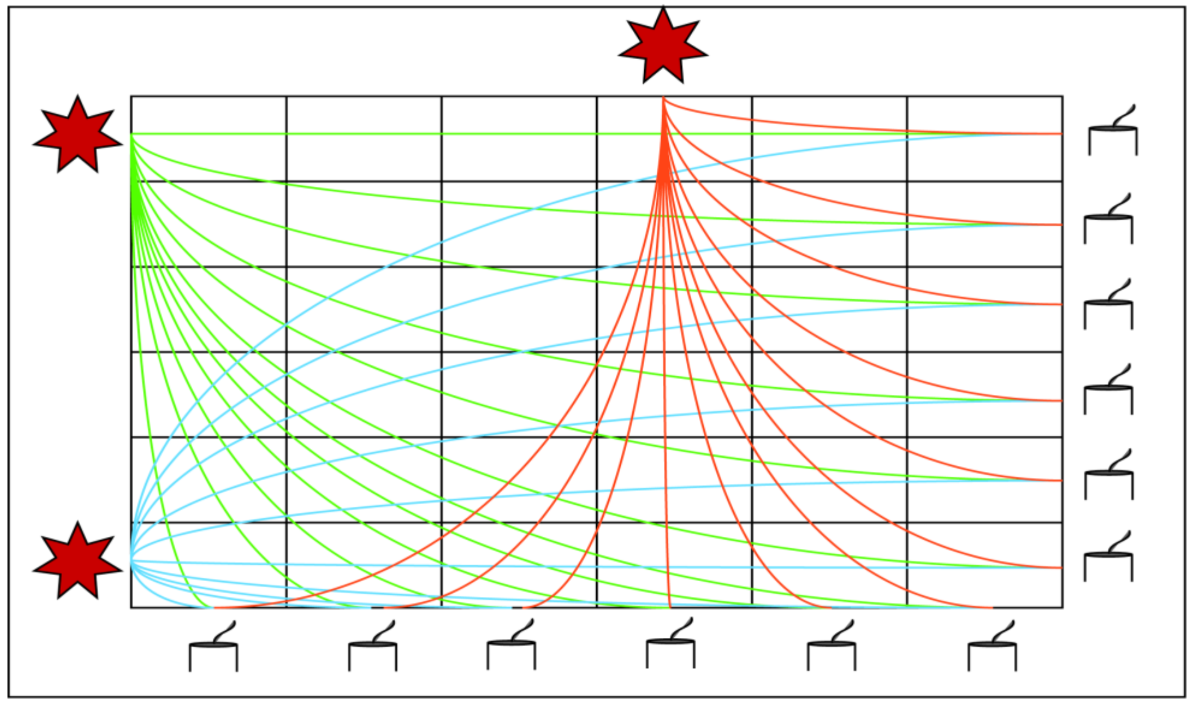
(After Leslie and Cheeseman, 1949)

UPV Test Crossing Paths for Straight vs. Curved Ray Paths using Velocity Tomographic Analysis

Straight Ray



Bending Ray



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.

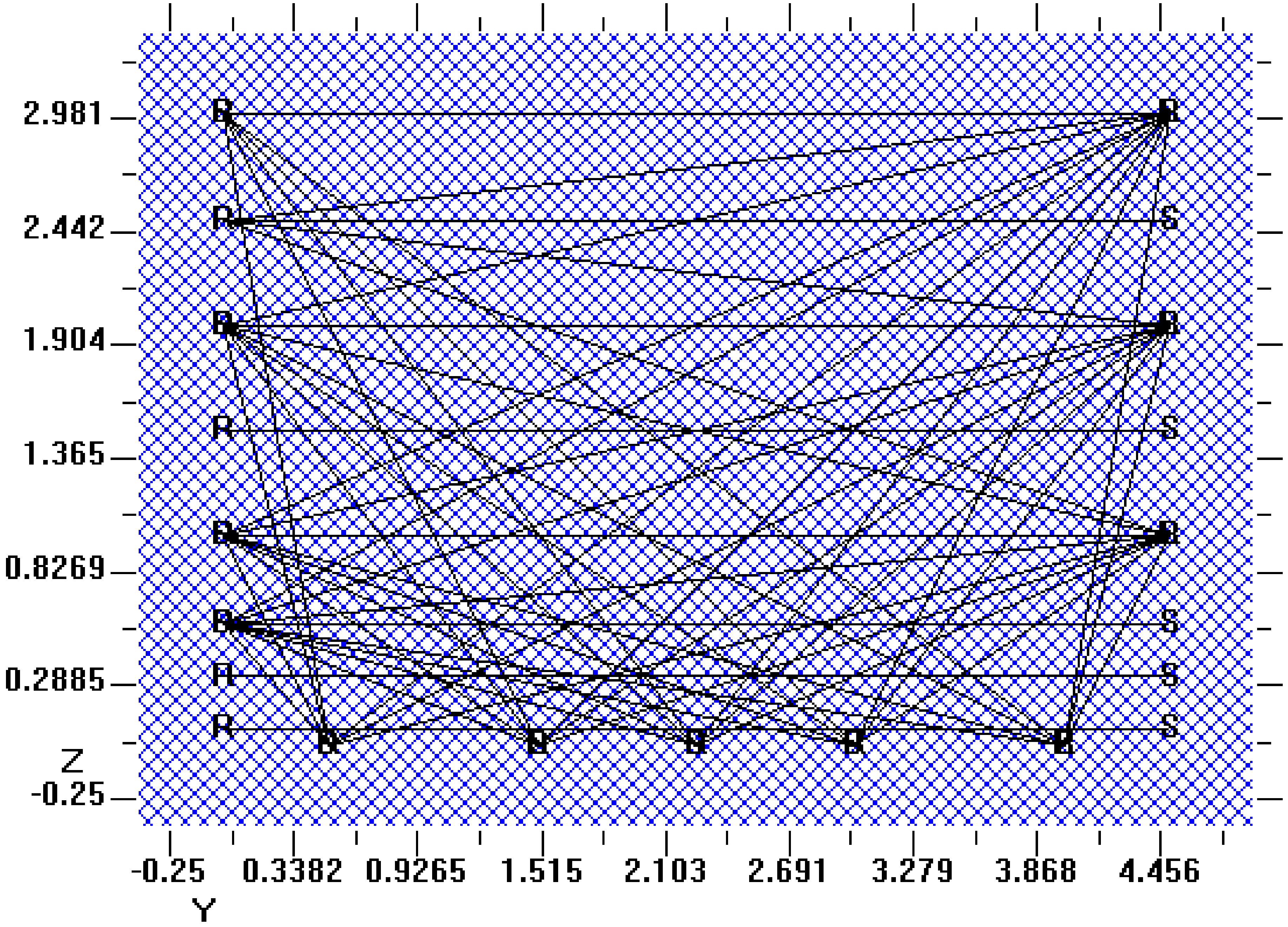
Geotom CG Velocity Tomography Software

Inversion Software used by Olson for Tomographic Velocity Imaging of Concrete Honeycomb/Void using Ultrasonic Pulse Velocity data.

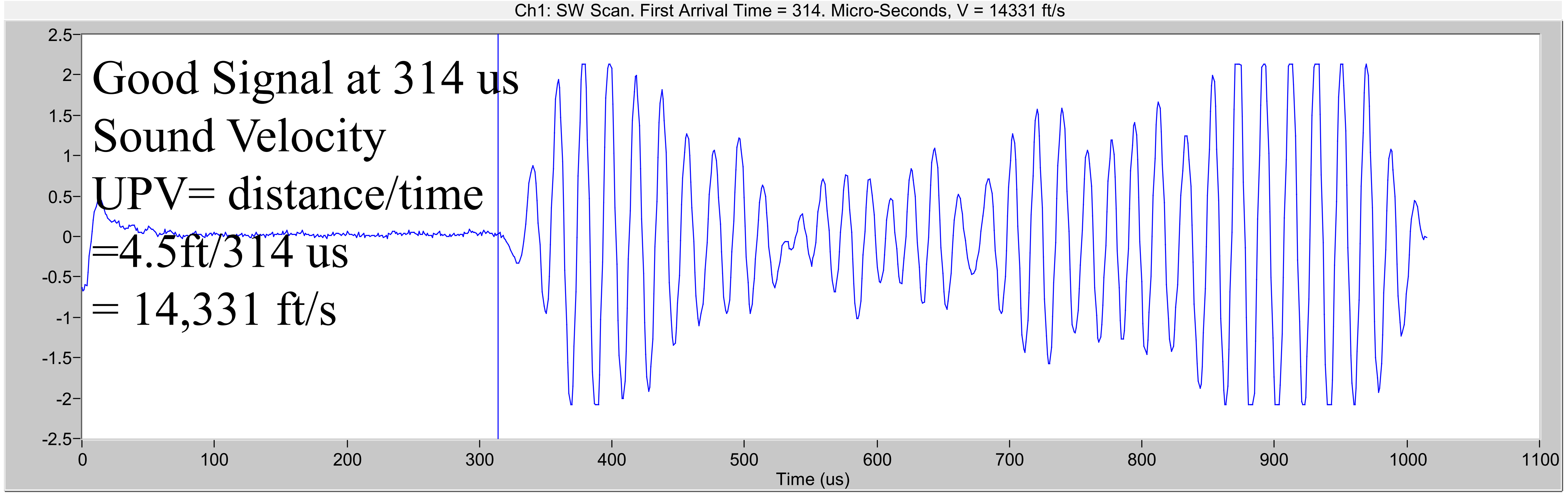
Features:

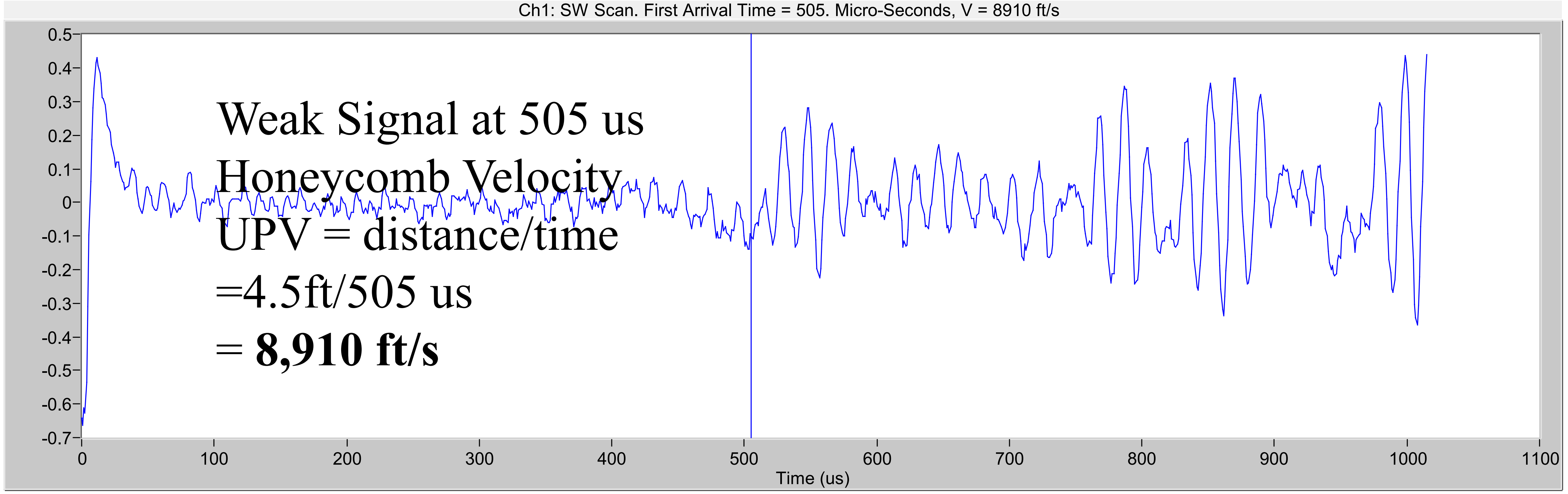
- Source-to-receiver travel times can be analyzed to calculate velocities
- Algebraic Reconstruction Technique to assign Pixel Velocities – slow vs. fast to show void/honeycomb vs sound concrete
- Source and receiver positions can be in any configuration within a 2-D or 3-D grid.
- The tomographic analysis calculates velocity at points (pixels or voxels) within the grid.
- Ray Paths can be straight or curved.

UPV Tests of Transfer Beam with 50 kHz Source/ Receiver Transducers and Tomography Test Paths

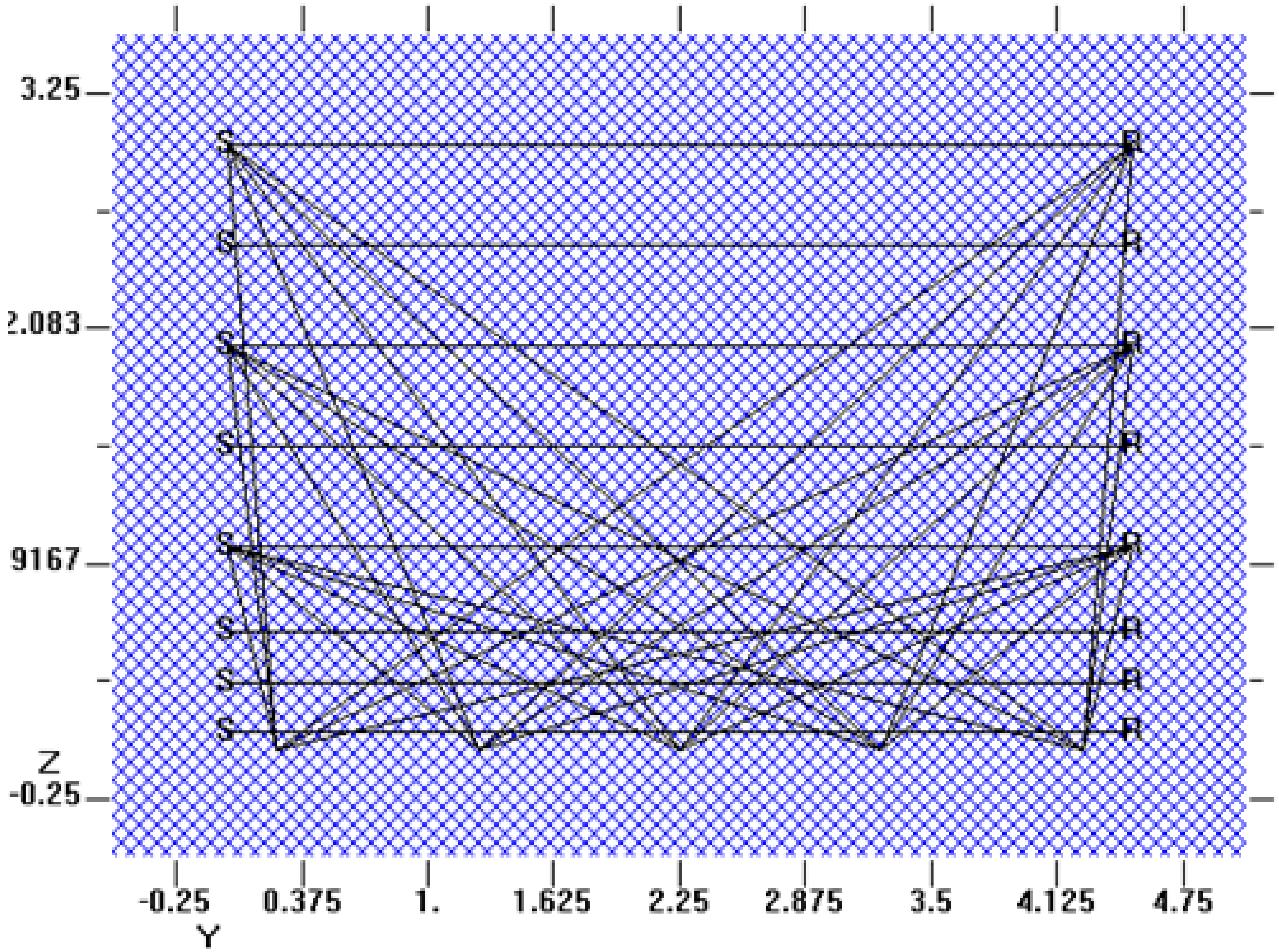


UPV Sound (top) and Honeycomb (bottom) Receiver Voltage vs. time Test Results



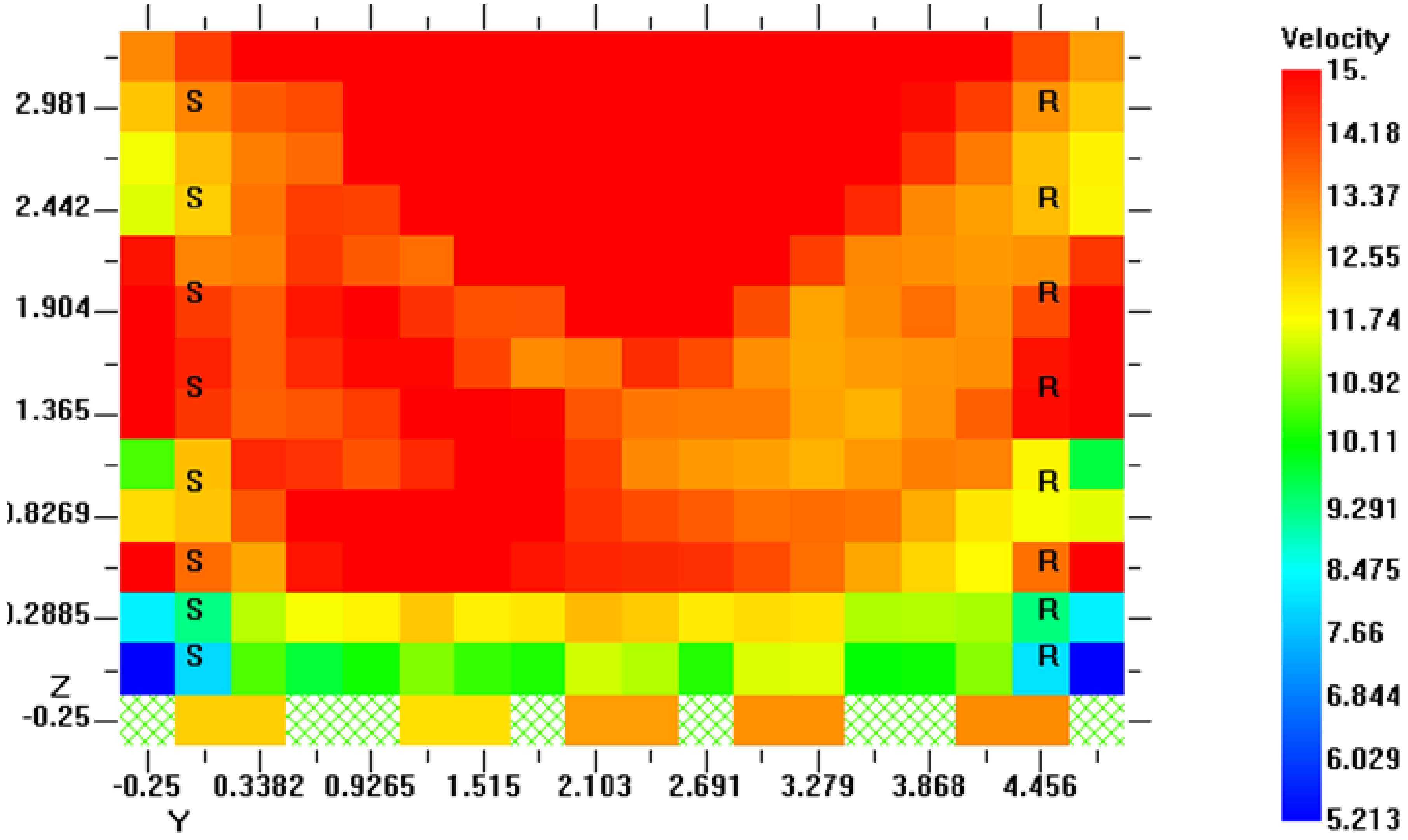


Direct and Angled UPV Tests for Velocity Tomography Analyses and Direct Velocities that show honeycomb/void at beam bottom

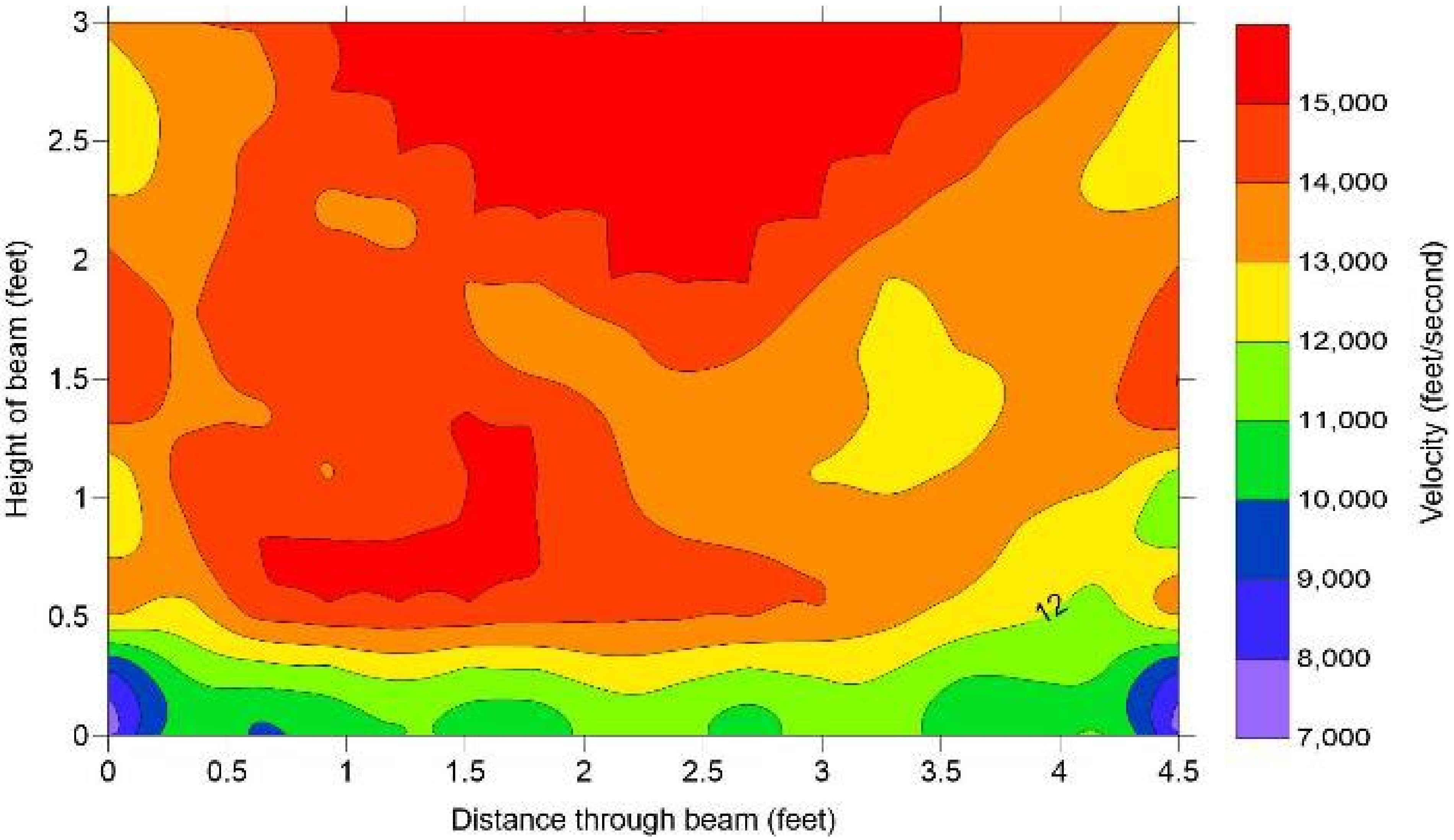


36" – 15203ft/s
30" – 15254
24" – 14469
18" – 14107
12" – 13932
7" – 14063
4" – 13274
1" - 7785

Geotom Velocity Tomogram Analyses Results with Source (S) and Receiver (R) Locations - 11 ft Velocity x1000 ft/s Honeycomb/void at Bottom/Edges



Smoothed Compressional Wave Velocity Tomogram Plot



Building Transfer Beam with Honeycomb/Void

13′ 11′

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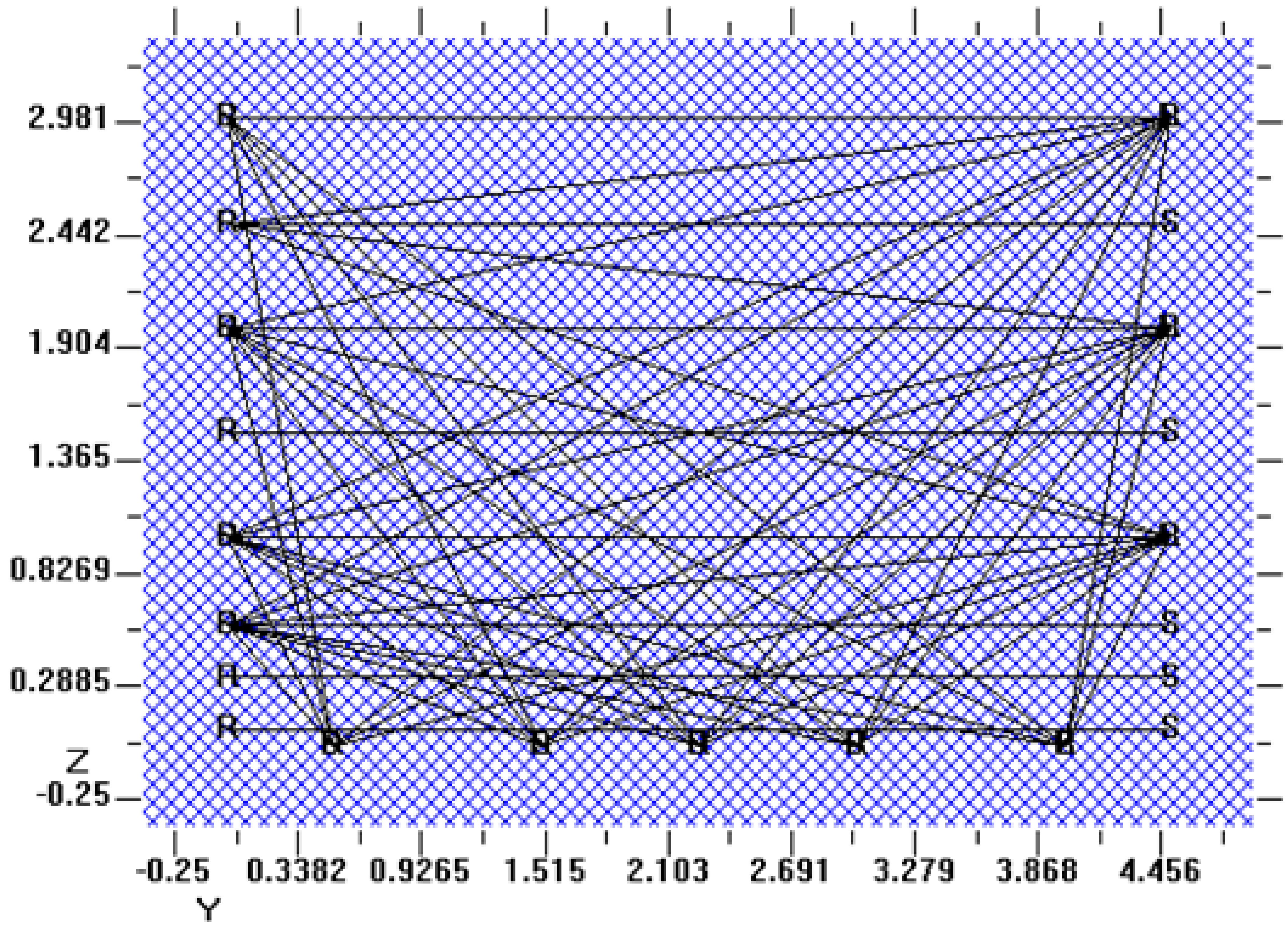
Direct and Angled UPV Tests for Velocity Tomography Analyses and Direct Velocities that show honeycomb/void at beam bottom



36" – 14658 ft/s
30" – 14286
24" – 14151
18" – 13932
12" – 14019
7" – 13761
4" – 13196
1" - 6016

Geotom Velocity Tomogram Analyses Results with Source (S) and Receiver (R) Locations – 17 ft Velocity x1000 ft/s Shows Honeycomb at Bottom/Edges

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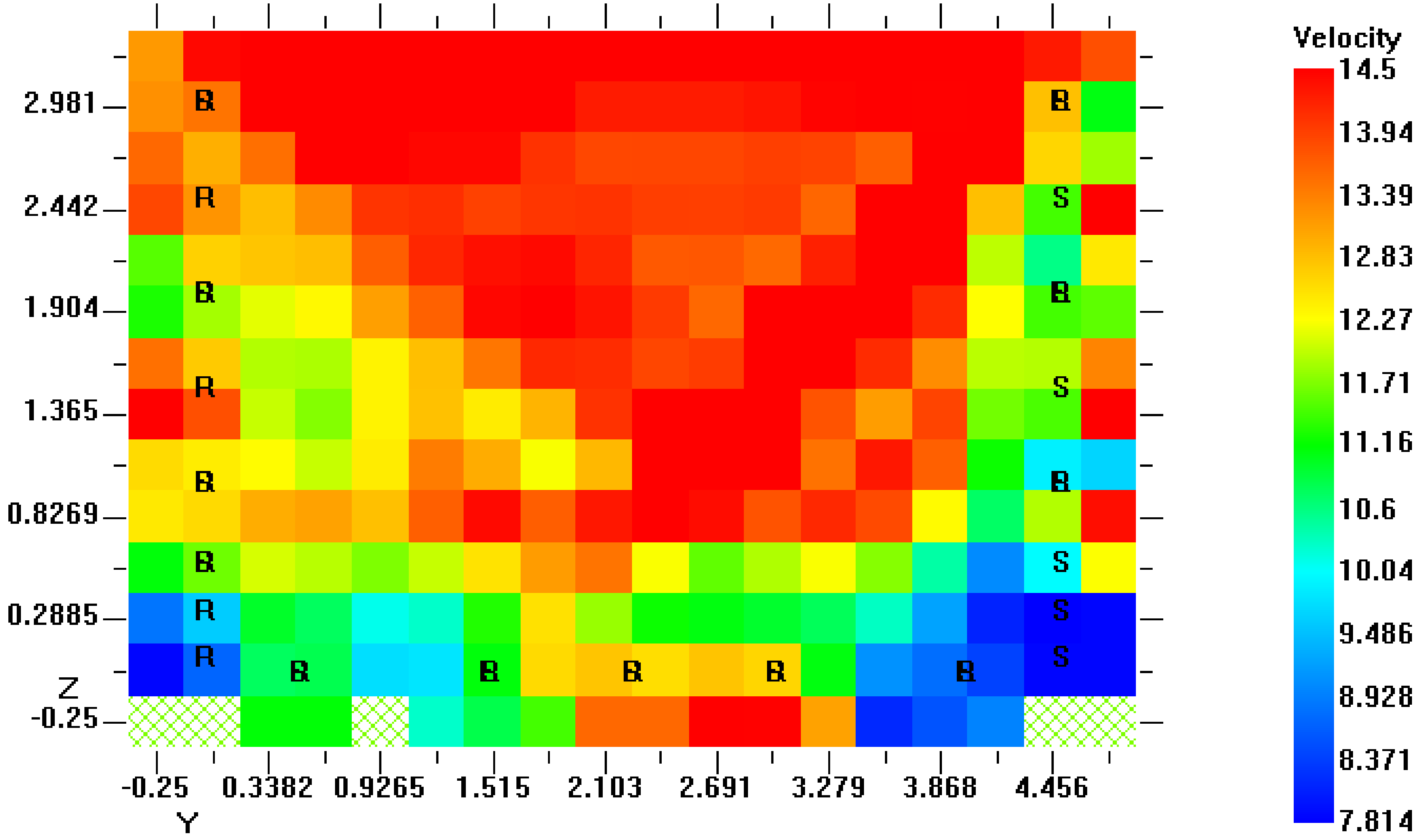
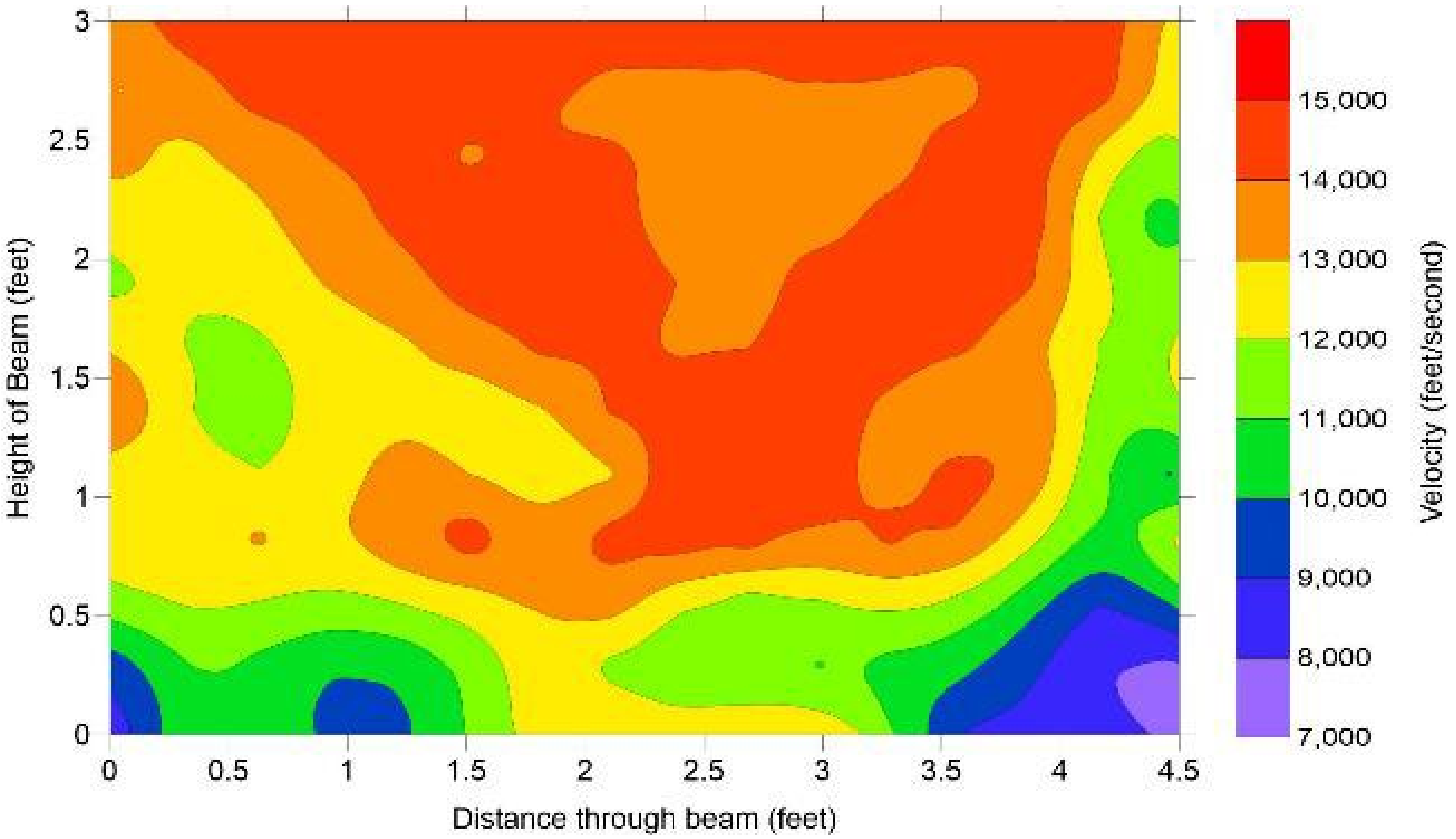


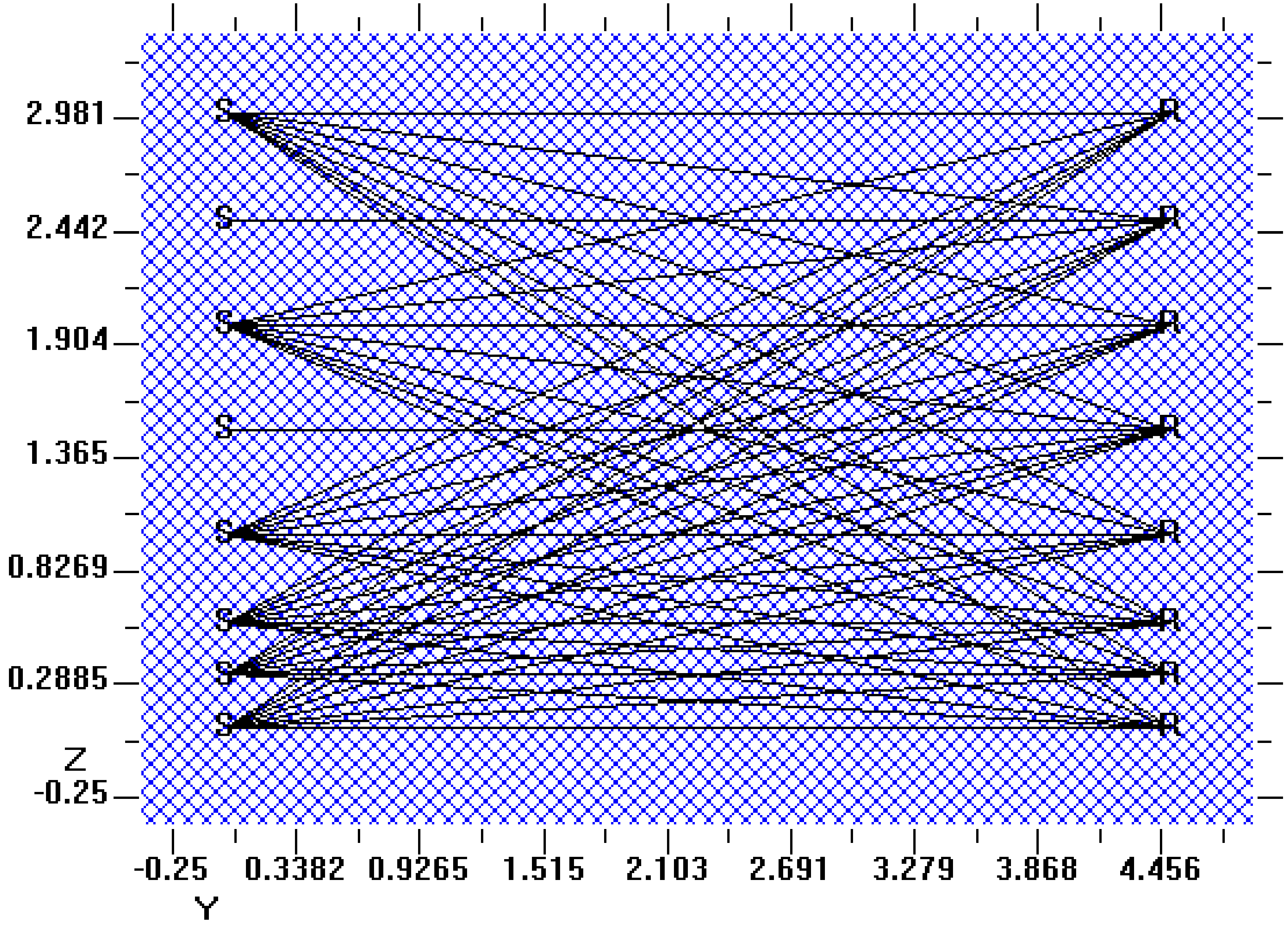
Smoothed Compressional Wave Velocity Tomogram Plot



Building Transfer Beam with Honeycomb/Void

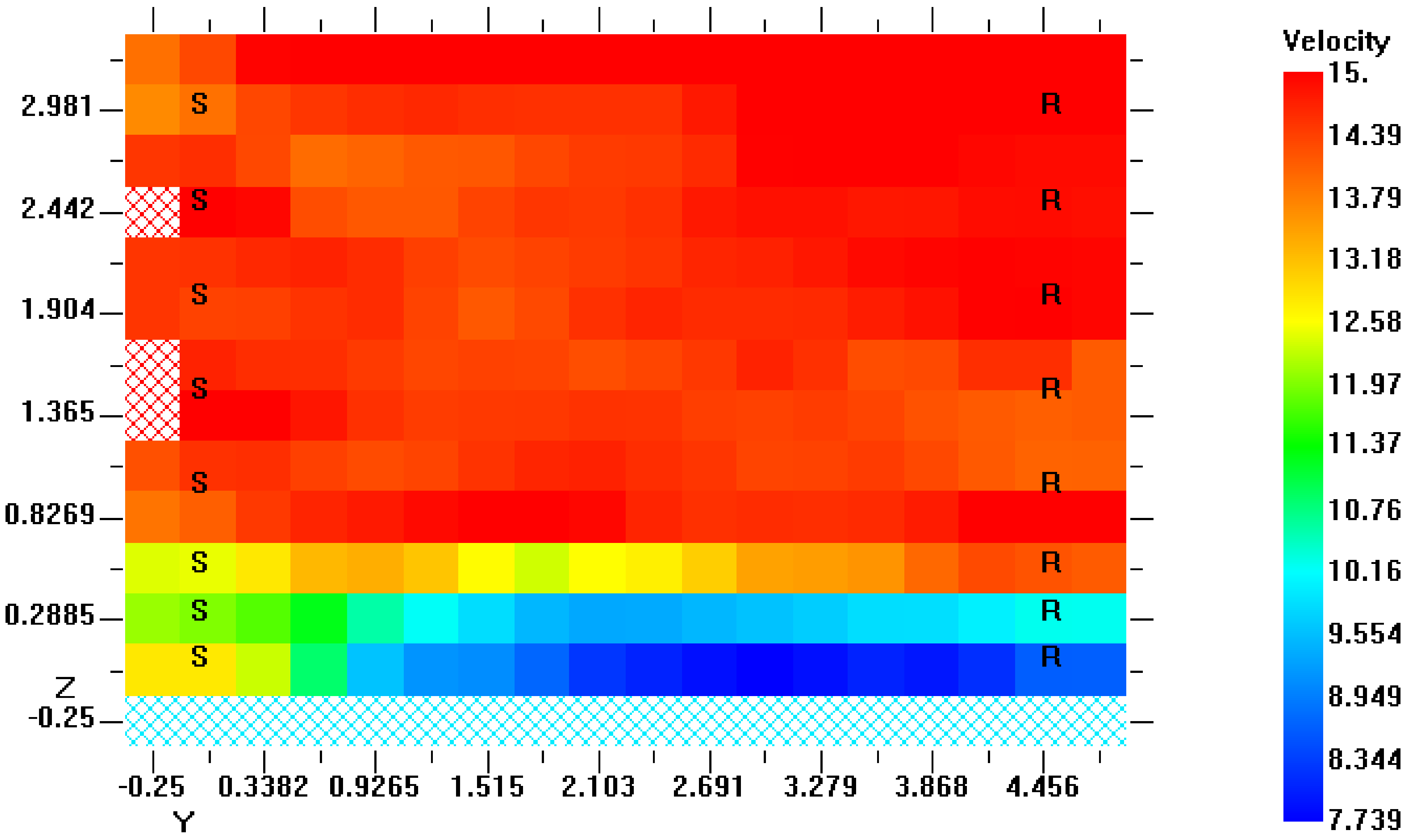
17′ 13′

Direct and Angled UPV Tests for Velocity Tomography Analyses and Direct Velocities that show honeycomb/void at beam bottom

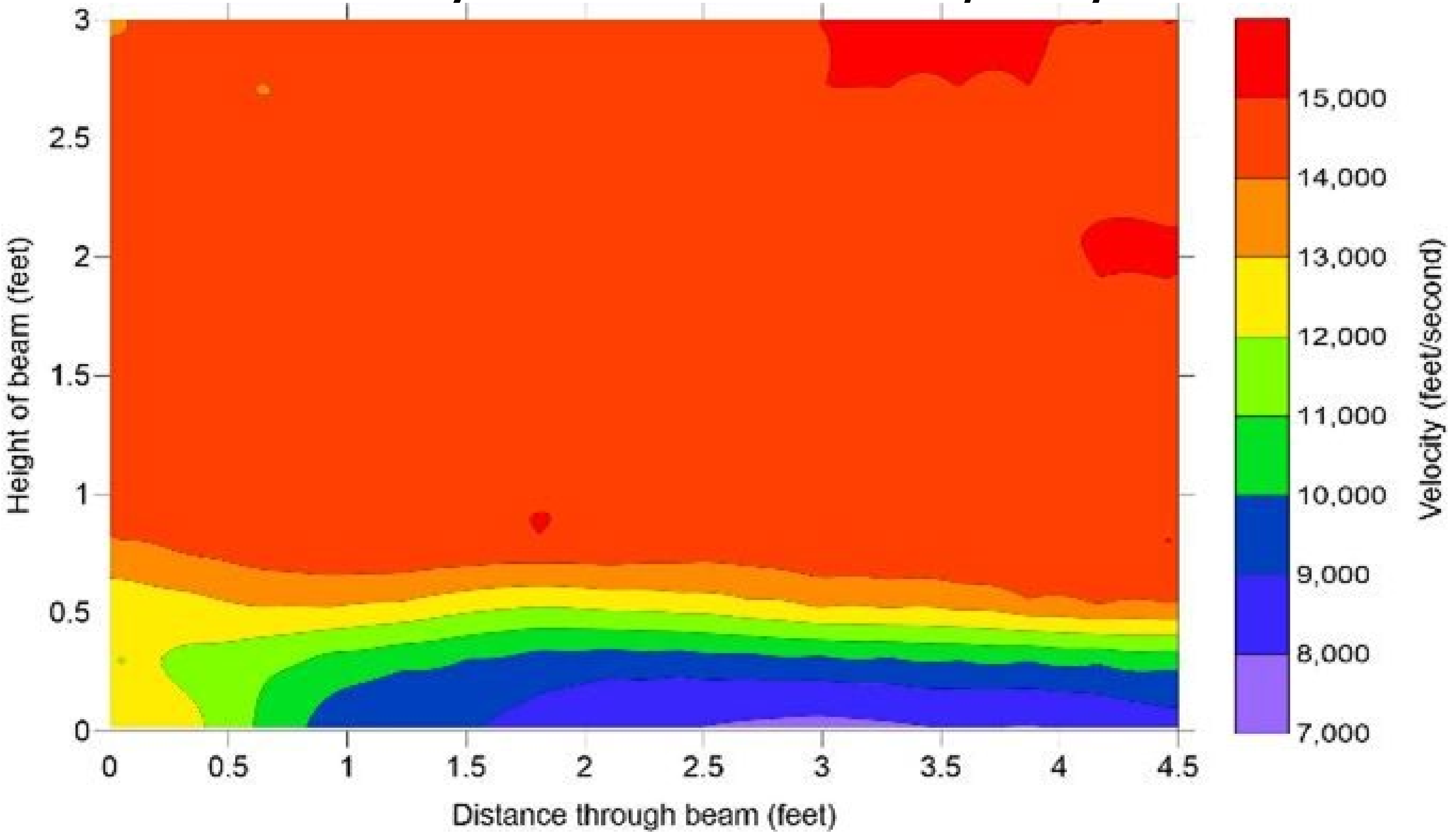


36" – 14851 ft/s
30" – 14851
24" – 14851
18" – 14563
12" – 14331
7" – 14151
4" – 8911
1" - 8364

Geotom Velocity Tomogram Analyses Results with Source (S) and Receiver (R) Locations – 27 ft Velocity x1000 ft/s



Smoothed Compressional Wave Velocity Tomogram Plot Shows Honeycomb at Bottom/Edges



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Building Transfer Beam with Honeycomb/Void

30′ 27′

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Ultrasonic Pulse Velocity Tomogram Results at Sections 11, 17 and 27 ft South of the North End of Transfer Beam

- Direct and semi-direct angled UPV tests were conducted at these three cross-sections minor to severe visible beam bottom honeycomb/void with the most severe honeycomb/void visibly apparent at Section 17
- 2-D velocity tomograms indicated that the slowest velocity conditions are generally present in the bottom 0.5 to 1 ft of the beams with higher velocities indicative of good to very good quality concrete above this very poor to poor quality concrete / slow velocity zone
- The UPV and UPV Velocity Tomograms indicated the bottom 1, 4 and 7 inches of the Transfer Beam consisted generally of very poor to poor to questionable quality concrete over most of its length with only occasional areas of good quality concrete. Very good quality concrete generally was found at heights of 12 to 18 inches above the beam bottom and for concrete zones above the visible lift line.

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

Example Photogrammetry Image of Drilled Shaft

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

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)

Digital Photogrammetry Pro's and Con's

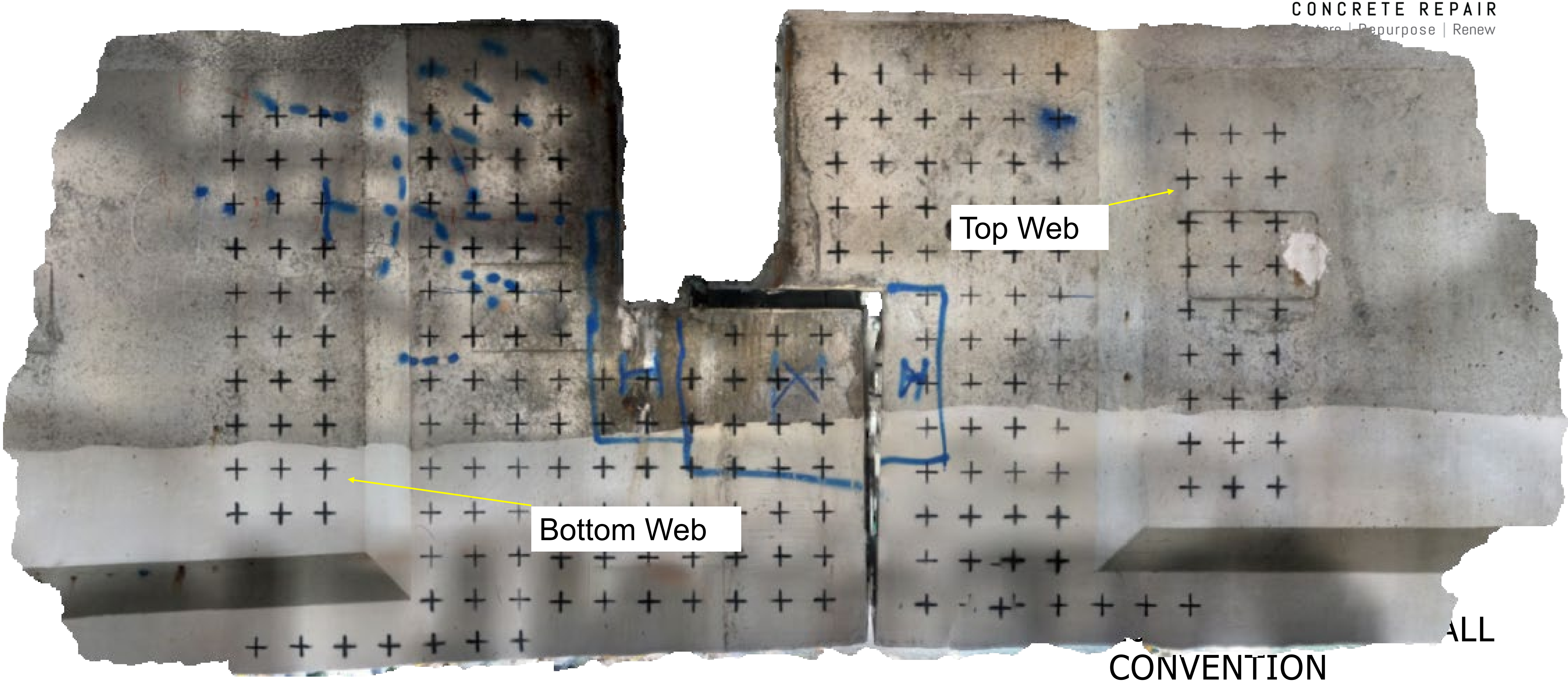
Advantages:

- 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

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



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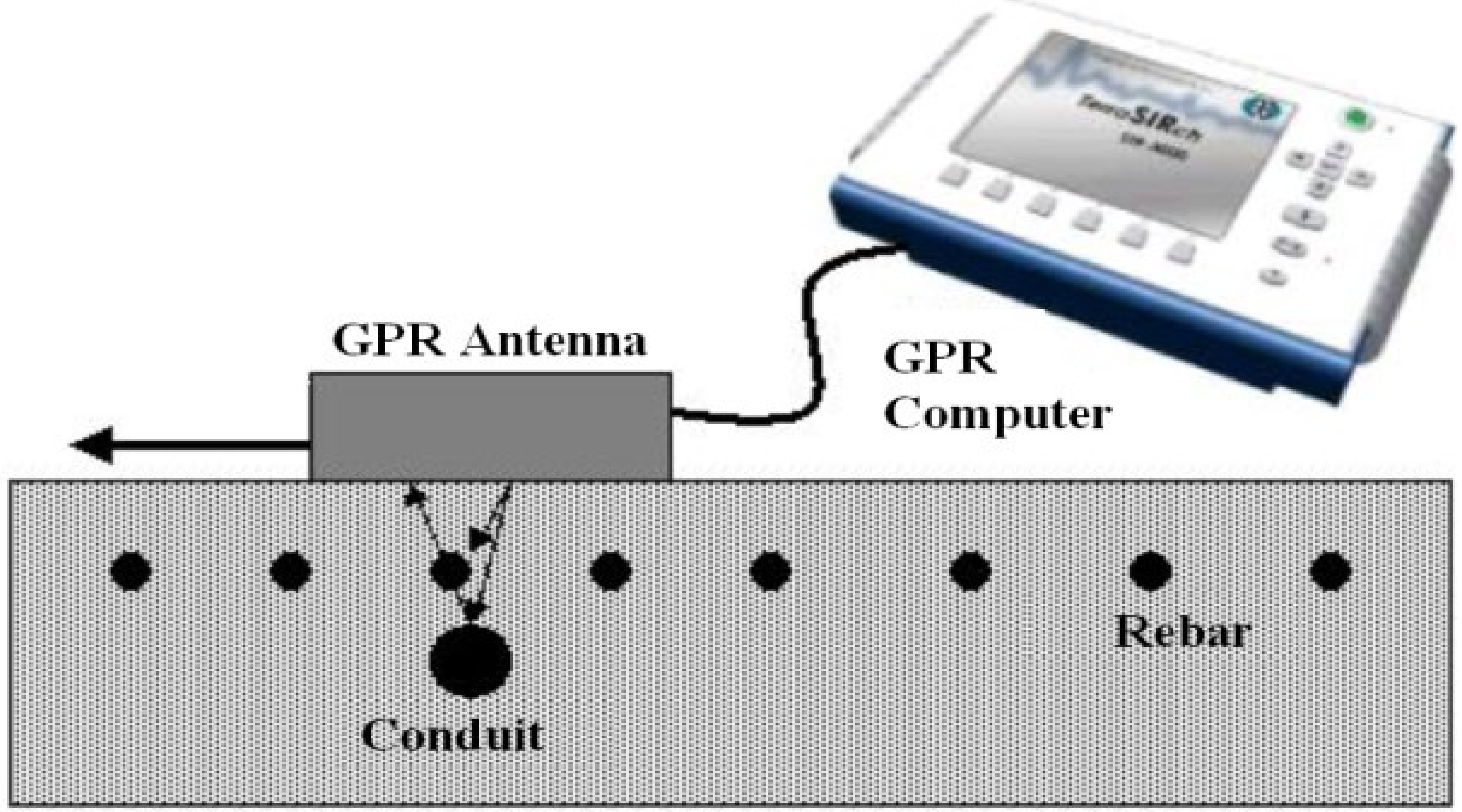
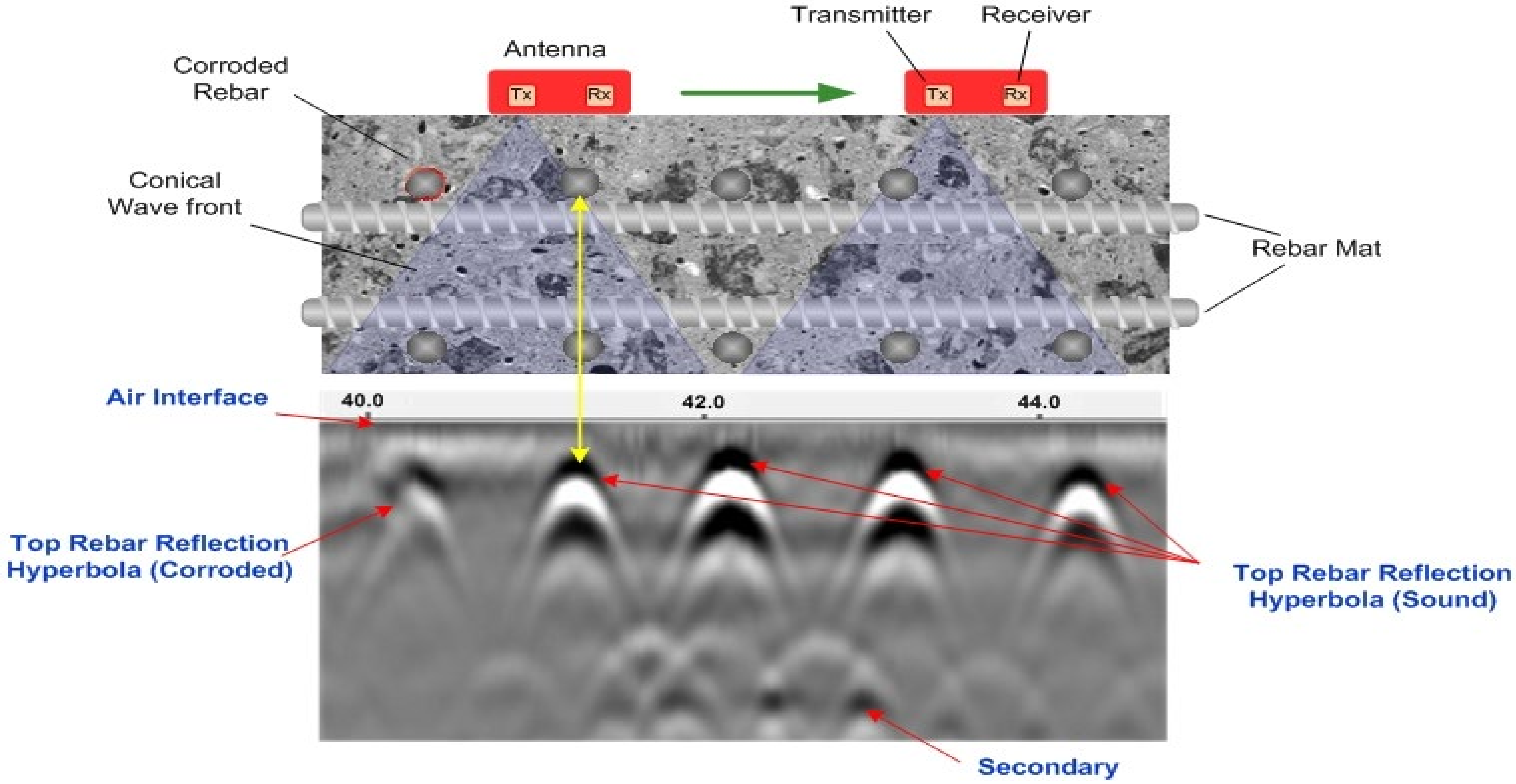
Physical Principle of GPR – ASTM D6087 - 08(2015)e1

- 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



Physical GPR Principle (continued)



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

2-D GPR Scan Data Analysis

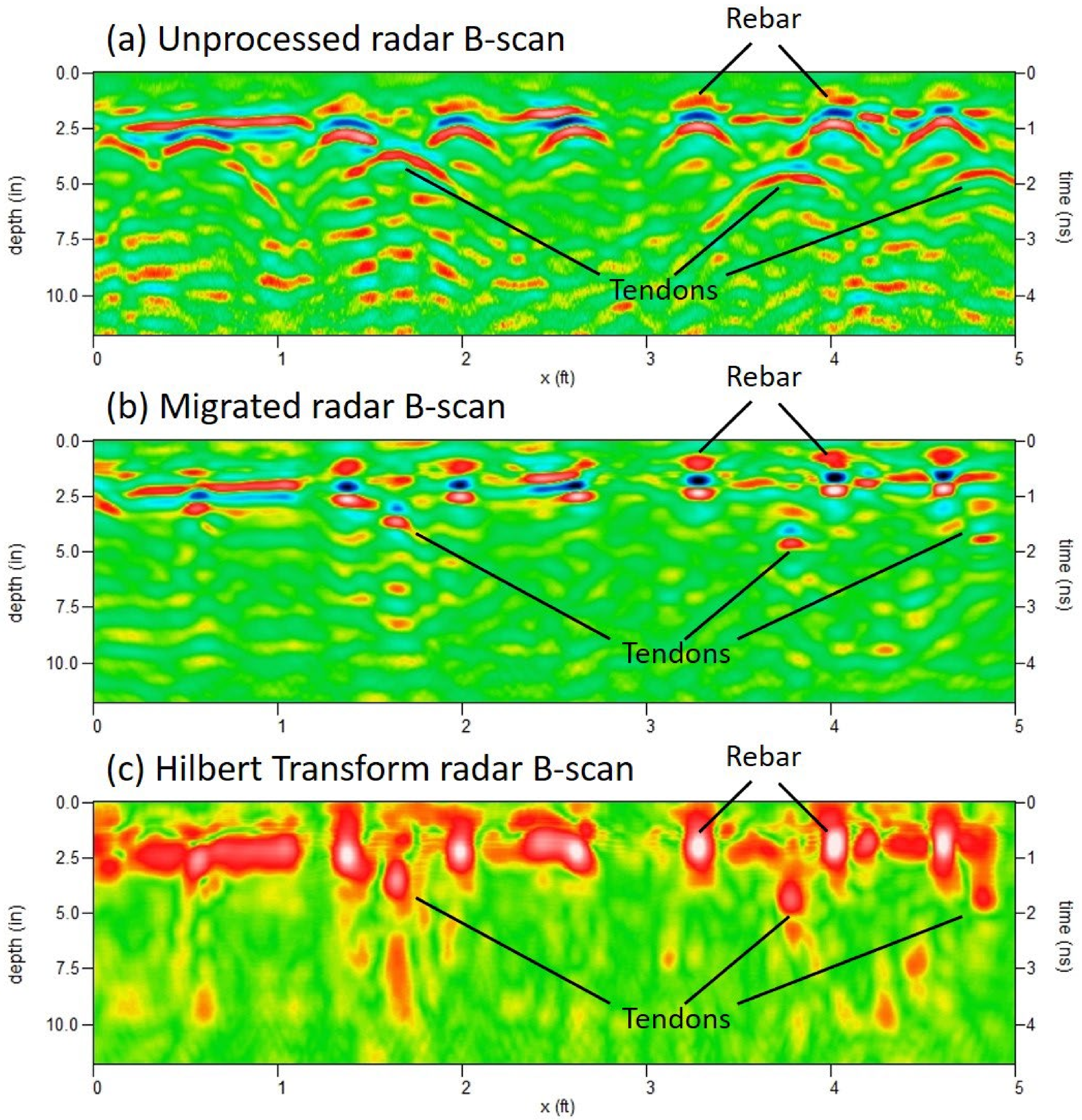
(a) the raw GPR data is shown with the hyperbola reflections from a 2D scan across the rebar and ducts;

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

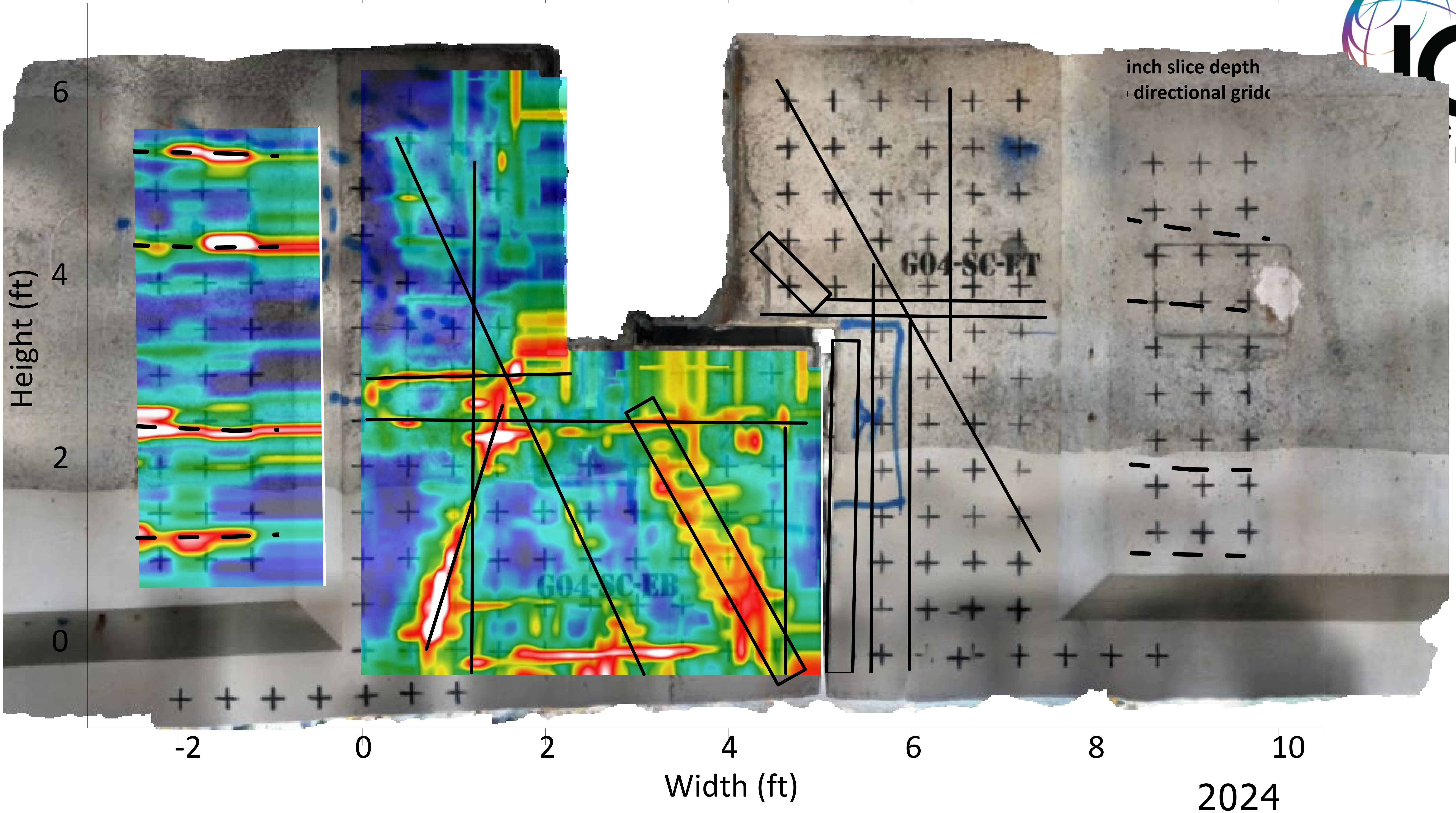
(c) the pulses are merged into a single pulse envelope via a Hilbert Transform

(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

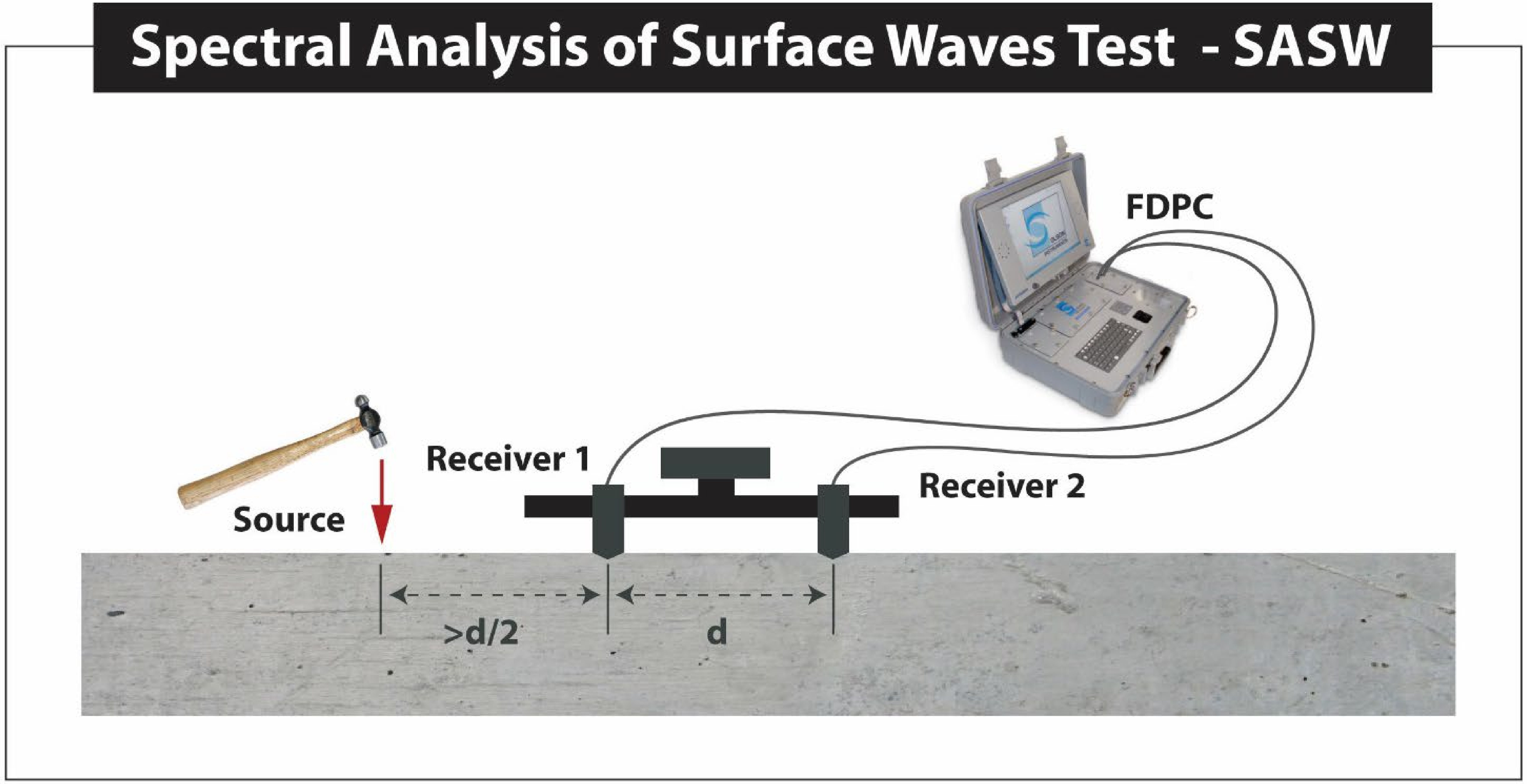


Data Fusion - 3D GPR Depth Slices for PT Ducts, Rebar and Plates



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



NDE Data Acquisition Platforms and SASW Systems

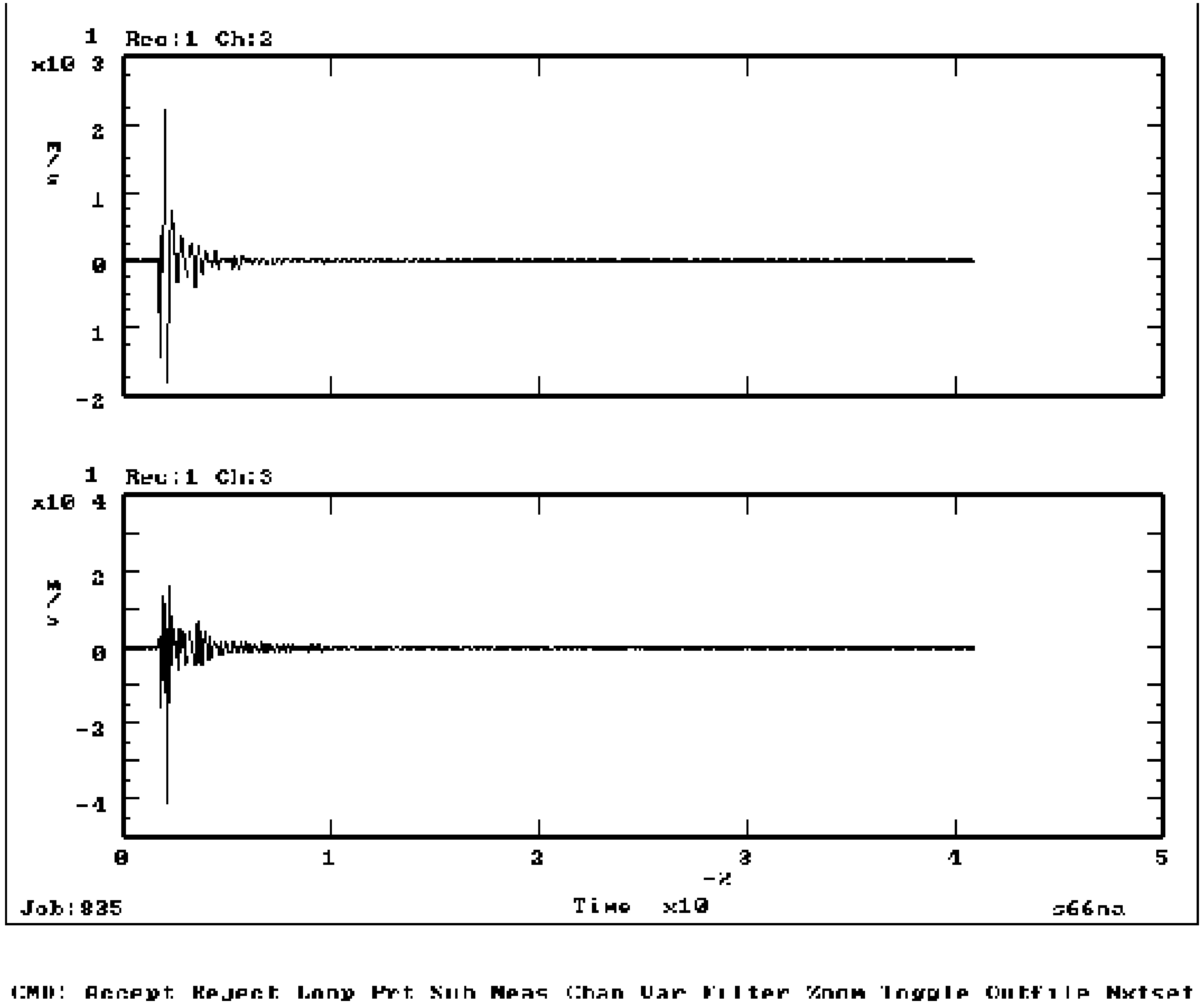
Freedom Data PC - Windows 11 - Ruggedized

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

Example Time Domain Test Results SASW

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



SASW Phase Plot from Sound Concrete Area

for 2.62ft SASW Bar spacing = 1 wavelength (–360º phase),

Velocity=frequency x wavelength= 2628 Hz x2.62 ft =6900 ft/s

Signal Coherence 1

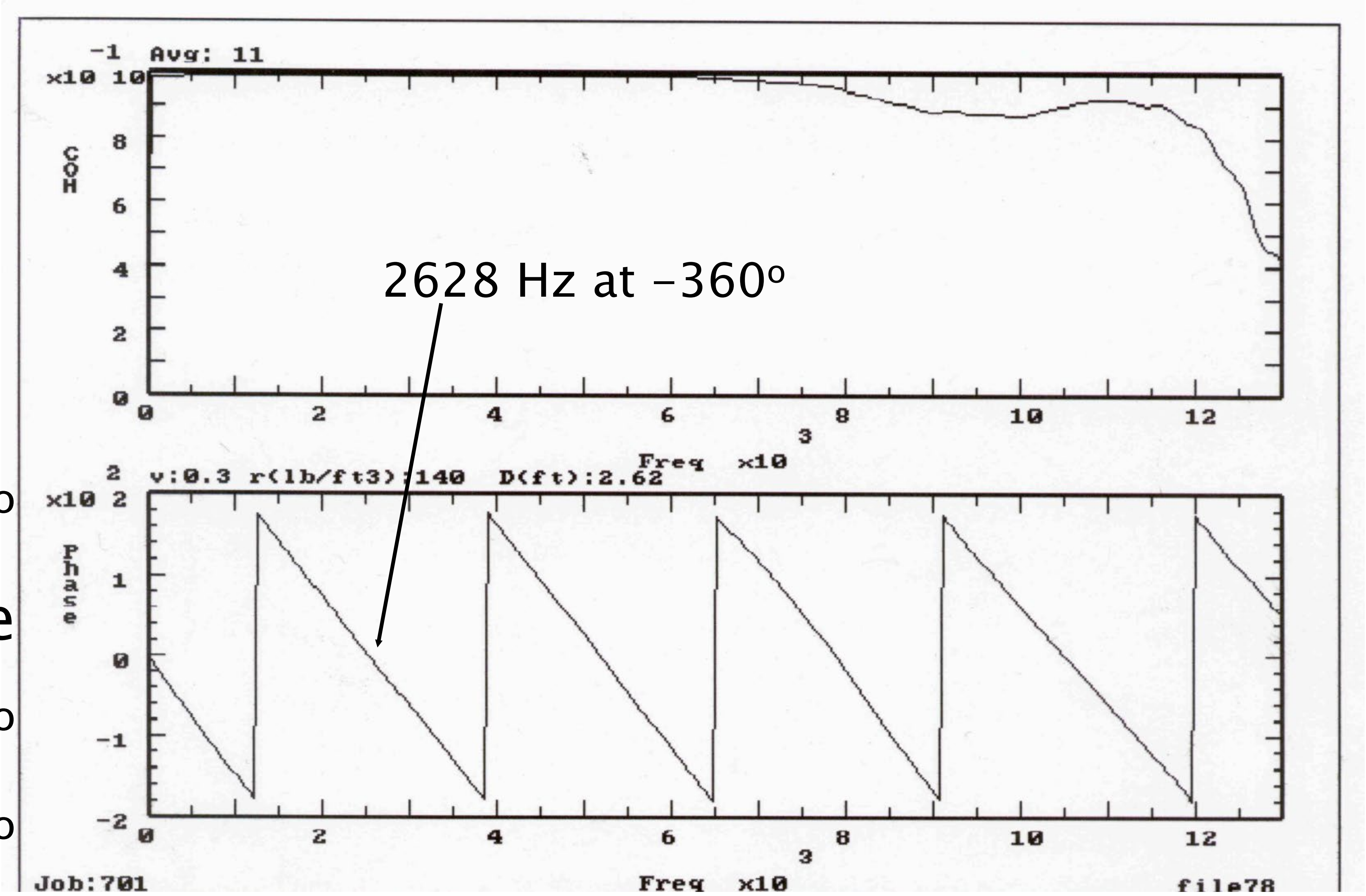
0

+180º

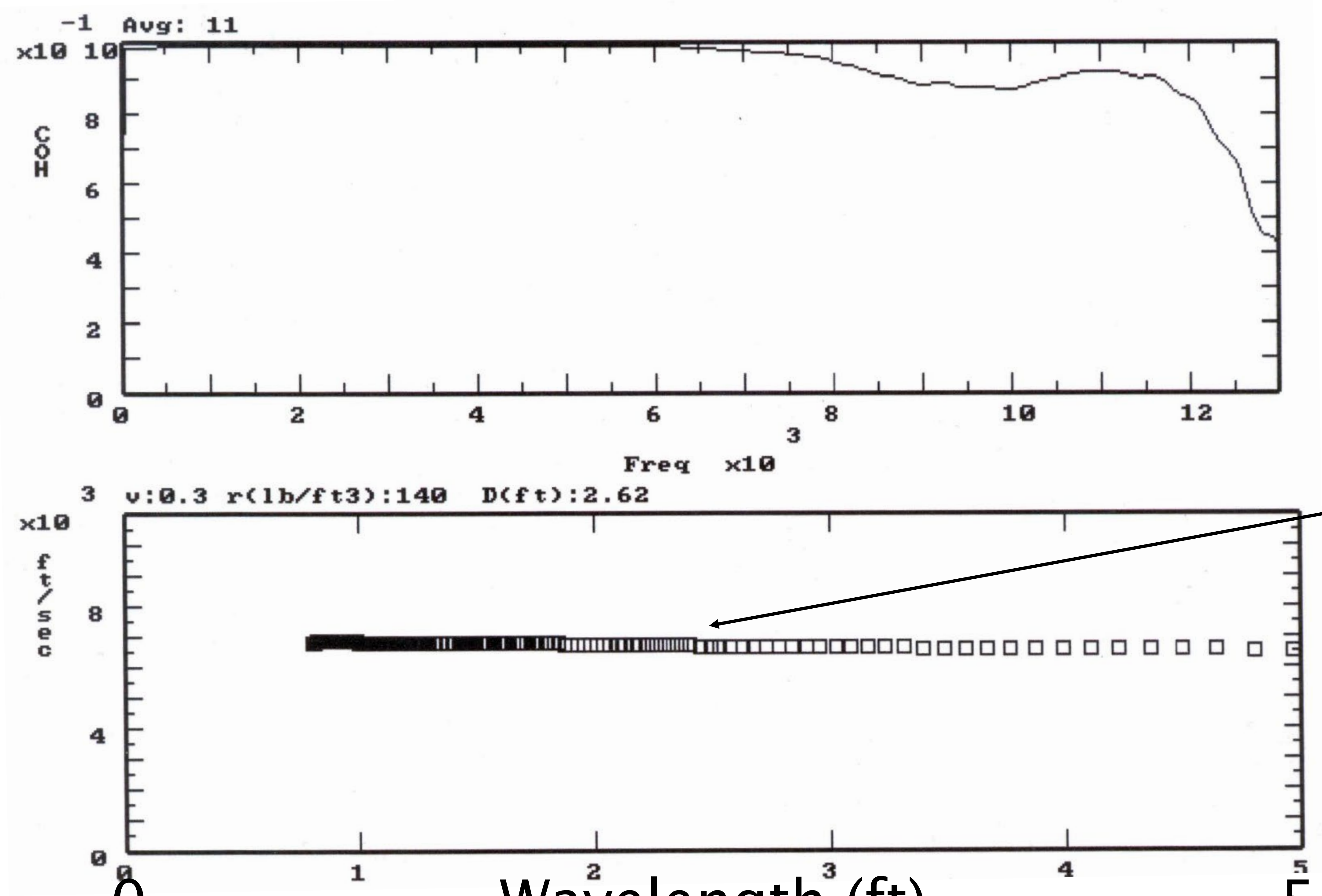
Wrapped Phase

0º

–180º



Surface (Rayleigh) Wave Velocity vs. Wavelength (~depth)



1.0

Signal Coherence

0

8,000

Surface Wave Velocity (ft/s)

0

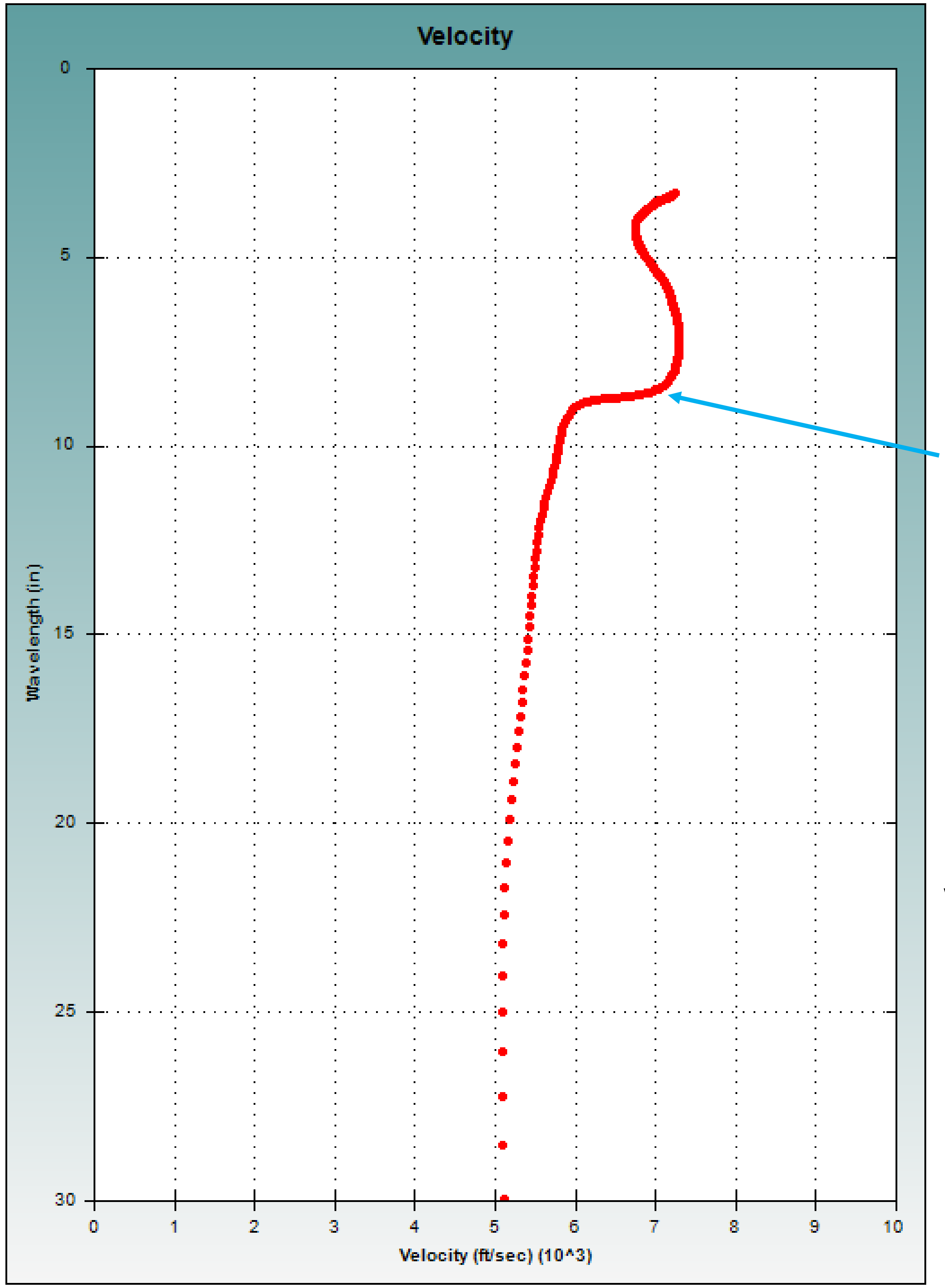
0 Wavelength (ft) 5

V_R =6900 ft/s Surface Wave Velocity for Sound Concrete

Spectral Analysis of Surface Waves (SASW) testing across crack for its depth

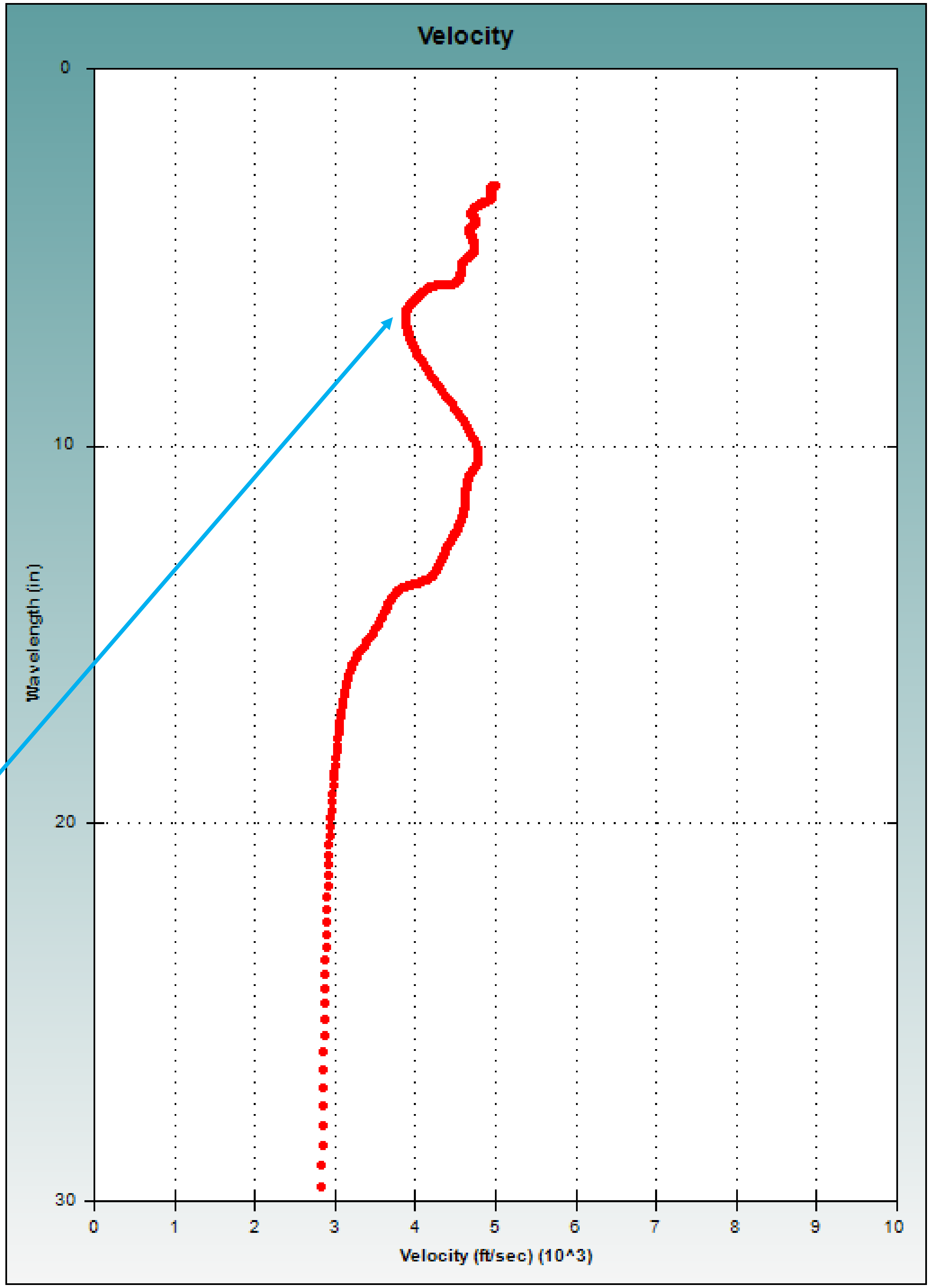
Note: SASW bar with two displacement transducers spaced 1.31 ft apart with a 2-oz metal ball-peen hammer impactor for in-line impacts

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



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

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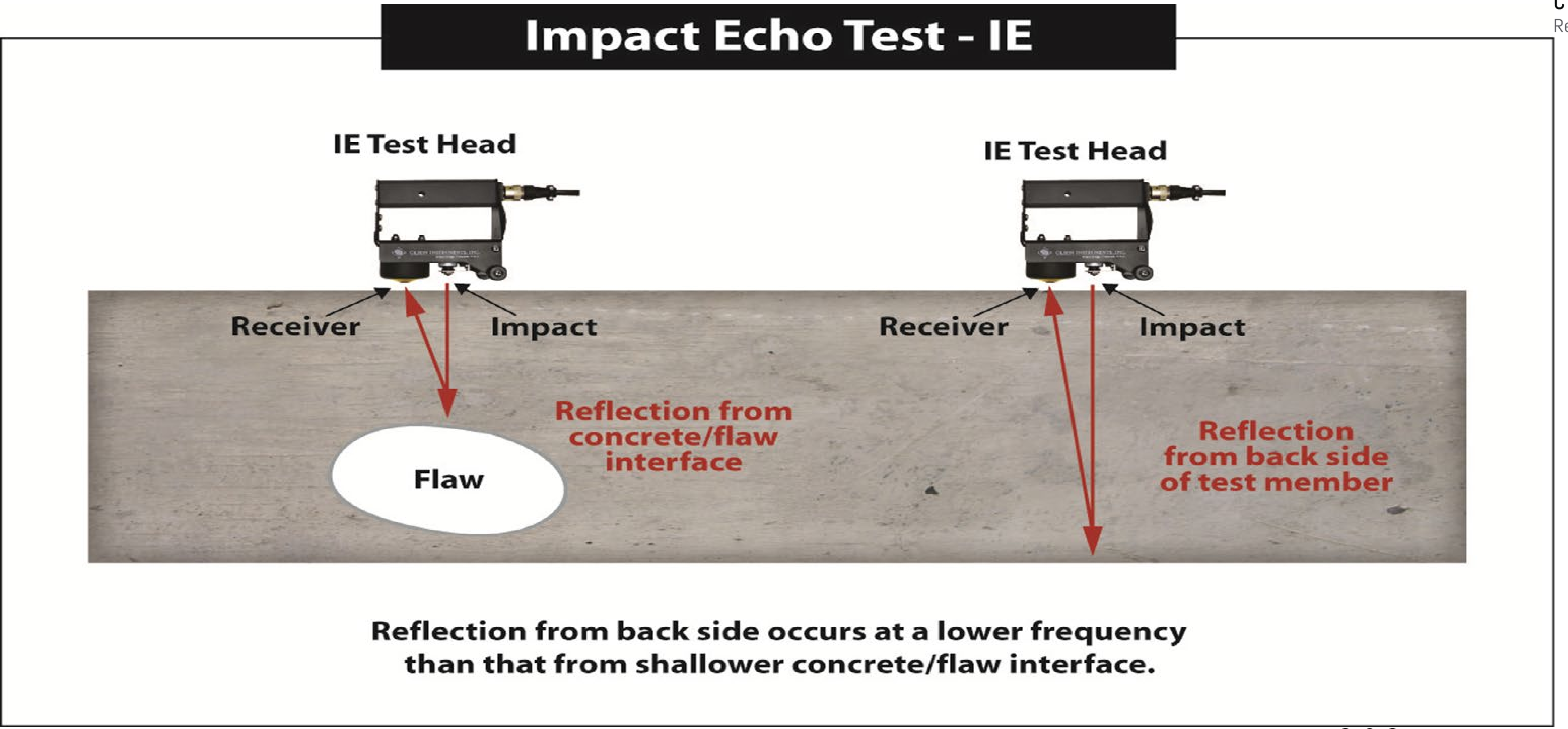
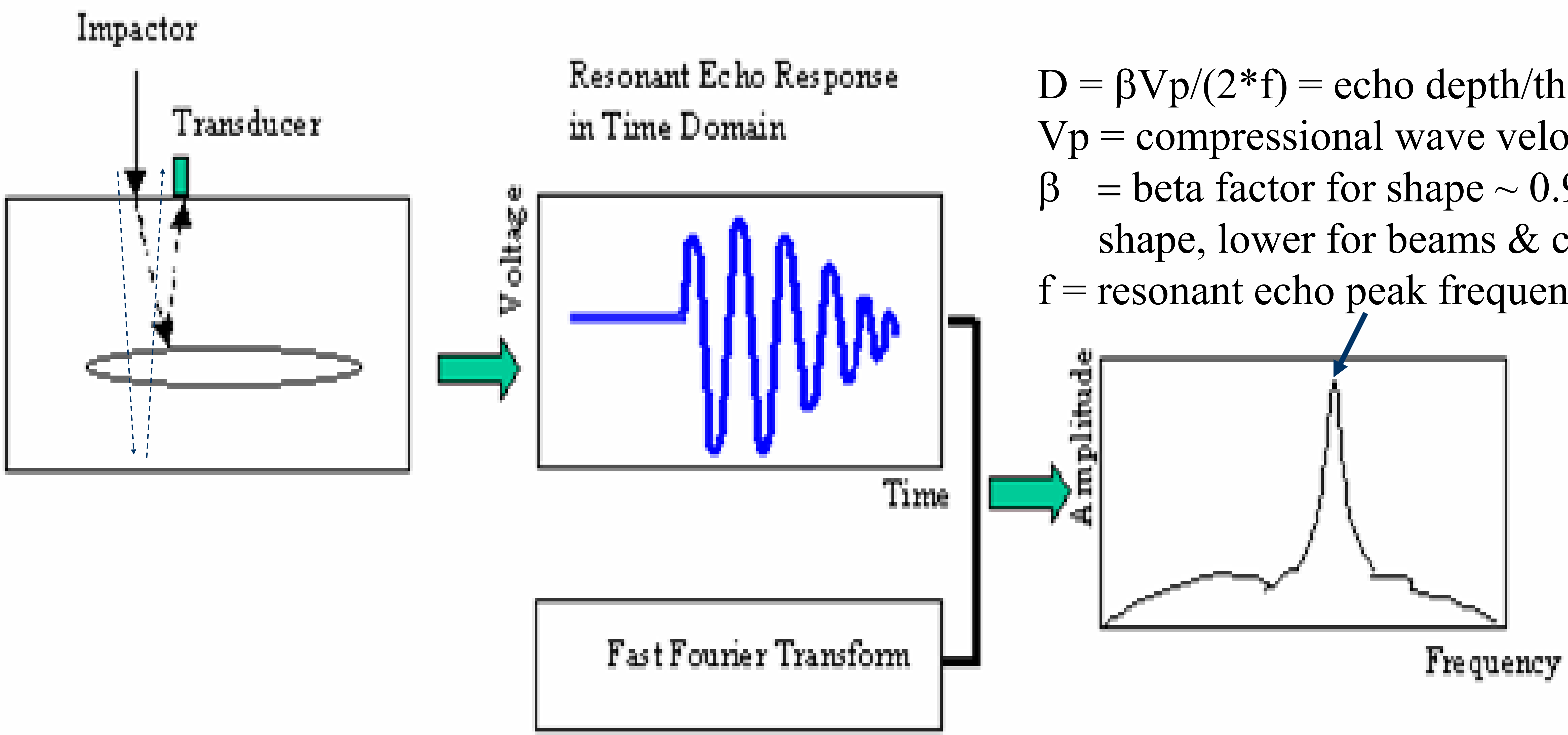
Sunshine Skyway Bridge in Tampa, FL

(Courtesy of Florida Department of Transportation)

Impact Echo Method (ASTM C1383-15(22)) Point-by-Point

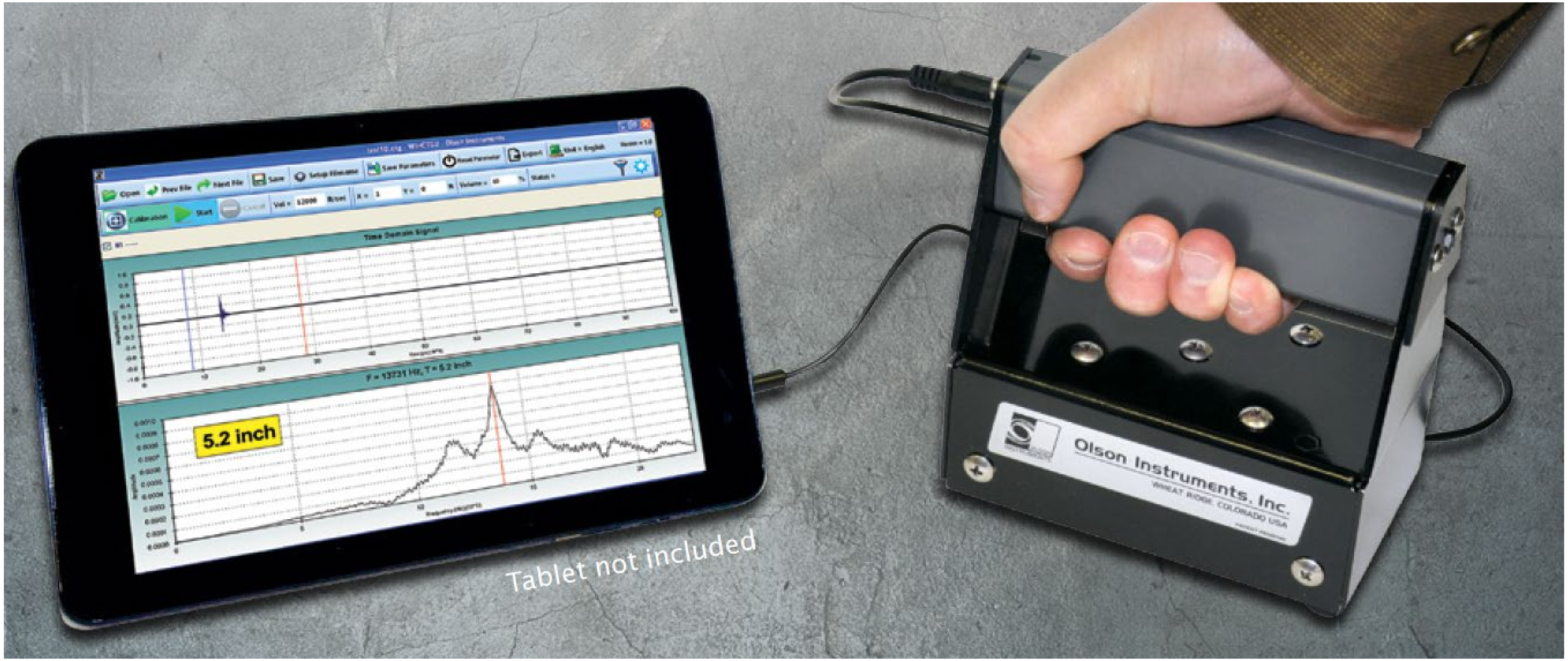


Impact Echo Data Analysis



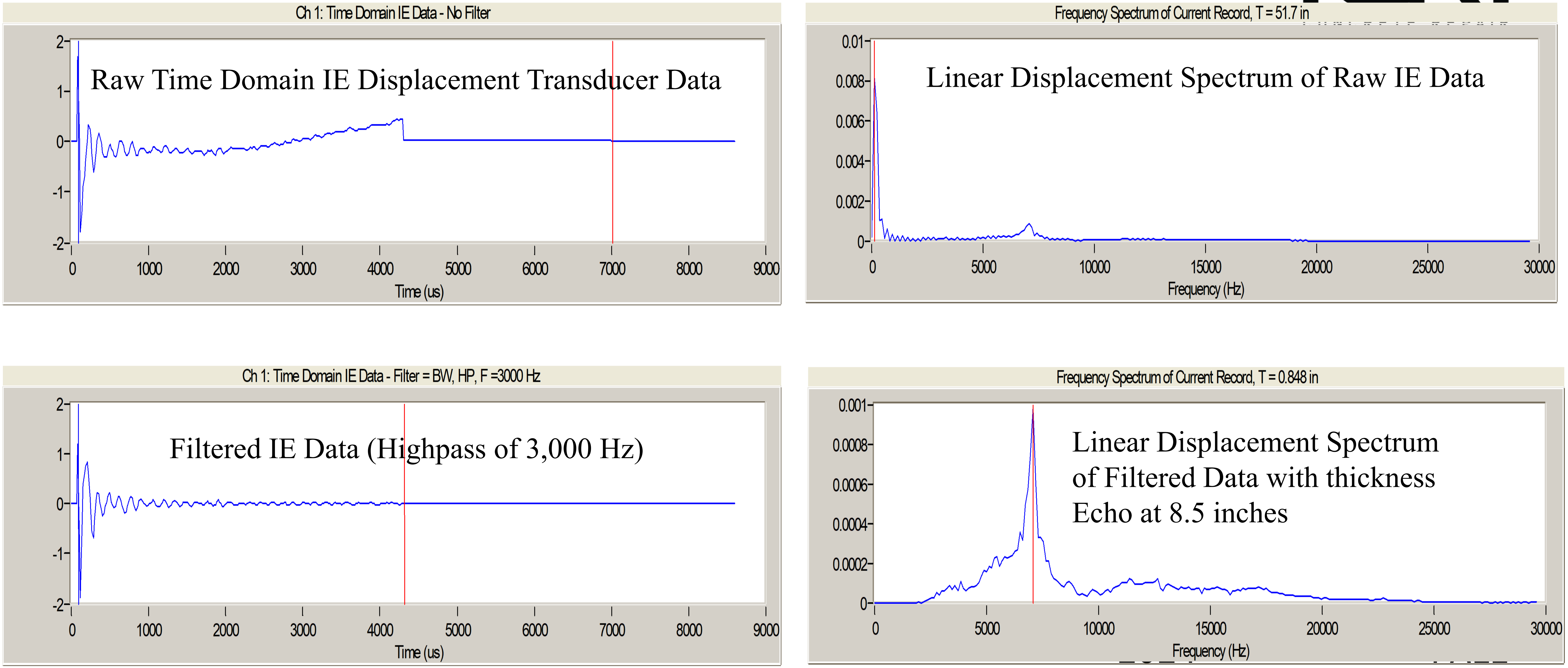
D = βVp/(2*f) = echo depth/thickness
Vp = compressional wave velocity
β = beta factor for shape ~ 0.96 for slab shape, lower for beams & columns
f = resonant echo peak frequency (Hz)

Impact Echo Gauge for 1 Sided Concrete Thickness & Flaws such as Cracks, Void, Honeycomb



Concrete Thickness Gauge (CTG-2)

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



Impact Echo Scanner (IES) Features

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- Rolling displacement transducer/ solenoid impactor scanner system that covers more testing area in less time with a test every inch vs. point-by-point testing

- Generate 2-D and 3-D plots of Impact Echo results

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Test Girder for Bridge Research

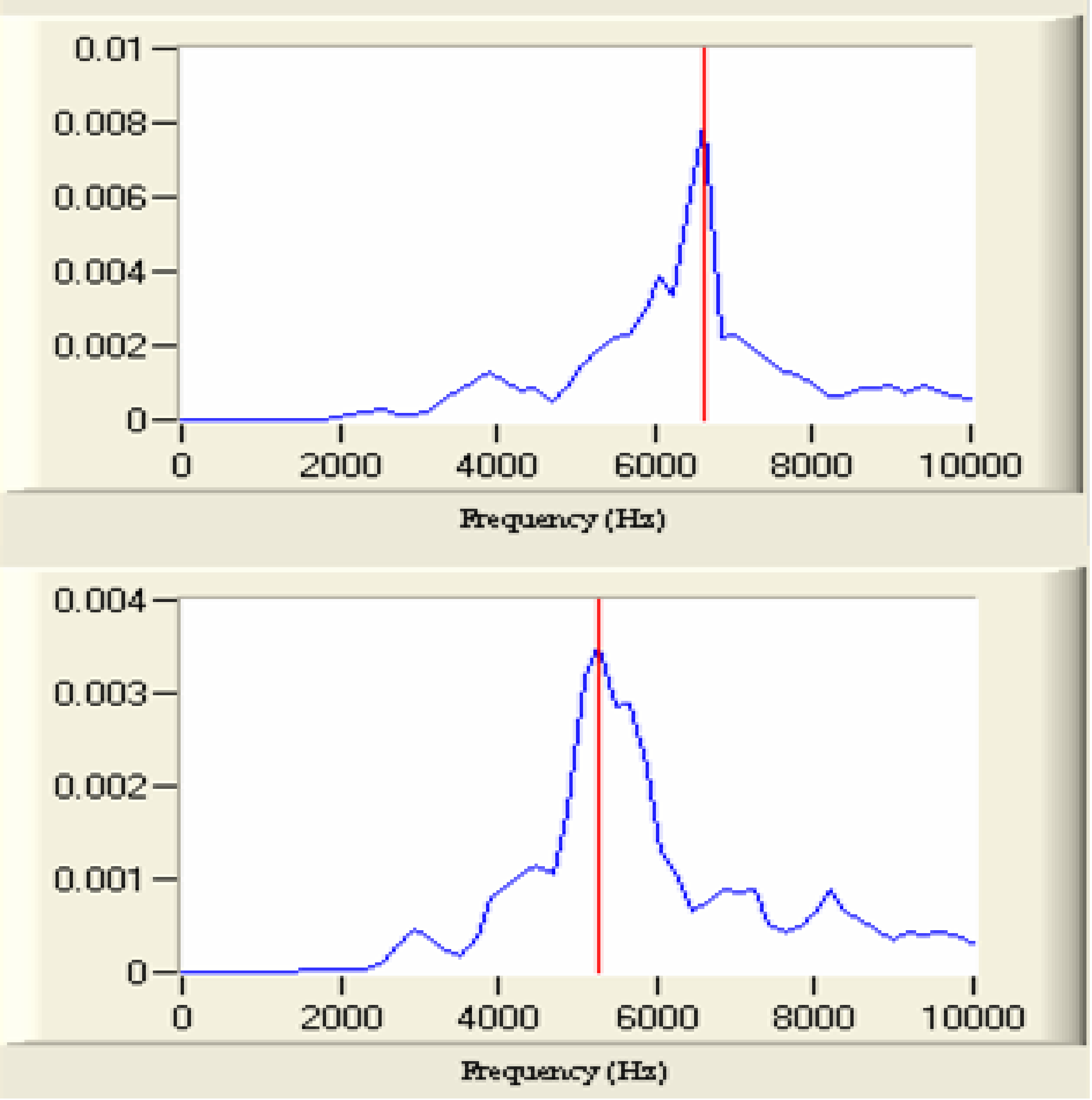
NCHRP IDEA Research Contract No. 102

- 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)

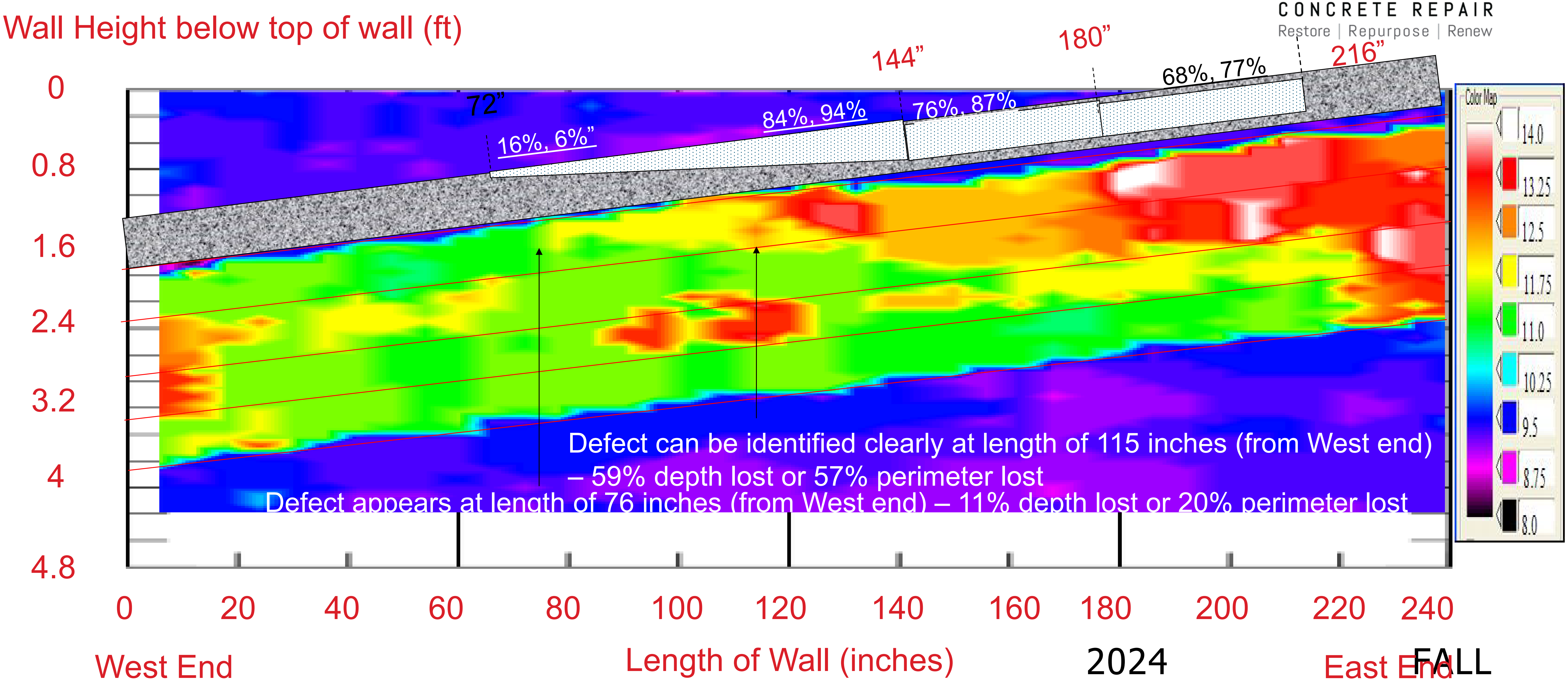
Grout Defect Simulation with Styrofoam Voids

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

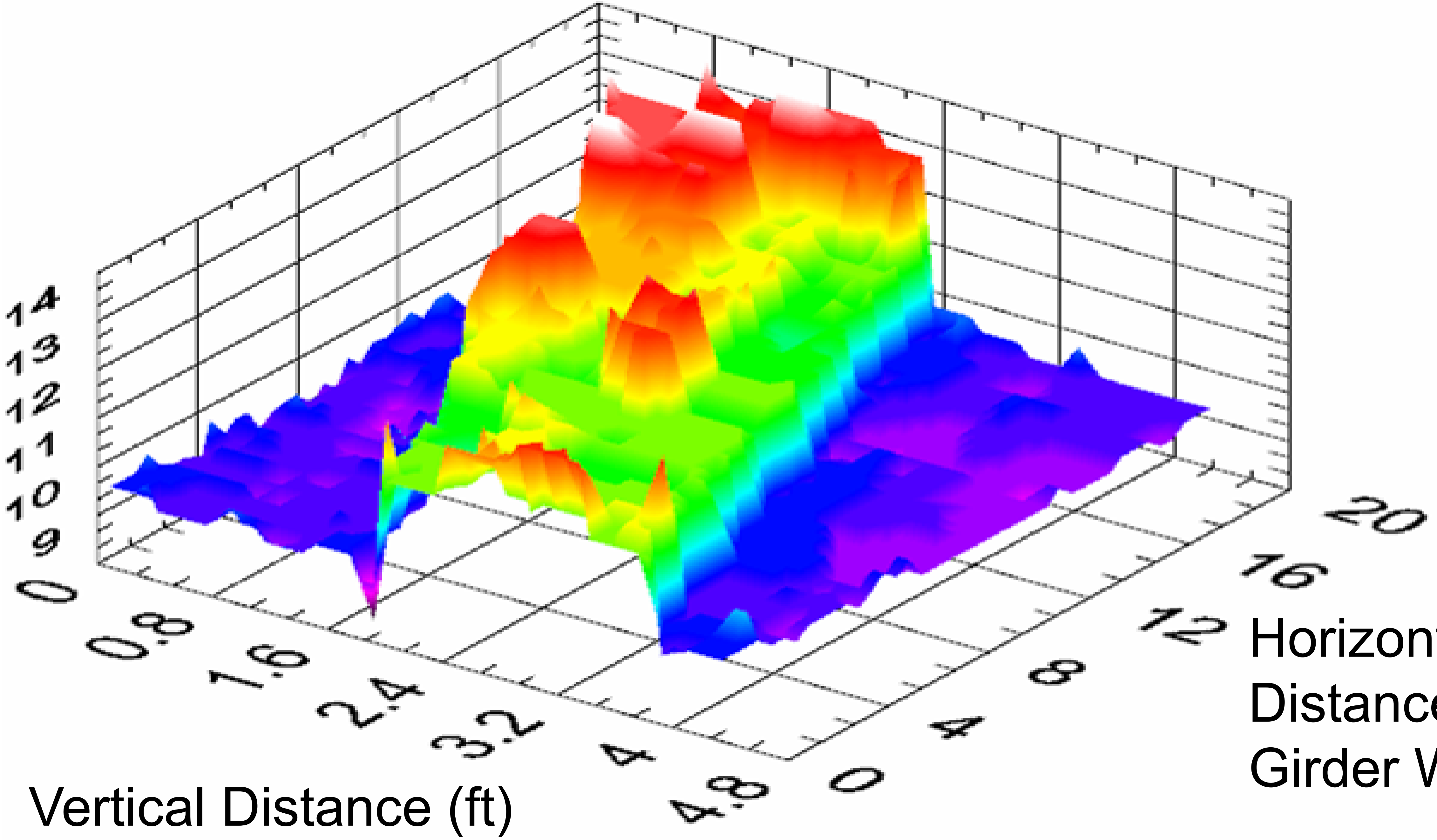


IE Surface Thickness Results



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

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



IES Thickness Echo (inches)

Vertical Distance (ft) down Girder Web Wall

Horizontal Distance (ft) from Girder West End

Vertical Impact Echo Scanning (IES) on 6 inch lines on Bridge Girder

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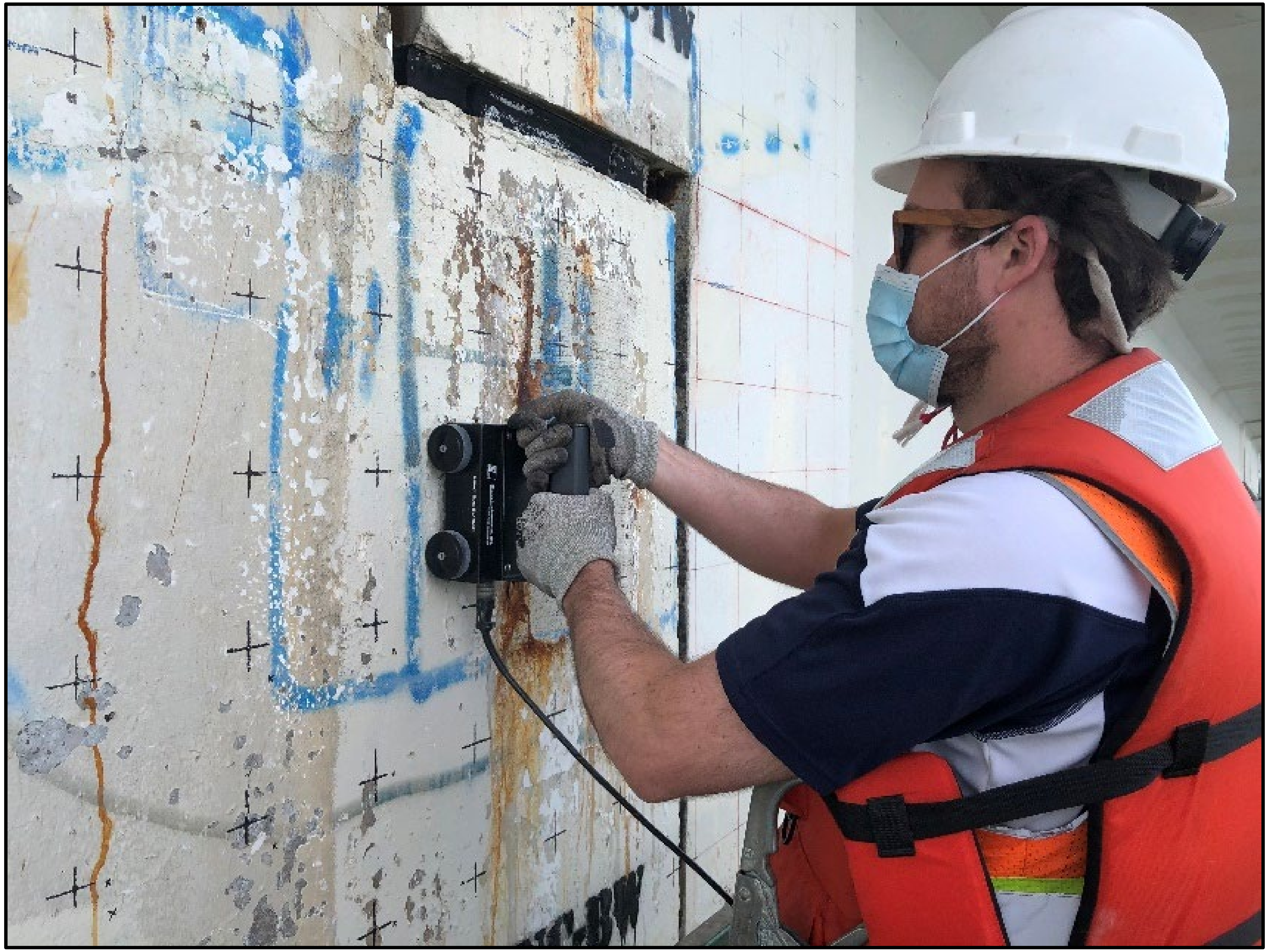
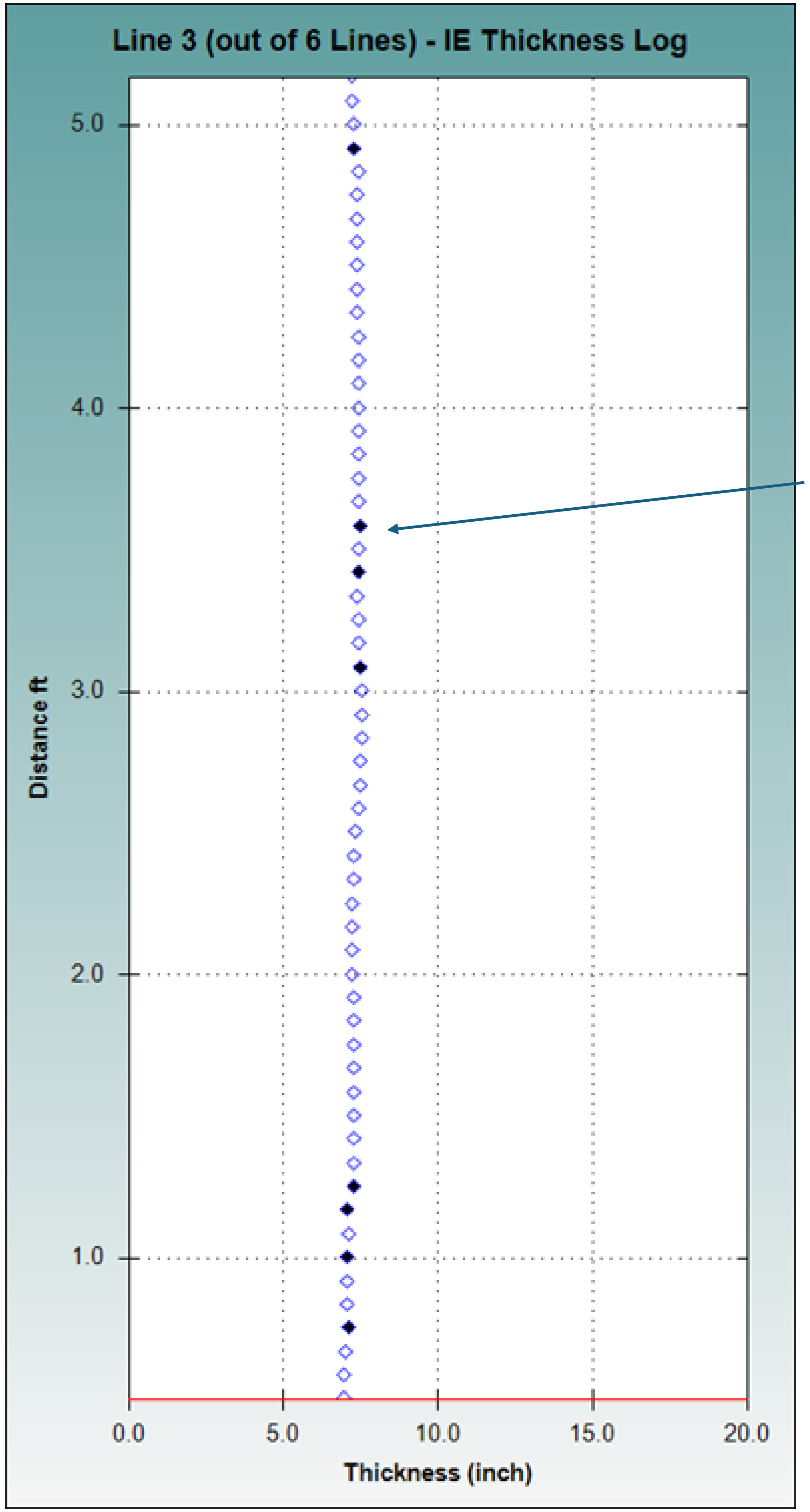
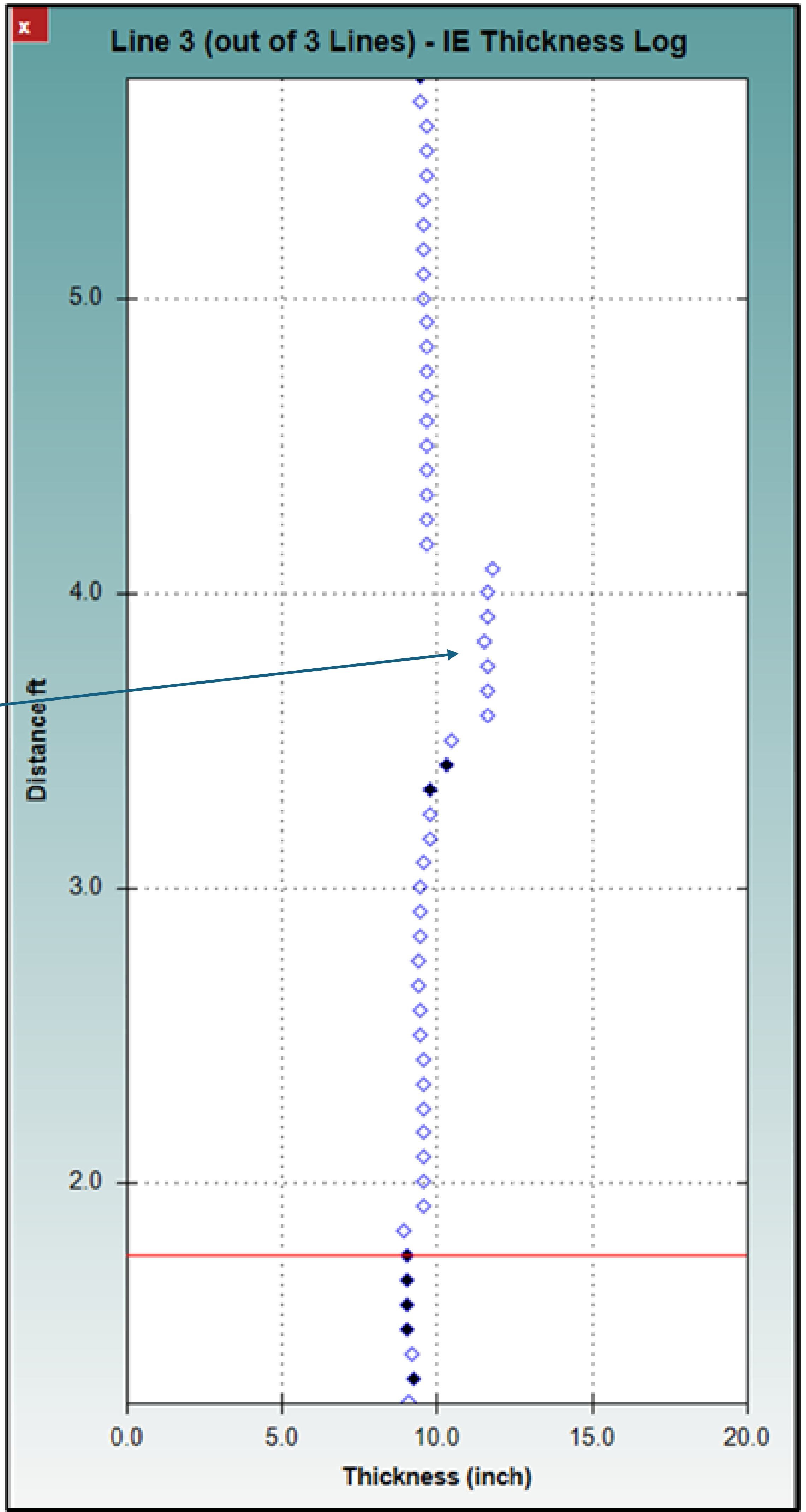




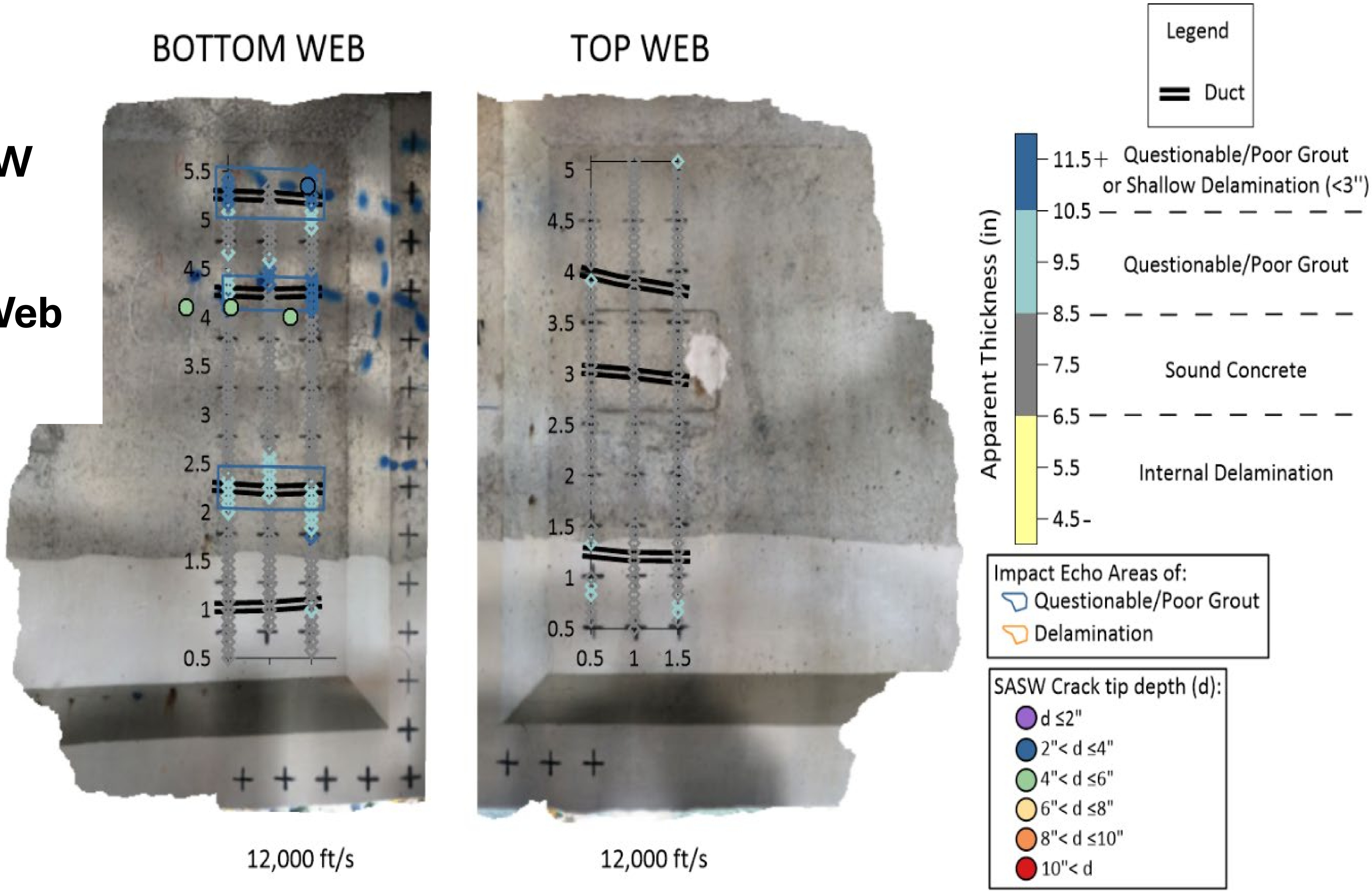
IES Results – Grouted vs. Voided Ducts in Girder Webs

Web IES "Sound" scan (Left), with well-grouted ducts ~7.5 inch echo thicknesses

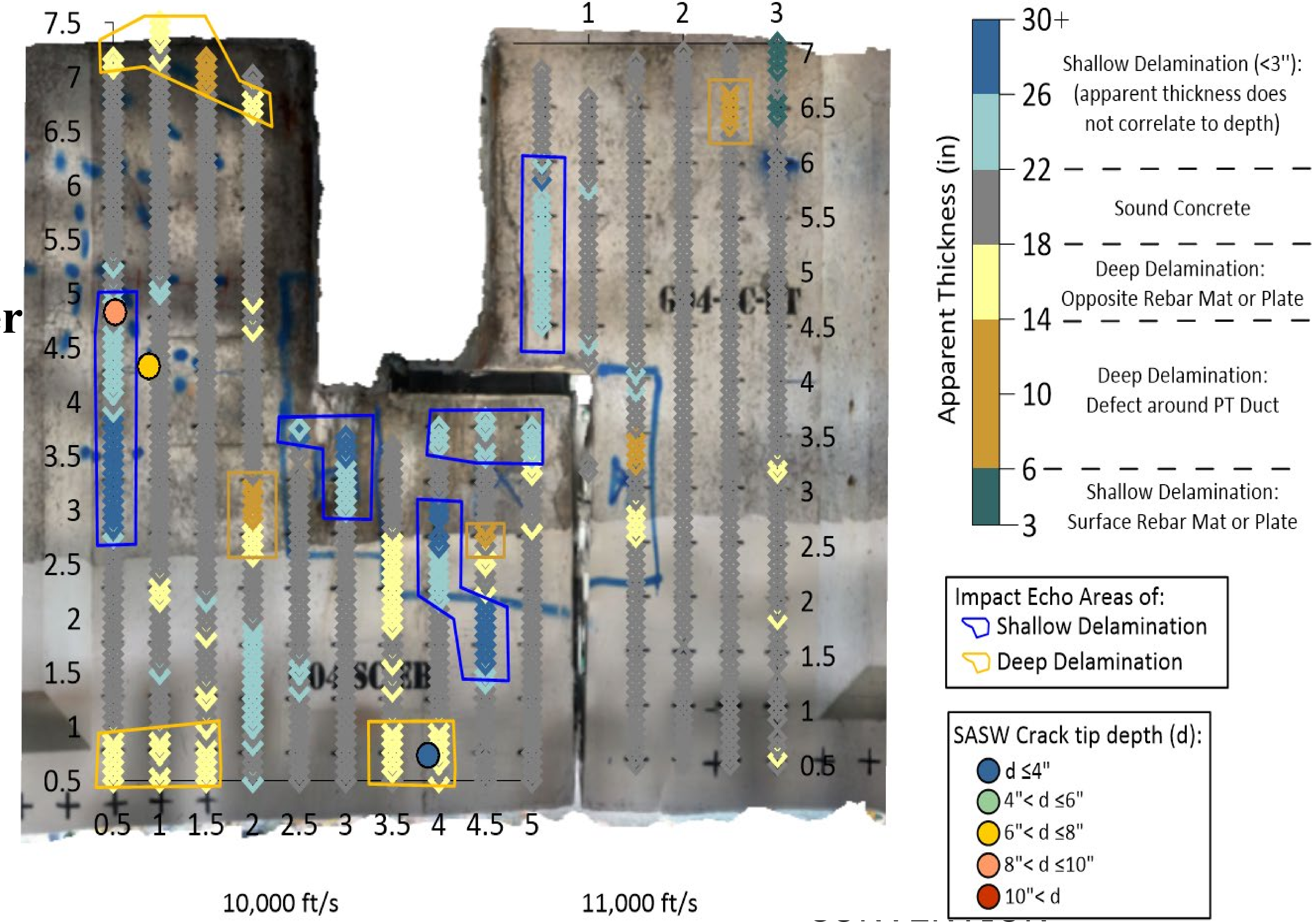
"Poor/Void" duct grouting conditions scan (Right) at a distance between 3.5 to 4.2 ft as marked by the increase in echo thickness from 8 to 9 inches to 12 inches



Data Fusion of Impact Echo Scanning, SASW and GPR Duct Grouting and Locations for Web Walls



Data Fusion of Impact Echo Scanning, SASW and GPR Duct Grouting and Locations for Girder End Walls



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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**

NDE Methods used in research to detect concrete defects behind ½ inch steel plate in a 6x6x1 ft (1.8x1.8x0.3 m) Concrete Wall #1 and Robotic Scanning

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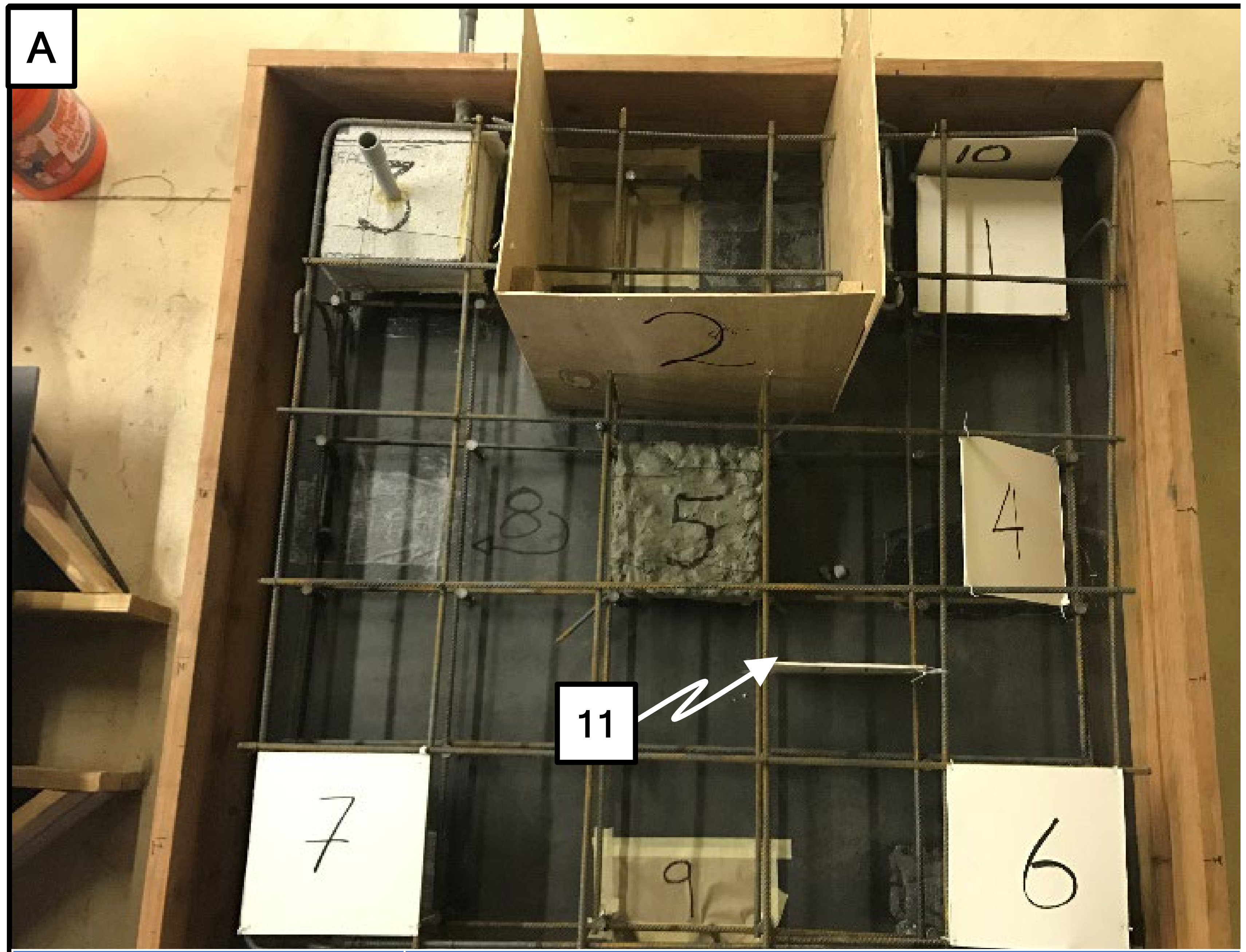
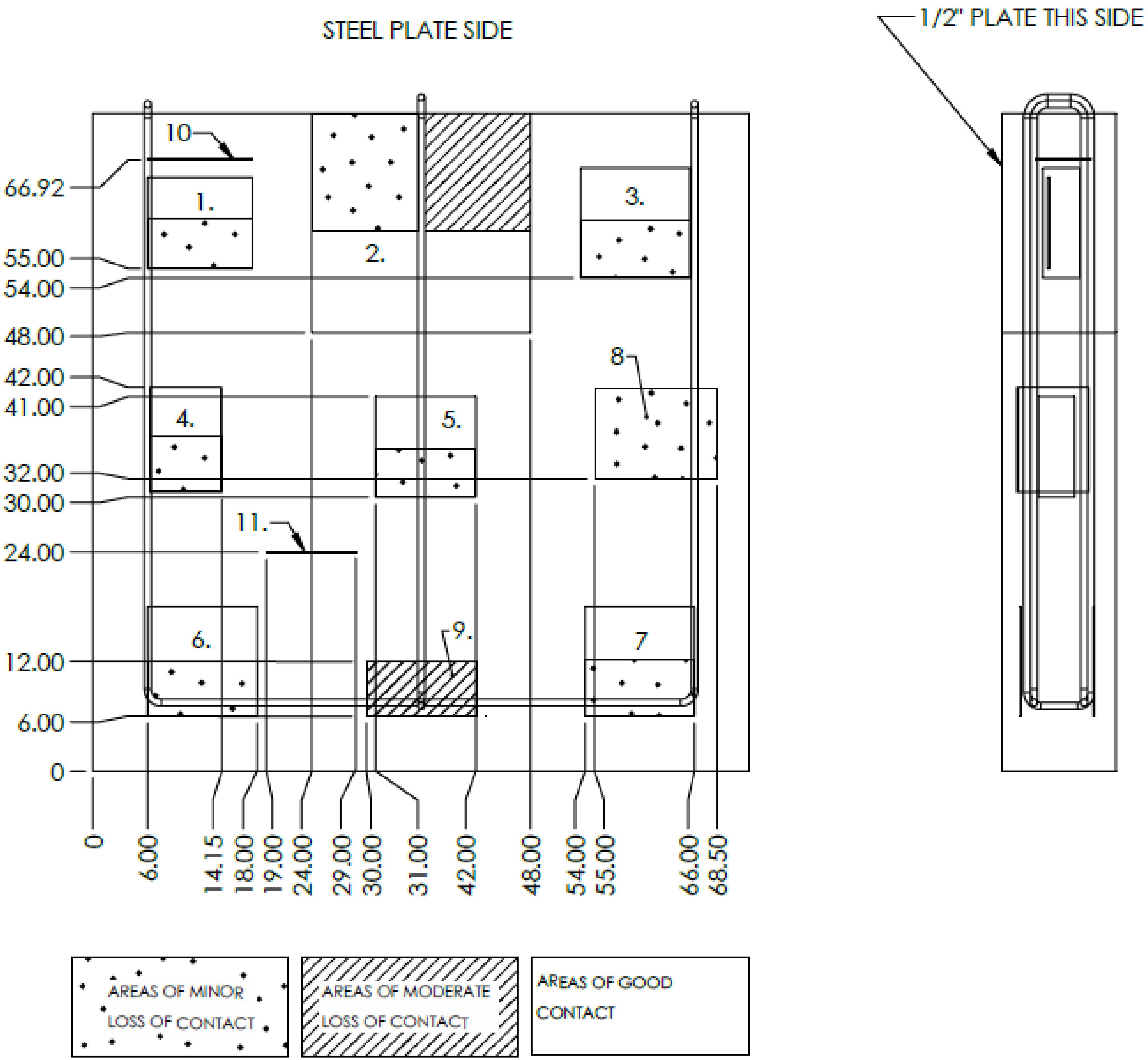
- **Impact Echo Scanning (IES) -** cracking, corrosion delamination damage, honeycomb, thickness, voided vs. grouted post-tensioning ducts - ASTM C1383-15(2022)
- **Spectral Analyses of Surface Waves (SASW) –** cracking extent, perpendicular crack depths, void/honeycomb and velocity/modulus - ACI PRC-228.2-13
- **Slab Impulse Response (SIR)** – detection of debonding of steel plate/concrete interface and overall structural integrity evaluation - ASTM C1740-16 (not discussed herein)

Research Sponsored by CANDU Owners Group for QA of Concrete Placement in Steel Plated Containers for Spent Fuel Rods of Nuclear Power Reactors

Wall #1 steel plate/concrete defects



Constructed Flaw Number	Flaw name/type
1	4 mm vertical crack
2	Weak concrete
3	Air/Water void
4	4 mm crack
5	4 in thick honeycomb
6	corrosion delamination
7	corrosion delamination
8	Minor loss of contact/debonding over sound concrete
9	Moderate loss of contact/debonding over sound concrete
10	4 mm horizontal crack horizontal plane
11	4 mm horizontal crack angled in vertical plane



Government Experience:
USAF Missile Silo

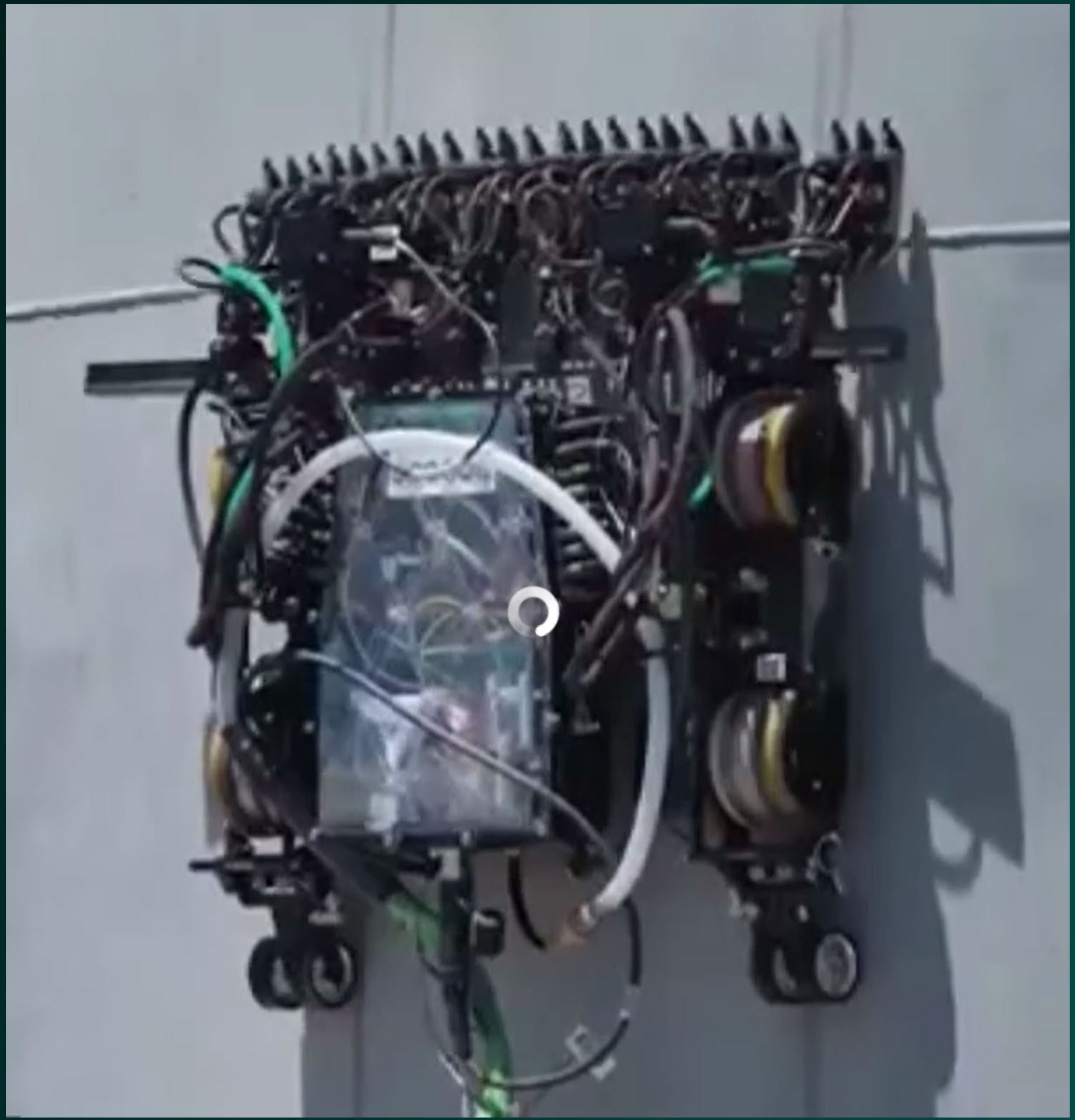
Dual-Focused Assessments: Inspecting Steel Liners & Evaluating Concrete Through Them

Gecko Monarch Robot with Olson **Impact Echo + Surface Waves Scanning for Concrete** Integrity and Flaws behind ½ inch (12.5 mm) steel plate of Wall #1 with 2 inch scan lines

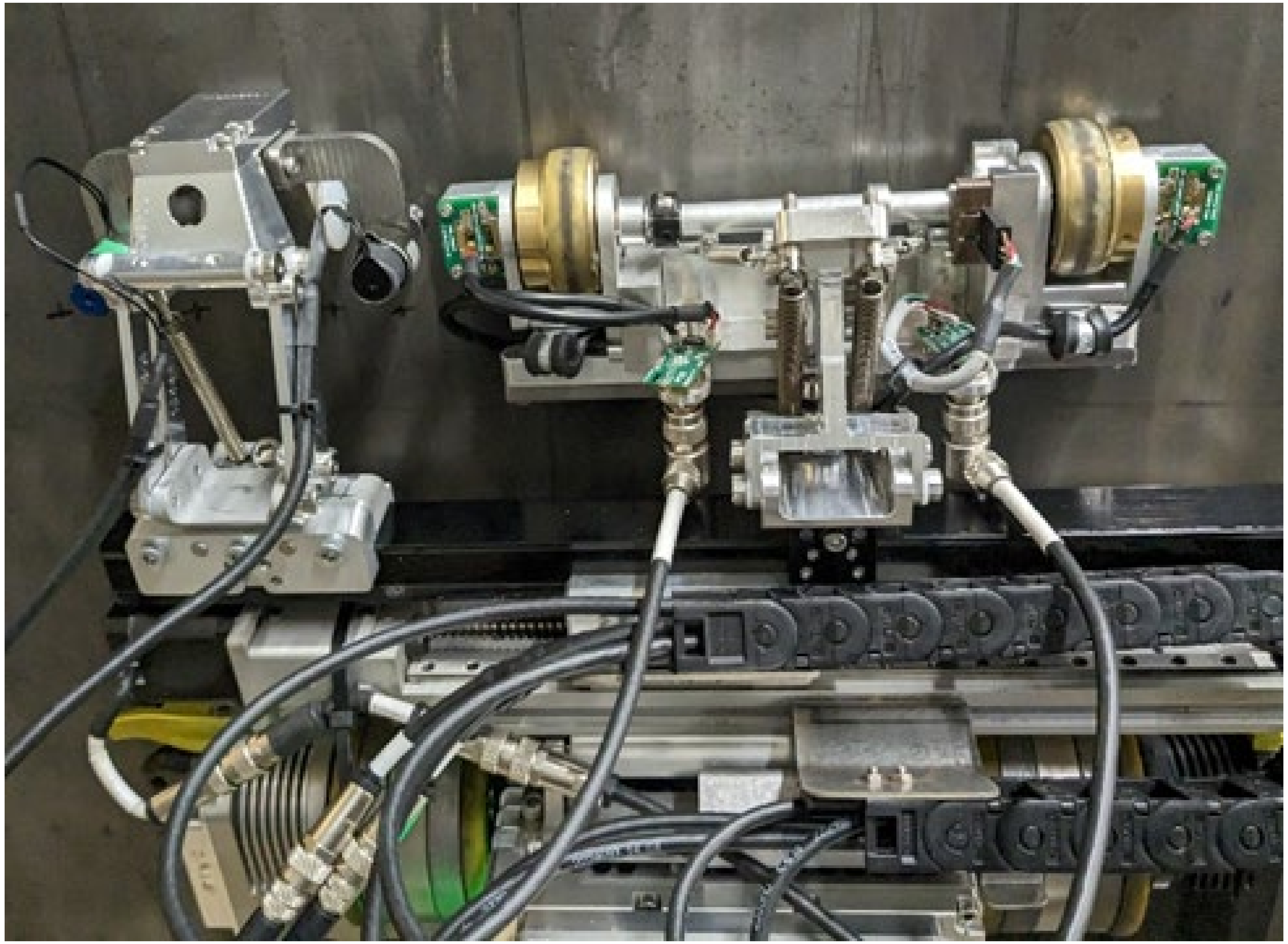
gecko robotics

Olson ENGINEERING

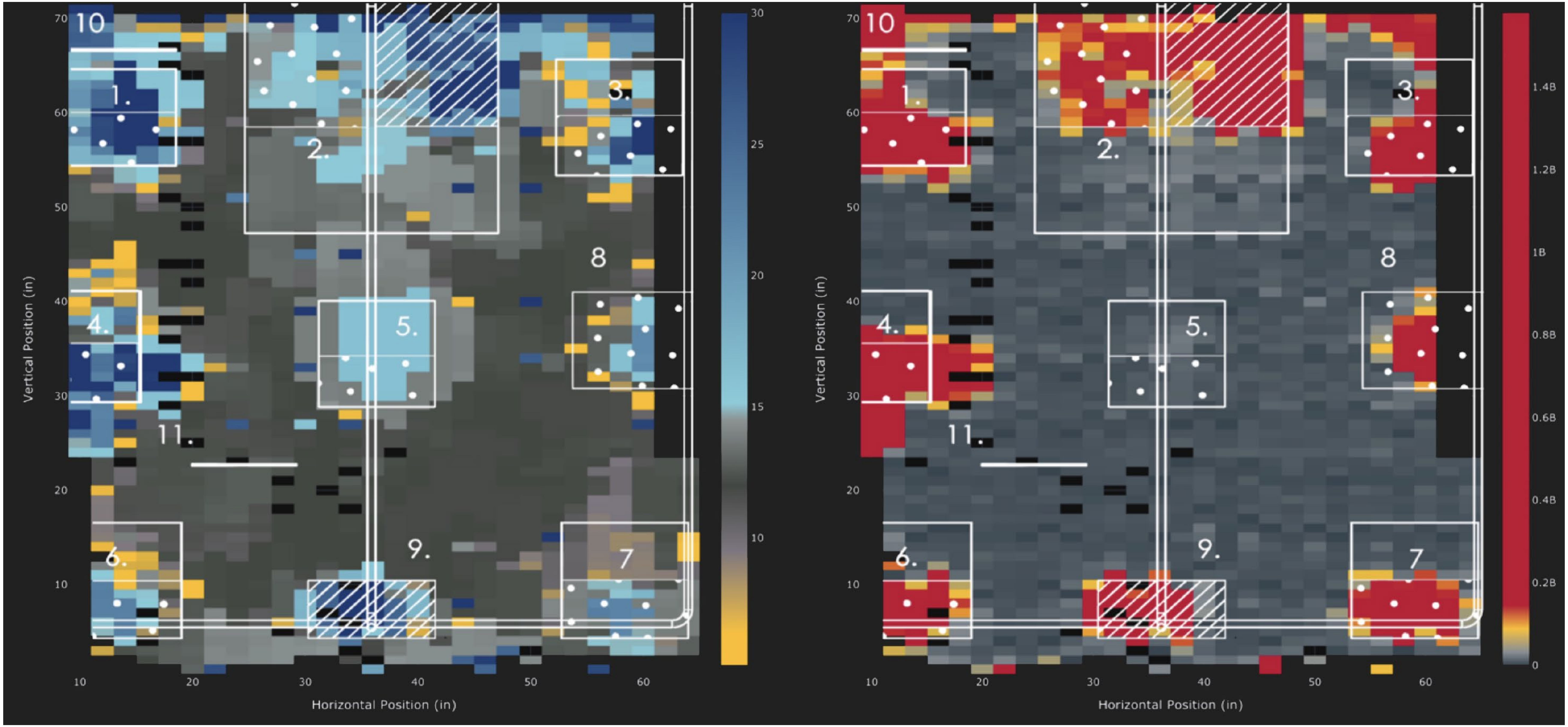
Gecko Robot - **Ultrasonic Pulse Echo Scanning of Steel** with 24 Sensors for thickness/integrity/corrosion – 1 inch (25 mm) spacing of scan lines



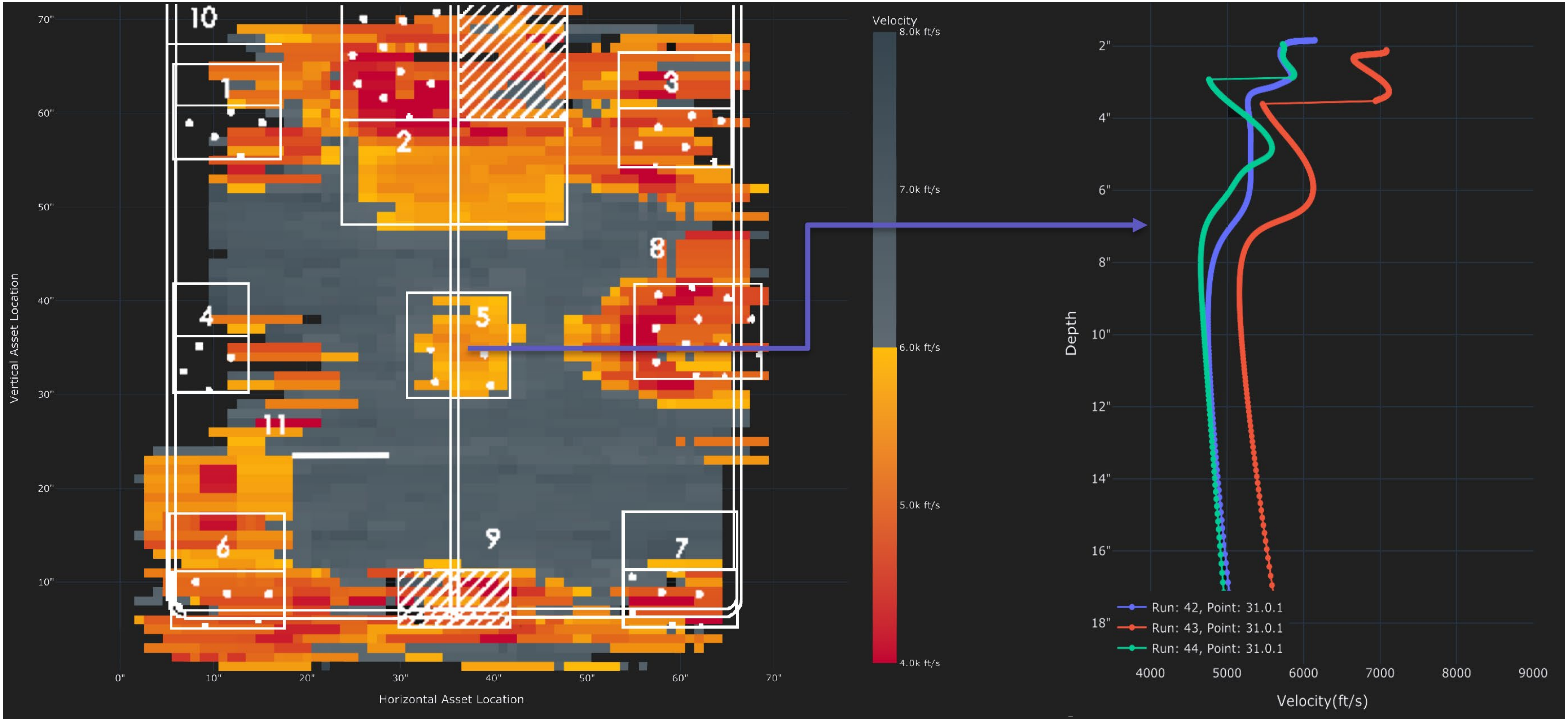
Monarch IE+SASW Scanning Robot on Wall #1 on right.
Below is a view of **solenoid impactors** (on the left) and **two dry-coupled rolling displacement transducer wheels** for **tests every 1 inch (25.4 mm) with IE** (left wheel) and **SASW tests over 6 inches (152.4 mm)** between left and right wheels



Monarch Impact Echo (IE) Scan Results for 2 inch spaced vertical lines overlaid on defects from Wall #1 with IE dominant thickness echo depths (inches) on left and IE echo amplitudes plotted on the right.



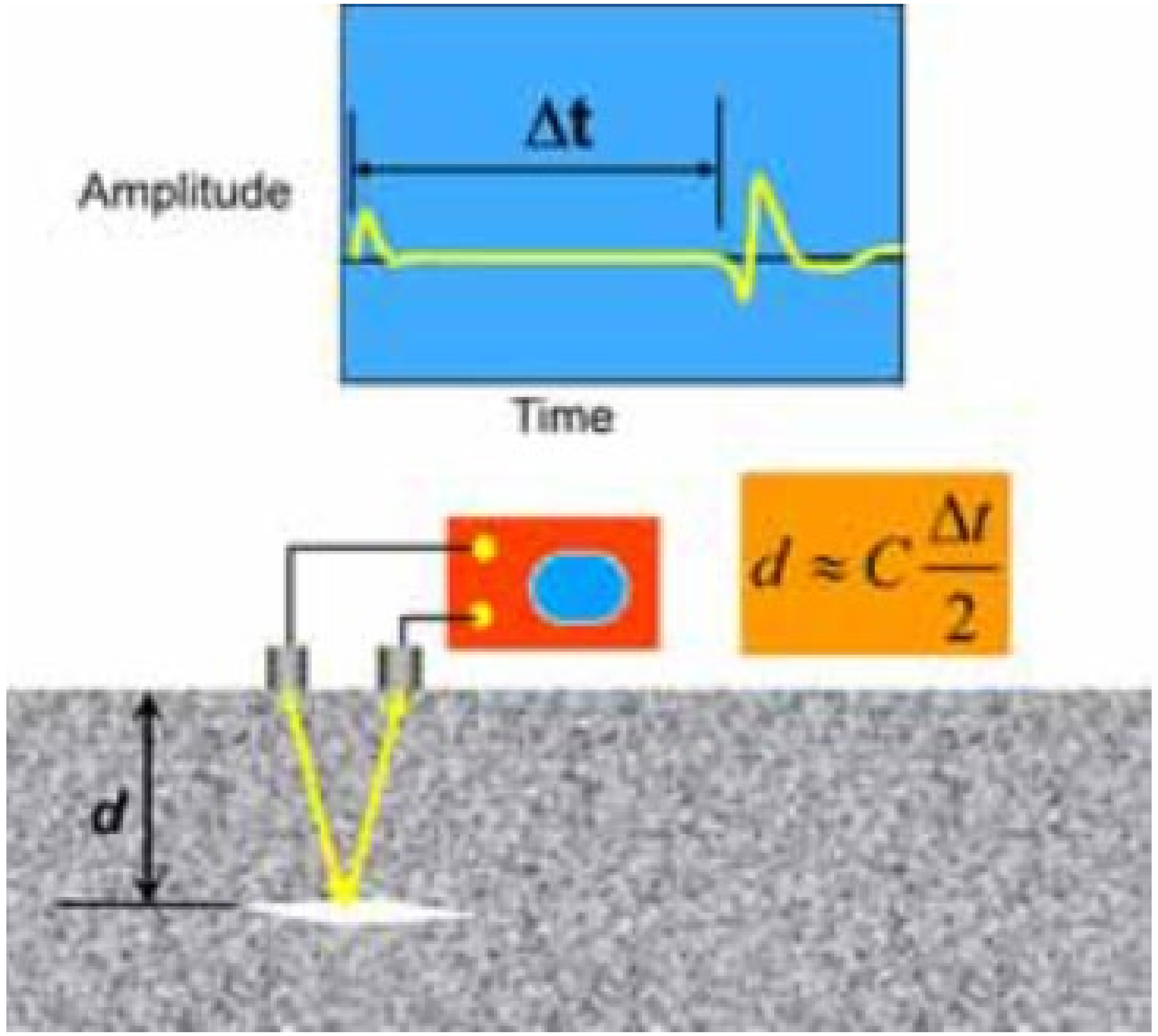
Monarch Spectral Analyses of Surface Waves (SASW) Scan Results for 2 inch spaced vertical scans and 6 inch sensor wheel spacing overlaid on defects from Wall #1 – velocity plot (left) & velocity vs. ~depth for Flaw #5 Honeycomb at 4 inches deep (right)



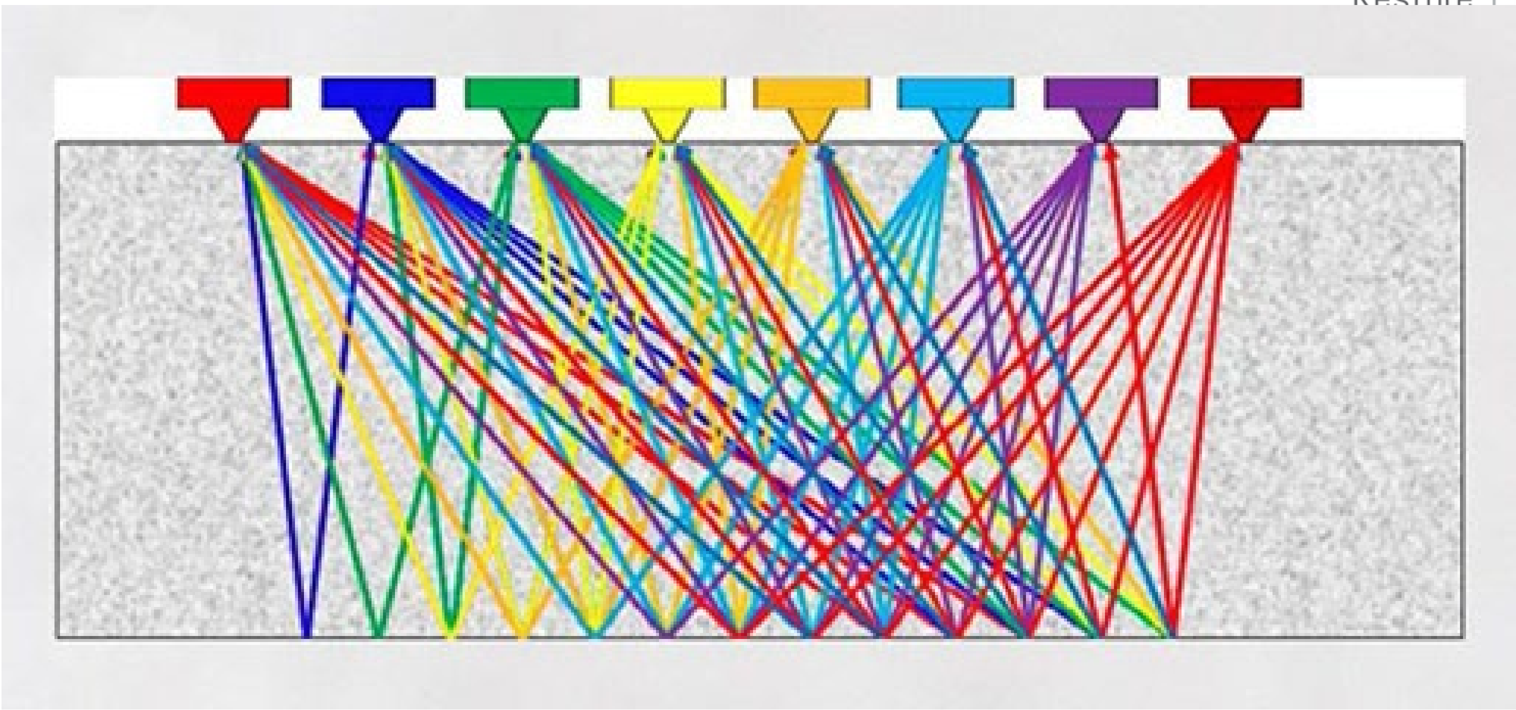
Summary and Conclusions of NDE Research on Detecting Concrete Defects behind Steel Plates with Robotic Scanning

- Impact Echo Scanning (IES) and Spectral Analyses of Surface Waves (SASW) best detected the embedded concrete defects in Wall #1.
- IES and SASW with IES being the method that is most sensitive. The ability to detect a flaw within the concrete depends on at least partial bonding of the plate/concrete interface and decreases substantially with severe debonding of the steel plate.
- Robotic Scanning with the IE and SASW methods through steel plates are able to provide much more rapid and detailed mapping of concrete flaws such as cracks, voids, and other defects versus point-by-point testing.
- The **Gecko Ultrasonic Pulse Echo Robotic Steel Scanning** system can now be combined with the **Gecko Monarch Robot Concrete Scanning** system for thickness/integrity/ corrosion evaluations for detailed "inch by inch" condition assessment of such steel-plated concrete structures as missile silos and nuclear reactor containment domes.

Ultrasonic Pulse Echo (UPE) – Shear Wave Tomography Method



d = C * Δt / 2 where d is echo depth, C is shear wave velocity and Δt is the echo reflection time



Phased UPE Array for Shear Wave Reflections for 8 sensor combinations

Screening Eagle Proceq PD8050 (left)
Ultrasonic Pulse Echo-Shear Wave Tomography Unit

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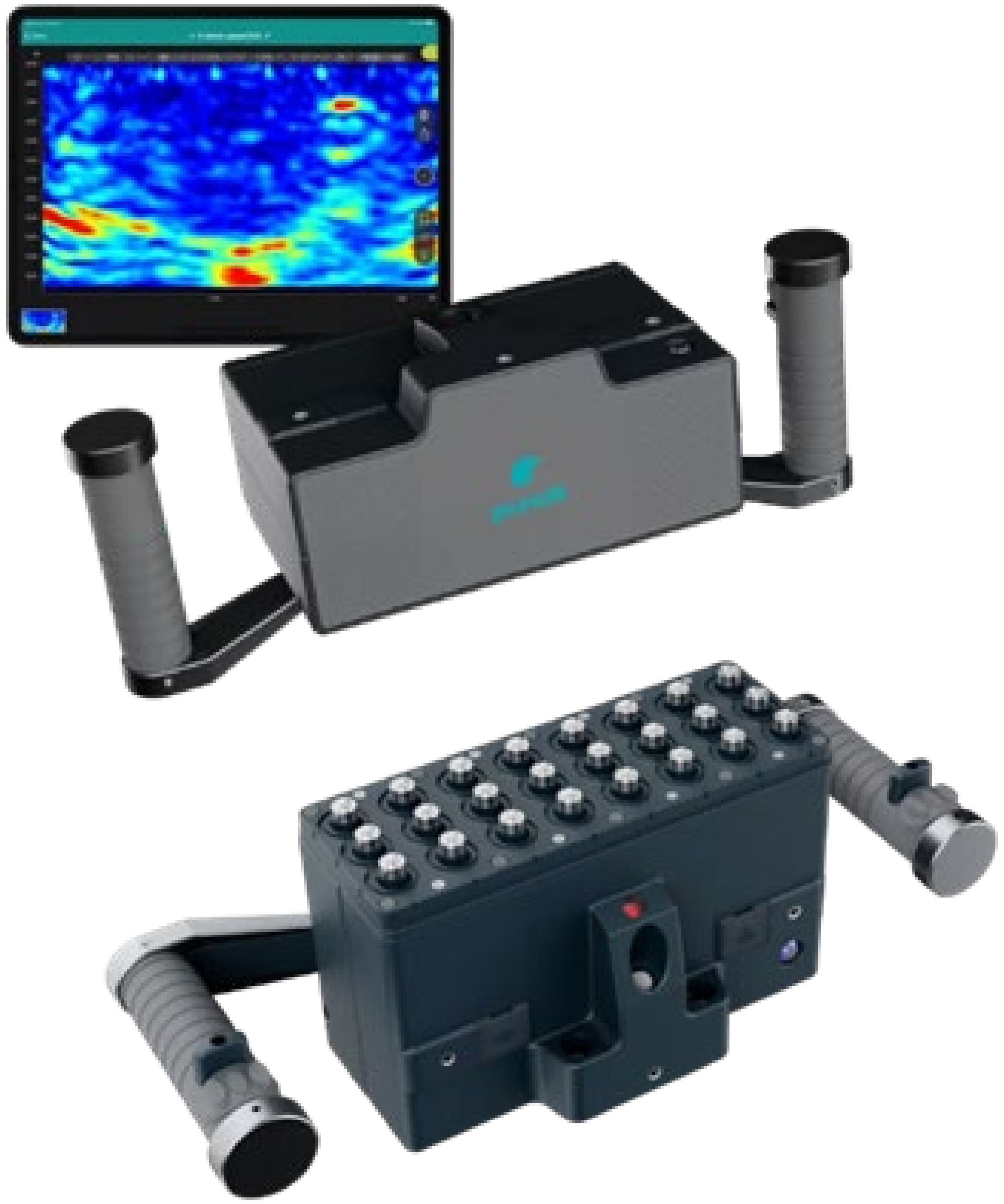

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Pundit 8050 UPE system used in Stripe Scan 3D Mode with the Apple iPad for Data Acquisition performed on Surface K with the AI automatic position strip scan mode utilized along the tape mounted on the beam

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Example Stripe Scan depth slice (C-Scan display) results for a Sound (Top Plot) depth range of 0 to 28.3 inches with no anomalies at a test strip location at mid-beam height and for the Anomaly reflections in yellow to red (Bottom Plot) for a display depth range of 0 to 4.3 inches for this UPE test strip location from the side of the beam near the beam bottom Note the void/honeycomb anomalies are generally 2 to 3 inches in size.

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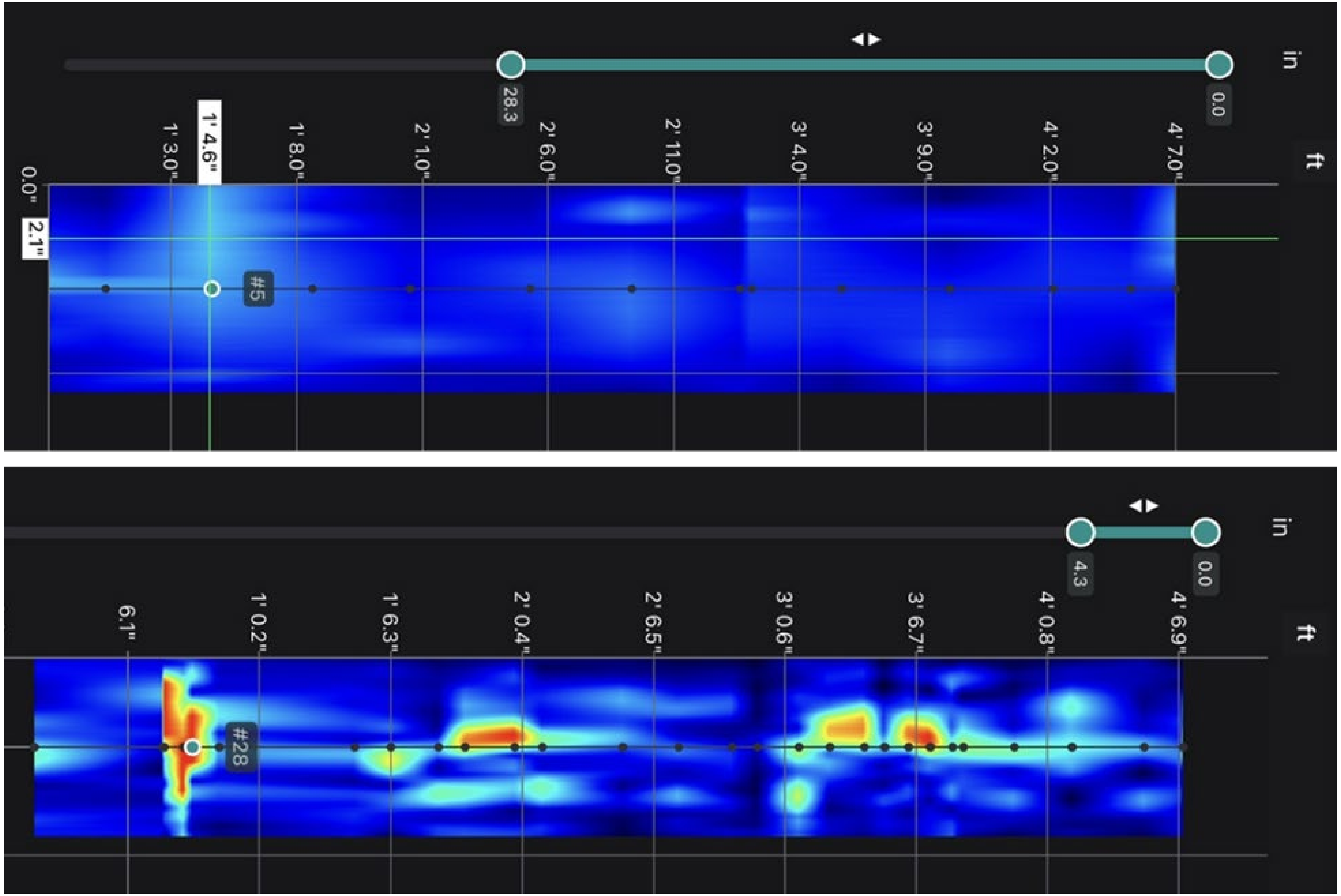

Example Stripe Scan 3D rendering of the example Bottom Plot depth slice in Figure 8 showing a majority of the anomalies found from 0 to 3.5 inches from the surface with some from 3.5 to 9.8 inches from the surface, and limited anomalies from 9.8 to 18.5 inches from the surface (color depth scale on left side of plot) for this horizontal stripe scan from the side of the beam near its bottom.

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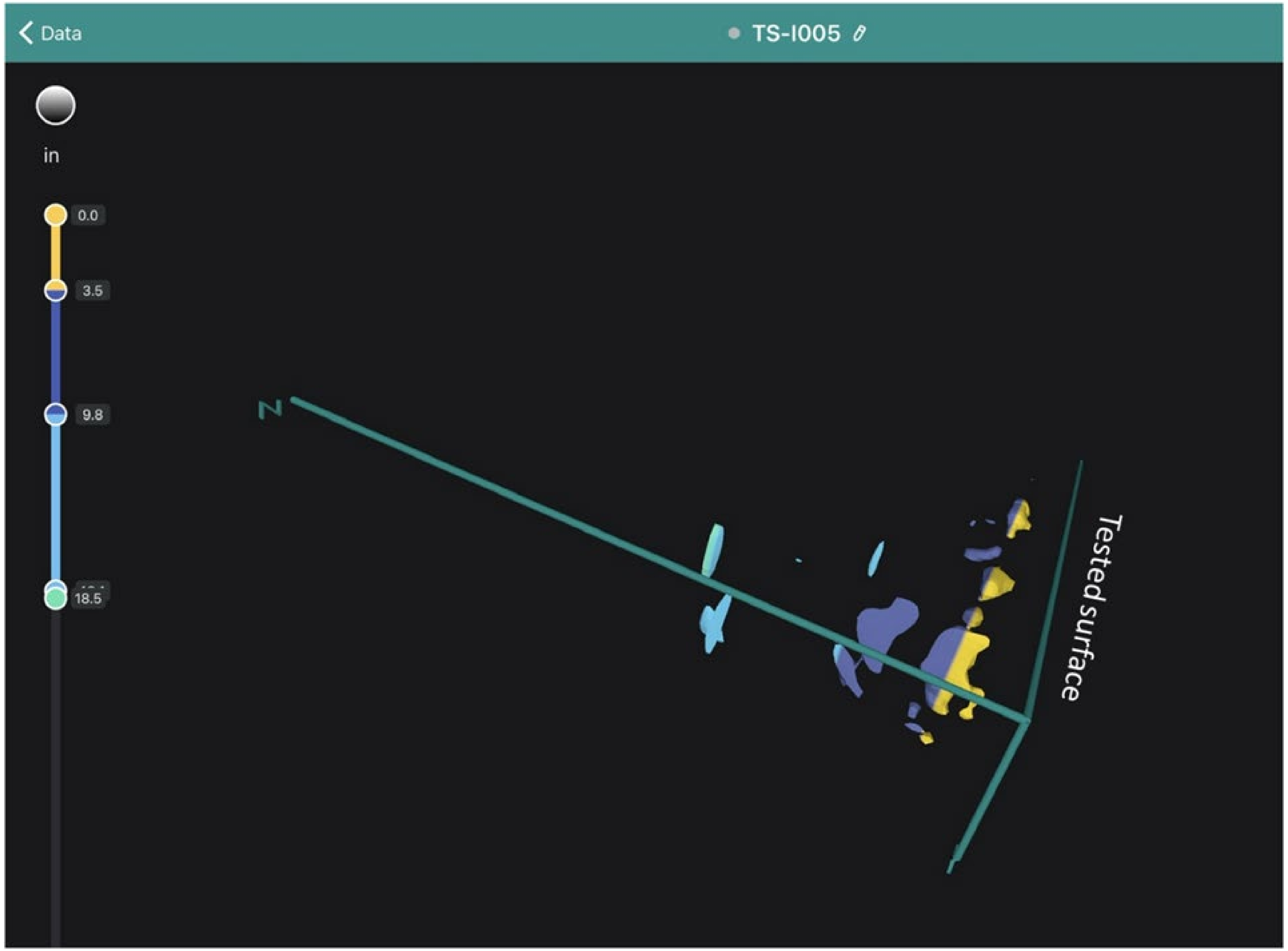
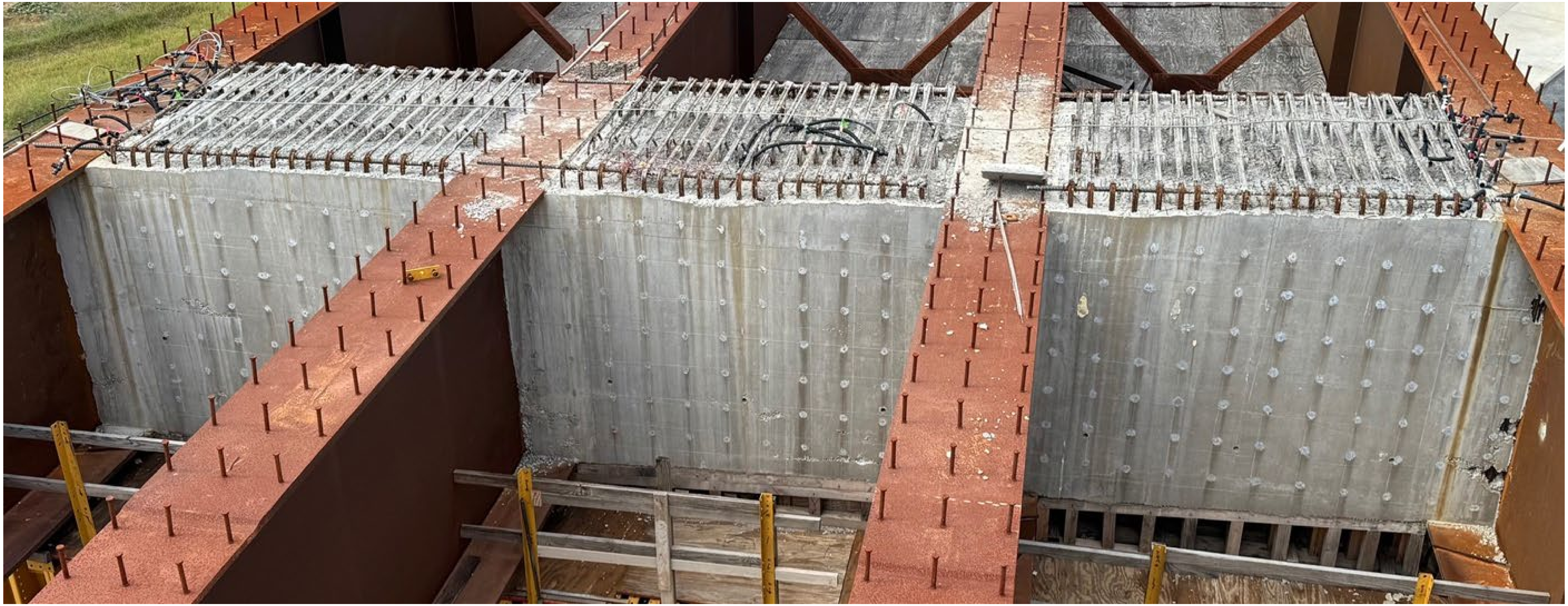


UPE Shear Wave Reflection Tomography Example Results - Post-Tensioned / Cap Concrete Beam with Honeycomb/Void



Proceq PD8050 UPE System with an Apple iPad. Note the 8 rows of 3 spring-loaded point contact transducers to generate and receive shear wave energy for the shear wave velocity reflection tomograms

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UPE Shear Wave 3D Tomography images of ungrouted PT Ducts at 12 inches deep clear at left side and less clear over honeycomb on right side due to lack of coupling on surface void

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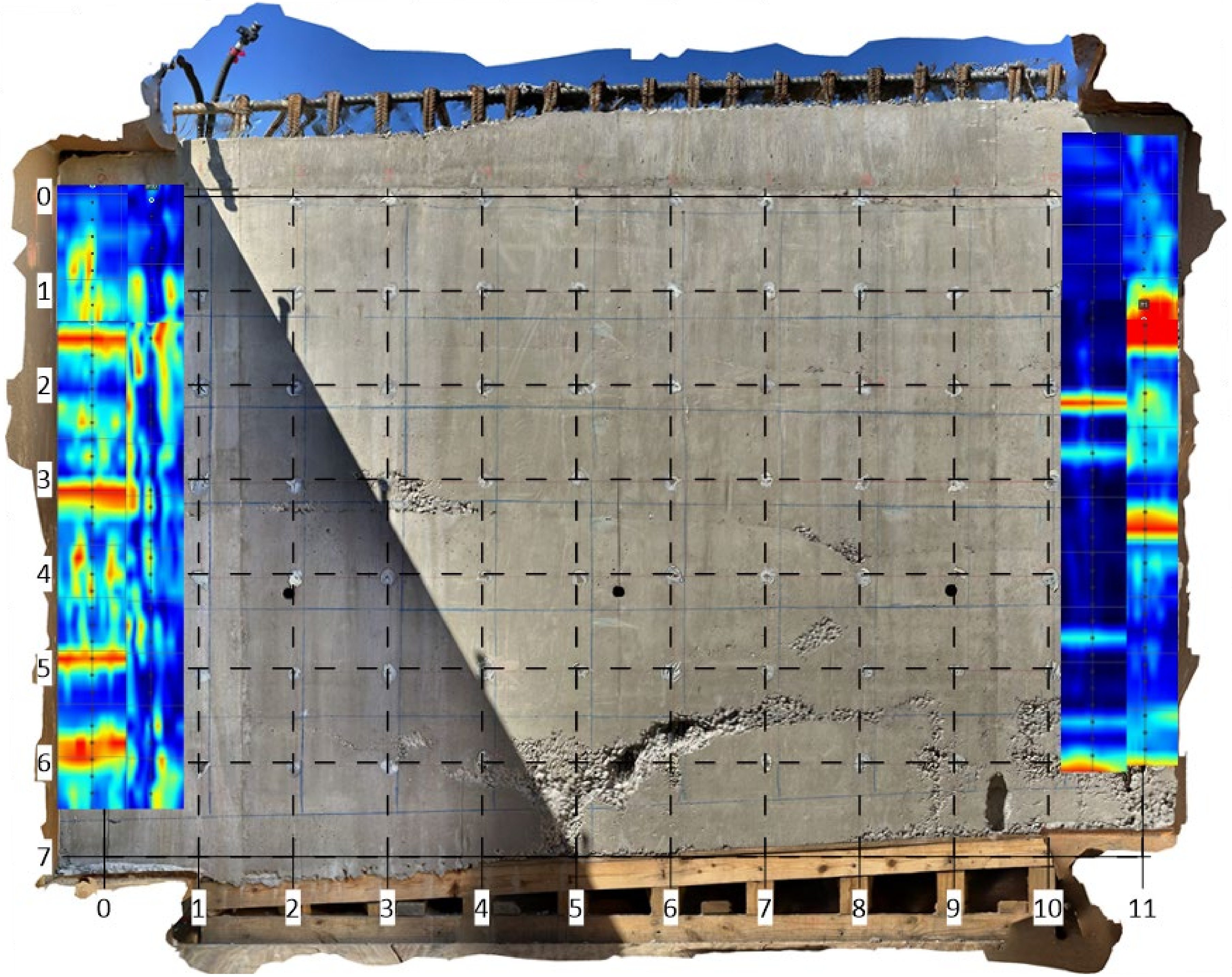

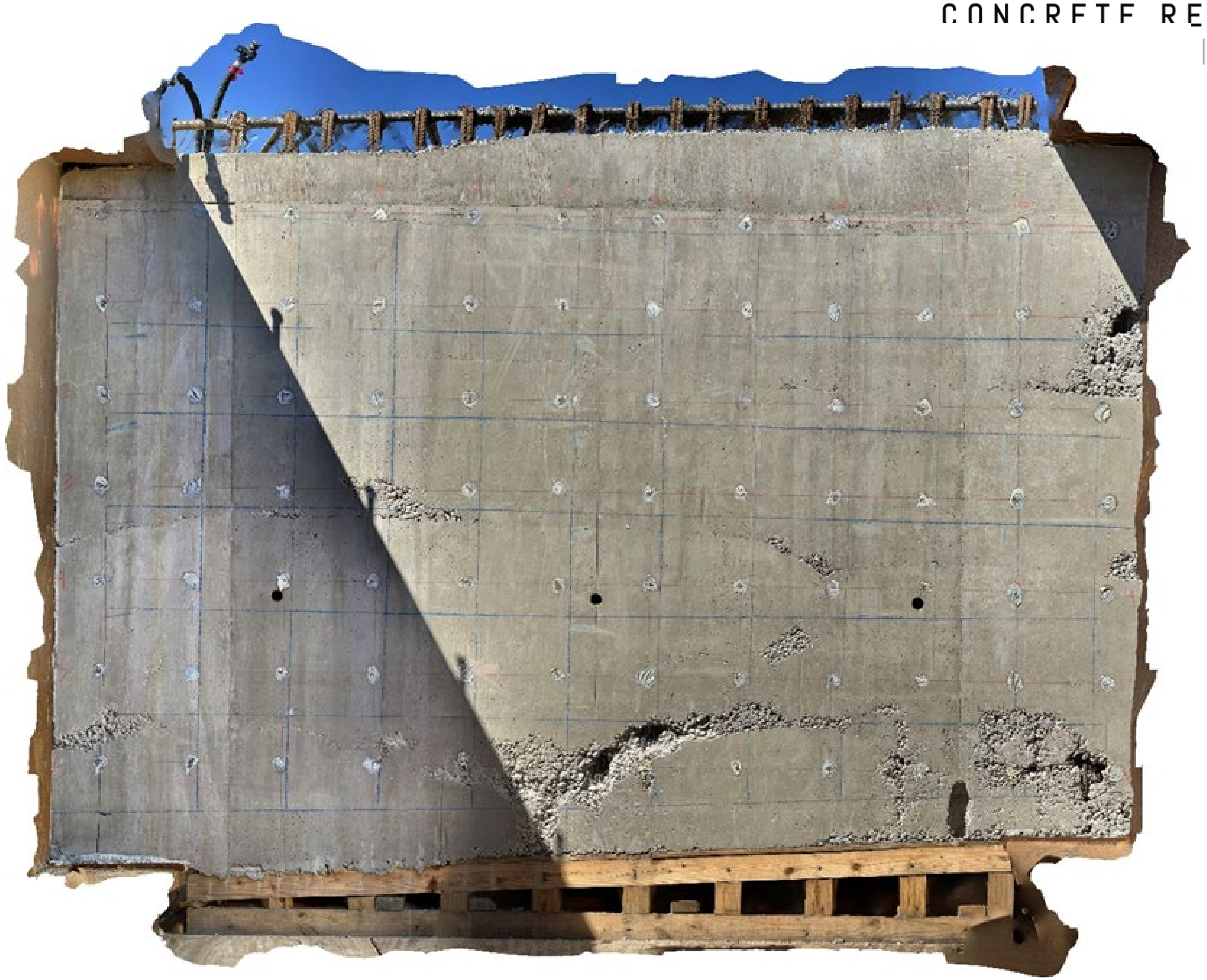

Ultrasonic Pulse Echo Shear Wave Reflection Tomography Applications

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- Void and delamination detection
- Bonding assessment
- Concrete cracks
- Thickness measurement to from 3 to 5 ft
- Honeycombing detection and size estimation of void/honeycomb
- Imaging of closely spaced rebars
  (more commonly done with ground penetrating radar)

ICRI Concrete Repair Bulletin Article in 2002 - NDE Methods for QA of Epoxy Injection Repairs

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, 2002)

- Concrete bridge over I-70 was impacted by a forklift carried by a truck
- Cracks and spalls were observed on the east side of the girder

Repair Procedures

- Chipping loose and damaged concrete
- Pre-saturate the surface with water
- Use structural repair mortar to patch the spalling
- Use epoxy injection for cracks

Nondestructive Quality Assurance Methods for Epoxy Repairs

(see Guide for Verifying Field Performance of Epoxy Injection of Concrete Cracks, International Concrete Repair Institute ICRI Guideline No. 210.1R -2016)

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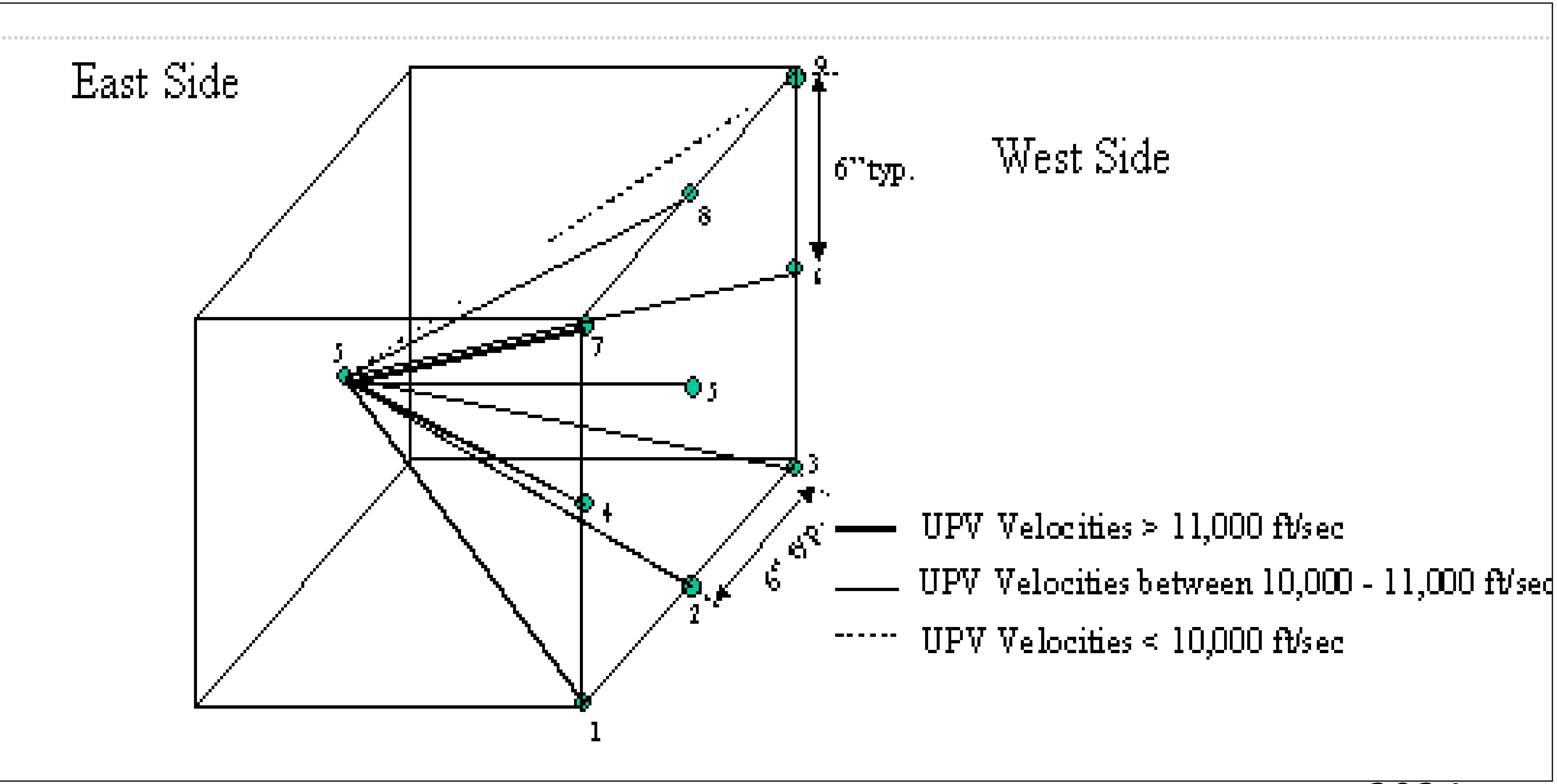
Impact Echo (IE)

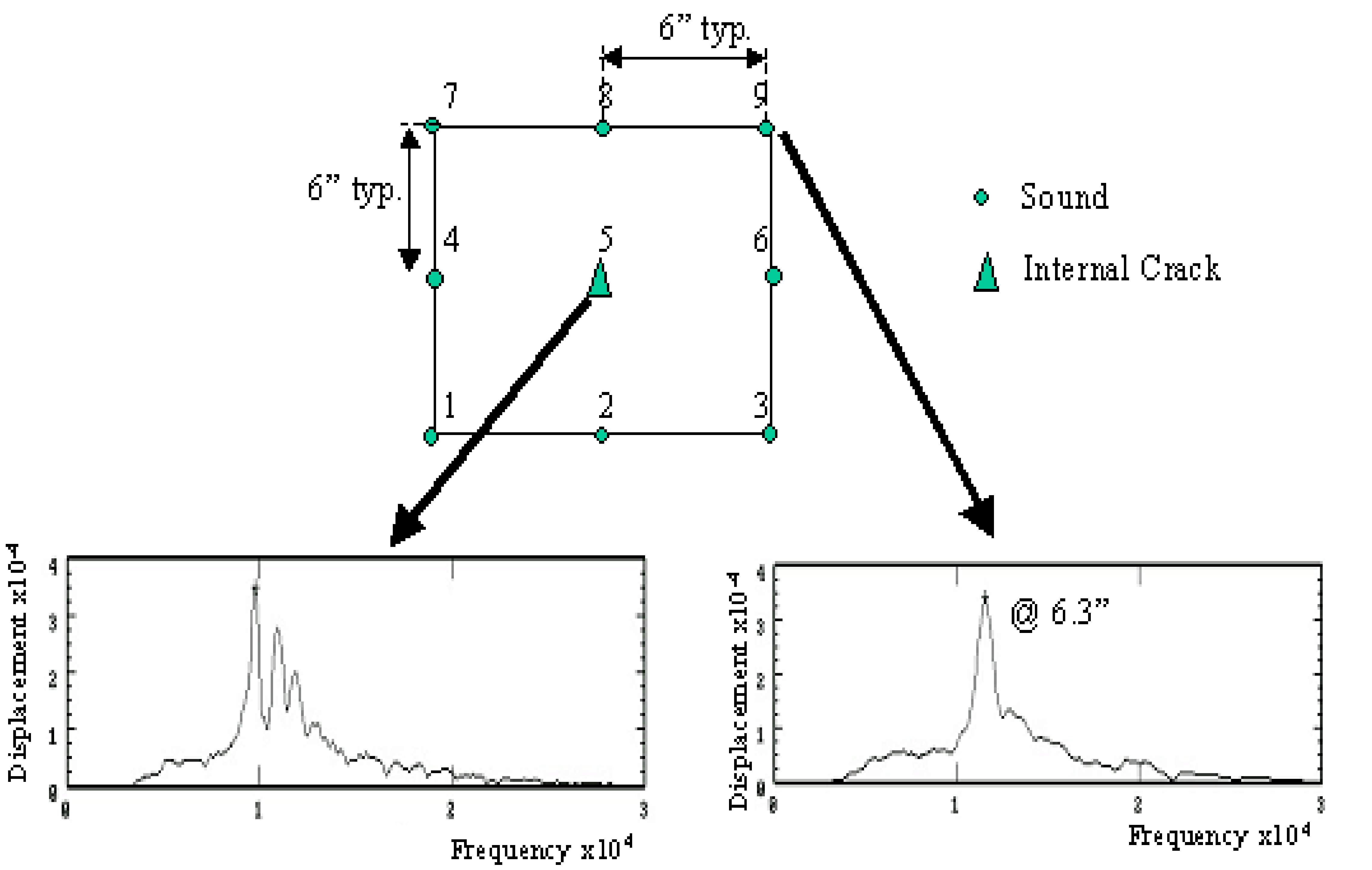
Ultrasonic Pulse Velocity (UPV)

Spectral Analysis of Surface Waves (SASW)

UPV Results through Epoxy Injected Web of Girder



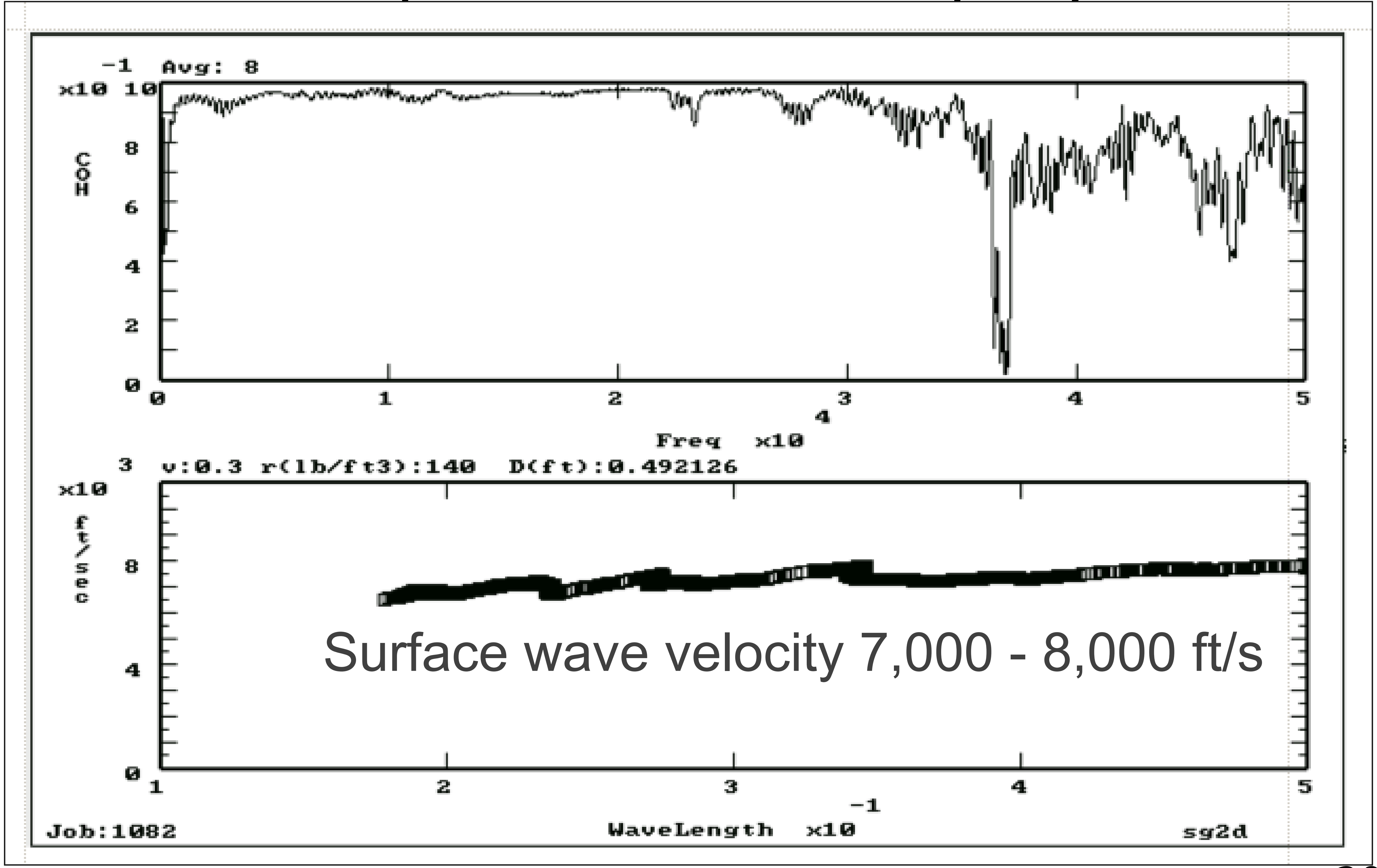
Impact Echo (IE) Example Results for Unfilled Crack and Epoxy Filled Crack (Sound)



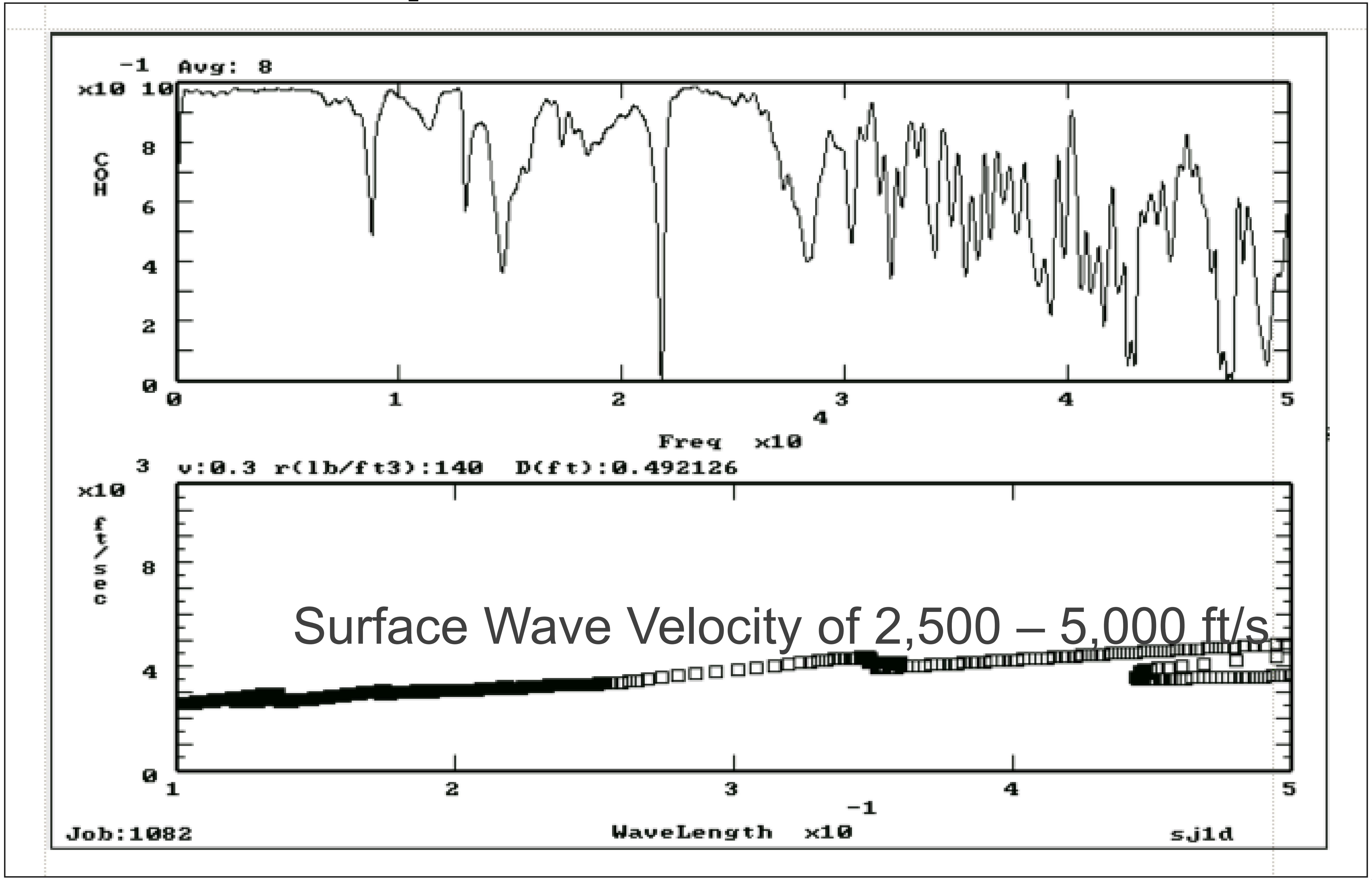
Typical Example of Impact Echo Record with Crack Signature

Typical Example of Sound Impact Echo Record

SASW Example Results from Epoxy Filled Crack



SASW Example Results of Unfilled Crack



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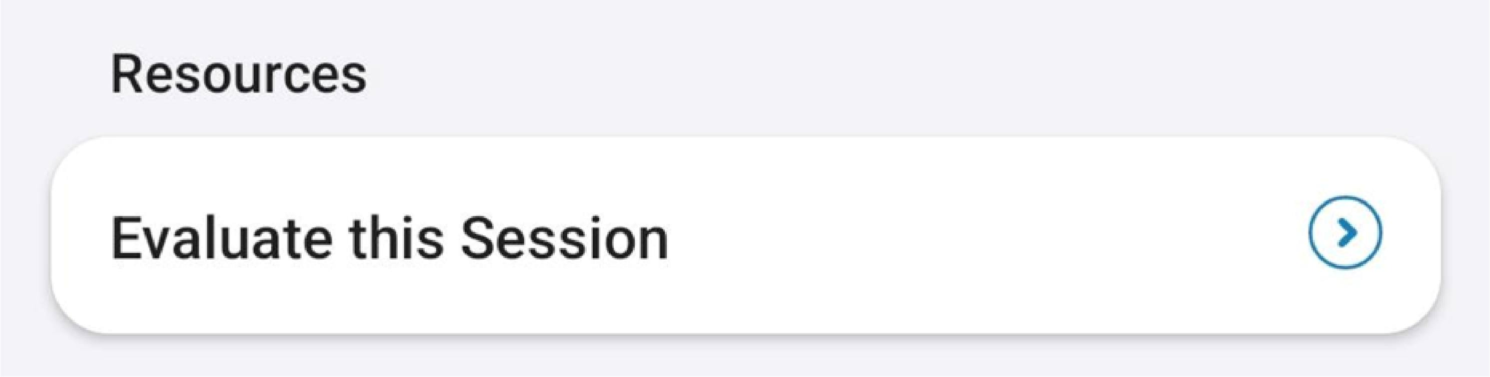
Live Content Slide

When playing as a slideshow, this slide will display live content

Poll: Which 2 of these NDE methods is able to provide an image of internal honeycomb/void in a concrete member?

SESSION EVALUATION



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